PSSE PV and QV Analysis Study Report

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October 16, 2025

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Chapter 1

Performing PV and QV Analyses

1.1 Introduction

The PV/QV analyses are designed for studies of low voltage stability, which could be analyzed as a steady-state problem. They are power flow based analyses used to assess voltage variations with active and reactive power change. Two methods are used to determine the loading limits imposed by voltage stability under the steady-state conditions. The PV/QV analyses do not provide solutions to specific problem but function as tools that can be directed by the user to perform analyses in the solution of problems associated with the steady-state voltage stability of power systems.

The objective of a PV and QV curves is to determine the ability of a power system to maintain voltage stability at all the buses in the system under normal and abnormal steady-state operating conditions. They are useful, for example:

- To show the voltage collapse point of the buses in the power system network.
- To study the maximum transfer of power between buses before voltage collapse point.
- To size the reactive power compensation devices required at relevant buses to prevent voltage collapse.
- To study the influence of generators, loads and reactive power compensation devices on the network.

The PV and QV curves are obtained through a series of ac power flow solutions. The PV curve is a representation of voltage change as a result of increased power transfer between two systems, and the QV curve is a representation of reactive power demand by a bus or buses as voltage level changes.

1.2 Description for System Under Study

The following section describes the system and system conditions for which PV and QV analysis is carried out. The focus of this study is to carry out PV and QV analysis on Bus 3005 in area 5 (WORLD) of the savnw system. The Figure 1.1 shows the Bus 3005 considered for the analysis.

The bus 3005 connections are as follows

- to bus 3003 by two lines
- to bus 3008 by two lines
- to bus 3006 by a single line
- to bus 3004 by a 2-winding transformer
- to load of magnitude 102+j51.0

Following contingencies at the bus 3005 are considered for conducting the analysis.

- Single open line 1 3005-3003(1)
- Single open line 2 3005-3003(2)

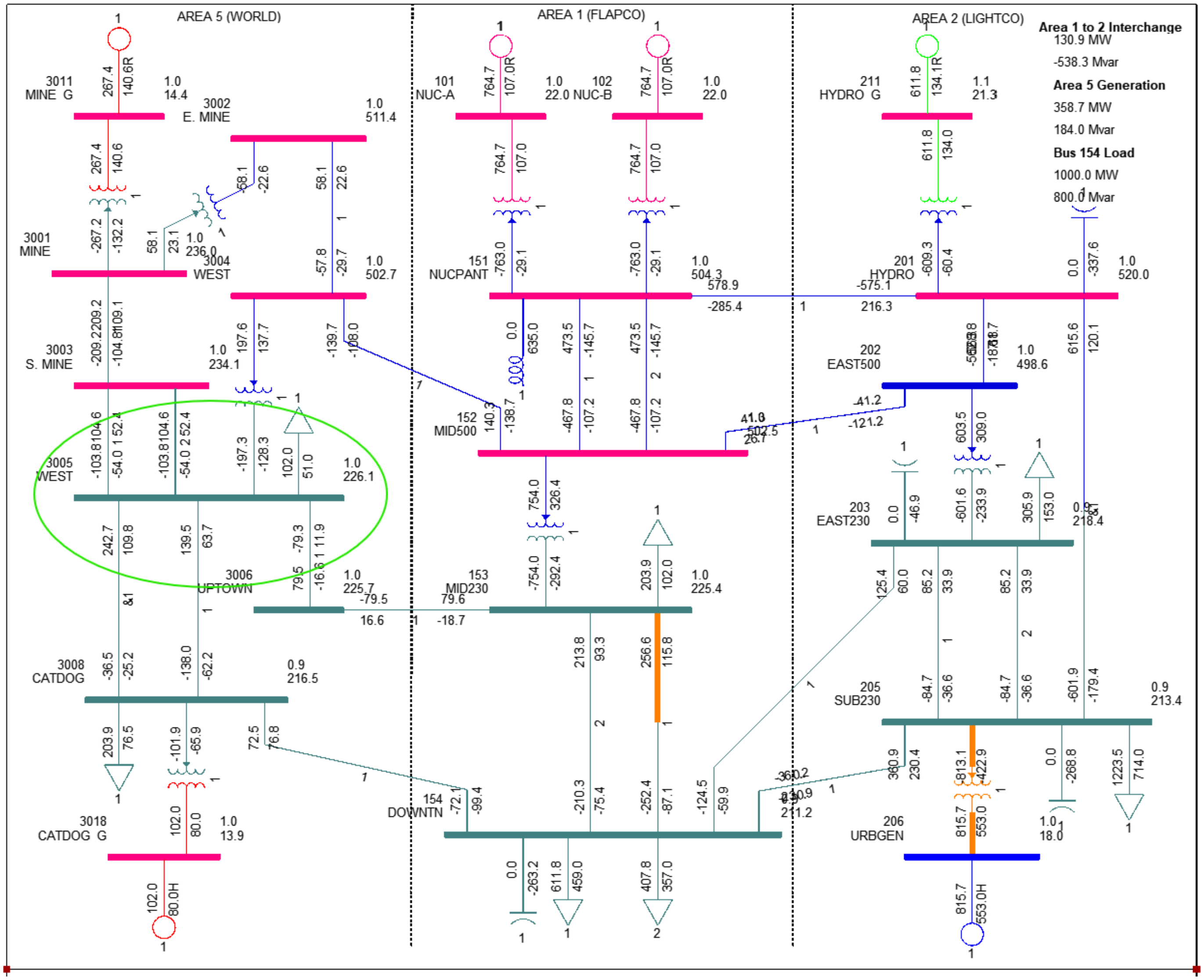

Figure 1.1: System/Bus for conducting PV and QV Analysis

- Single open line 3 3005-3004(1)
- Single open line 4 3005-3006(1)
- Single open line 5 3005-3008(&1)
- Single open line 3 3005-3008(1)

The various loads for which the analysis is carried out are

- 41+j30.6 (PF = 0.80 lagging)
- 20+j10 (PF = 0.89 lagging)
- 32+j6.4 (PF = 0.98 lagging)
- 40+j0 (PF = UPF)
- 41-j30.6 (PF = 0.80 leading)
- 20-j10 (PF = 0.89 leading)
- 32-j6.4 (PF = 0.98 leading)

The PV analysis is carried out for loads of various power factors to determine the incremental transfers possible from the defined source subsystem to the sink subsystem. The QV analysis is carried out to size the reactive power supporting elements that will be required to maintain a desired voltage at the studied Bus 3005. The configuration files (.sub, .mon and .con) for creating the distribution factor file for this study is as shown in Figure 1.2.

Subsystem Definition

```
SUBSYSTEM SOURCE
  BUS 3011
  BUS 3008
END

SUBSYSTEM SINK
  BUS 3005
END

SUBSYSTEM CON
   BUS 3005
END

SUBSYSTEM MON
   BUS 3005
END

END
```

Monitored Element

```
MONITOR VOLTAGE RANGE SUBSYSTEM MON 0.950 1.050
END
END
```

Contingency Definition

```
SINGLE LINE FROM BUS 3005
END
END
```

Figure 1.2: System/Bus for conducting QV Analysis

Chapter 2

PV Analysis

2.1 Introduction

PV curves are parametric study involving a series of ac power flows that monitor the changes in one set of power flow variables with respect to another in a systematic fashion. This approach is a powerful method for determining transfer limits that account for voltage and reactive flow effects. As power transfer is increased, voltage decreases at some buses on or near the transfer path. The transfer capacity where voltage reaches the low voltage criterion is the low voltage transfer limit. Transfer can continue to increase until the solution identifies a condition of voltage collapse; this is the voltage collapse transfer limit.

PV curves are typically used for the knee curve analysis. It is as named because of its distinctive shape at the point of voltage collapse as the power transfer increases. Depending on the transfer path, different buses have different knee point. The buses closer to the transfer path will normally exhibit a more discernible knee point.

Voltage instability occurs at the knee point of the PV curve where the voltage drops rapidly with an increase in the transfer power flow. The power flow solution will not converge beyond this limit, indicating voltage instability. Operation at or near the stability limit is impractical and a satisfactory operating condition must be ensured to prevent voltage collapse.

In PSSE, the PV curves are generated by selecting two subsystems where the power transfer between the subsystems is incremented in a defined step size for a series of ac power flow calculations while the bus voltages, generator outputs and the branch flows of the system are monitored. When the bus voltages are plotted as a function of the incremental power transfer the PV curves are obtained. One of the subsystems in the study must be defined as the study (source) system and another as the opposing (sink) system. The power flows from the study subsystem to the opposing subsystem.

In this chapter PV analysis is analysed to determine the maximum power that can be transmitted at any load factor. In the previous chapter the various load factors that will be considered for this analysis was listed.

2.2 PV Analysis in PSSE

The PV analysis is carried out for loads of various power factors to determine the incremental transfers possible from the defined source subsystem of generators connected in Bus 3011 and Bus 3018 to the sink subsystem of Bus 3005. By conducting PV analysis for the defined source and sink subsystem, the goal of this study is to determine the maximum power transfer possible for each of the considered cases and loads. Figure 2.1 shows the PV analysis parameters considered for this study.

Figure 2.2 shows the PV curves of a bus 3005 in an example network under normal and various contingency conditions for a load factor of 0.89 lagging. The maximum transfer limit for this bus in base case is approximately 400 MW. The maximum transfer limit decreases under contingency conditions. The response shown is expected because under network contingencies the loading of the line will increase. These curves can be used to set transfers or local generation dispatch so that the system will not fall below the knee point following a disturbance (i.e. loss of lines).

The complete results of PV analysis for each MW incremental transfer of every case and load obtained from PSSE is given in the Appendix A of this document.

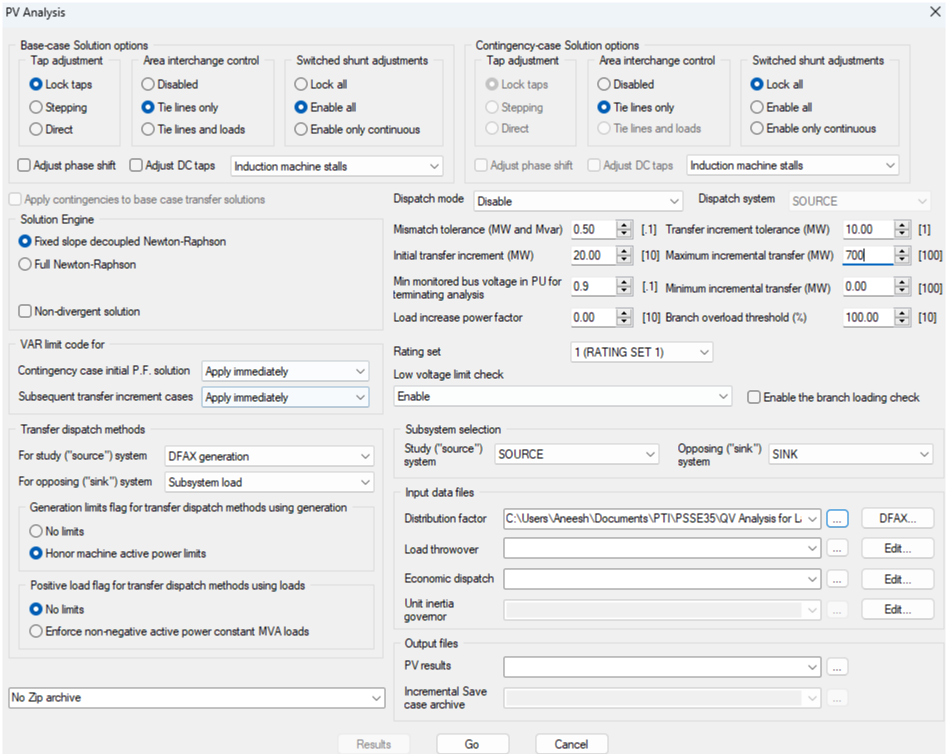

Figure 2.1: PV Analysis Study Parameters

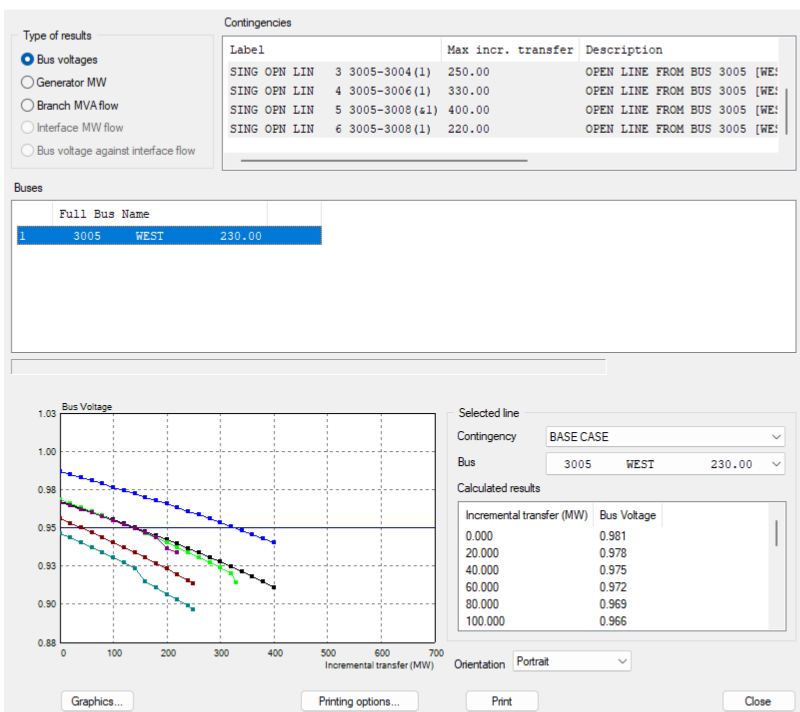

Figure 2.2: PV Curves Voltage and Incremental Power Transfer Characteristics for Bus 3005 under Different Network Conditions

2.3 Analysis of PV Solution for Different Network Conditions

As previously mentioned in Chapter 1 there are 7 contingency cases and 7 load factors considered for this analysis. Each of these loads are started with a low magnitude and the PV analysis scales these loads in MWs of 20 to give corresponding voltages at Bus 3005. Table 2.1 tabulates the maximum incremental transfers to the bus for base case and contingencies for each considered load factor.

Study Case	Load	Load Factor	Maximum incr. transfer	Voltage (PU)
BASE CASE	32-j6.4	0.98 leading	680	0.976
	20-j10	0.89 leading	700	1.021
	41-j30.6	0.8 leading	680	1.054
	40+j0	UPF	660	0.943
	32+j6.4	0.98 lagging	620	0.914
	20+j10	0.89 lagging	400	0.913
	41+j30.6	0.8 lagging	280	0.912
SING OPN LIN 1 3005-3003(1)	32-j6.4	0.98 leading	680	0.946
	20-j10	0.89 leading	700	1.003
	41-j30.6	0.8 leading	680	1.044
	40+j0	UPF	540	0.922
	32+j6.4	0.98 lagging	380	0.918
	20+j10	0.89 lagging	250	0.916
	41+j30.6	0.8 lagging	170	0.914
SING OPN LIN 2 3005-3003(2)	32-j6.4	0.98 leading	680	0.946
	20-j10	0.89 leading	700	1.003
	41-j30.6	0.8 leading	680	1.044
	40+j0	UPF	540	0.922
	32+j6.4	0.98 lagging	380	0.918
	20+j10	0.89 lagging	250	0.916
	41+j30.6	0.8 lagging	170	0.914
SING OPN LIN 3 3005-3004(1)	32-j6.4	0.98 leading	680	0.941
	20-j10	0.89 leading	700	0.999
	41-j30.6	0.8 leading	680	1.041
	40+j0	UPF	580	0.902
	32+j6.4	0.98 lagging	380	0.899
	20+j10	0.89 lagging	250	0.896
	41+j30.6	0.8 lagging	160	0.897
SING OPN LIN 4 3005-3006(1)	32-j6.4	0.98 leading	680	0.976
	20-j10	0.89 leading	700	1.026
	41-j30.6	0.8 leading	680	1.063
	40+j0	UPF	660	0.939
	32+j6.4	0.98 lagging	520	0.918
	20+j10	0.89 lagging	330	0.917
	41+j30.6	0.8 lagging	280	0.908
SING OPN LIN 5 3005-3008(&1)	32-j6.4	0.98 leading	680	1.01
	20-j10	0.89 leading	700	1.051
	41-j30.6	0.8 leading	680	1.092
	40+j0	UPF	660	0.98
	32+j6.4	0.98 lagging	620	0.954
	20+j10	0.89 lagging	400	0.948
	41+j30.6	0.8 lagging	280	0.945
SING OPN LIN 6 3005-3008(1)	32-j6.4	0.98 leading	680	0.975
	20-j10	0.89 leading	700	1.021
	41-j30.6	0.8 leading	680	1.056
	40+j0	UPF	600	0.942
	32+j6.4	0.98 lagging	370	0.94
	20+j10	0.89 lagging	220	0.94
	41+j30.6	0.8 lagging	140	0.939

Table 2.1: Maximum power transfer for considered study cases and load factors

From Table 2.1, looking at the results of base case and the contingency case of single open line 1 3005 - 3003 (1), the following inferences are derived.

For the base case, the maximum power transfer of 700 MW is achieved for a load factor of 0.89 leading at a bus voltage of 1.021 PU, which is below the upper limit of 1.05 PU. Besides the above case, the load factor 0.98 leading also has the maximum transfer of 680 MW achieved at a bus voltage of 0.976 PU. All other load factors considered have their maximum power transfers achieved outside of the normal operating limit of 0.95 PU to 1.05 PU.

For the single open line 1 3005 - 3003 (1), the maximum power transfer of 700 MW is achieved for a load factor of 0.89 leading at a bus voltage of 1.003 PU, which is below the upper limit of 1.05 PU. Besides the above case, the load factor 0.8 leading also has the maximum transfer of 680 MW achieved within the normal operating limit at a bus voltage of 1.044 PU. Similar to the Base Case all other load factors considered have their maximum power transfers achieved outside of the normal operating limit of 0.95 PU to 1.05 PU.

Chapter 3

QV Analysis

3.1 Introduction

QV (Reactive Power - Voltage) curve analysis focuses on reactive power support required to maintain voltage within acceptable limits at the studied bus. By injecting or absorbing reactive power at specified buses and observing voltage changes, it reveals the system's voltage sensitivity and strength. Together, these analyses provide a comprehensive view of voltage stability, guiding decisions on reactive power compensation and system reinforcements.

The QV analysis process does a series of power flow solutions with unlimited reactive power support at some bus and the estimated quantity is the bus voltage at the bus. Bus reactive support comes in two (2) ways

- Capacitive - increases bus voltage (supplying VARs to the system)
- Inductive - decreases bus voltage (absorbing VARs from the system)

QV in PSSE can be used to determine how many VARs are needed at the studied bus to maintain certain range of bus voltages defined (for both normal and outage conditions) QV curves are used to determine the reactive power injection required at a bus in order to vary the bus voltage to the required value. The curve is obtained through a series of ac power flow calculations. Starting with the specified maximum per unit voltage setpoint at the study bus, the reactive power injections can be computed for a series of power flows as the voltage setpoint is decreased in steps, until the power flow demonstrates convergence difficulties as the system approaches the voltage collapse point.

The bottom of the QV curve, where the change of reactive power, Q, with respect to voltage, V (or derivative dQ/dV) is equal to zero, represents the voltage stability limit. Because all reactive power compensator devices are designed to operate satisfactorily when an increase in Q is accompanied by an increase in V, the operation on the right side of the QV curve is stable, whereas the operation on the left side is unstable. Also, voltage on the left side may be so low that the protective devices may be activated. The bottom of the QV curves, in addition to identifying the stability limit, defines the minimum reactive power requirement for the stable operation. Hence, the QV curve can be used to examine the type and size of compensation needed to provide voltage stability. This can be performed by super-imposing the QV characteristic curves of the compensator devices on that of the system. For instance the capacitor characteristic can be drawn over the system's QV curves.

3.2 Analysis of QV Analysis Solution Using PSSE

QV analysis on the system is carried out to determine the reactive power support that would be required to maintain the voltage range of 0.90 PU to 1.10 PU at bus 3005 for the network conditions as well as for the load factors listed in Chapter 1. From the Figure 1.1, it can be seen that at present the bus does not have any reactive supporting elements connected to it. Bus 3005 has a load connected to it. There are 5 lines connecting the bus to other buses and a transformer branch to bus 3004. The normal voltage limit of operation for the system is 0.95 PU to 1.05 PU.

The goal of this study is to conduct analysis on obtained QV analysis results for various loads to determine the reactive power support needed to maintain the set voltage of 1.0 PU at bus 3005 for single line contingencies at Bus 3005. Figure 3.1 shows the QV analysis parameters considered for this study.

Figure 3.2 shows the QV curves of a bus 3005 in an example network under normal and various contingency conditions for a load of 32+j6.4 with a power factor of 0.98 lagging. To maintain a voltage of 1.0 PU at the studied

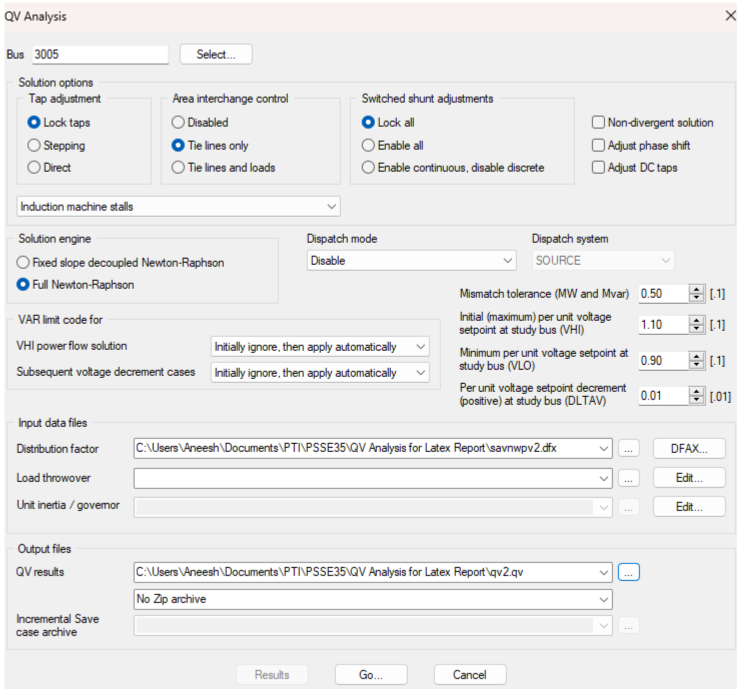

Figure 3.1: QV Analysis Study Parameters

bus, for the base case a reactive power support of 90.92 MVAR is required. For the same load under contingency condition - single open line of the transformer branch from 3005 to 3004, a reactive power support of 171.96 MVAR is required. Similarly for other contingency cases the reactive power support required to maintain 1.0 PU of voltage at the Bus 3005 can be determined.

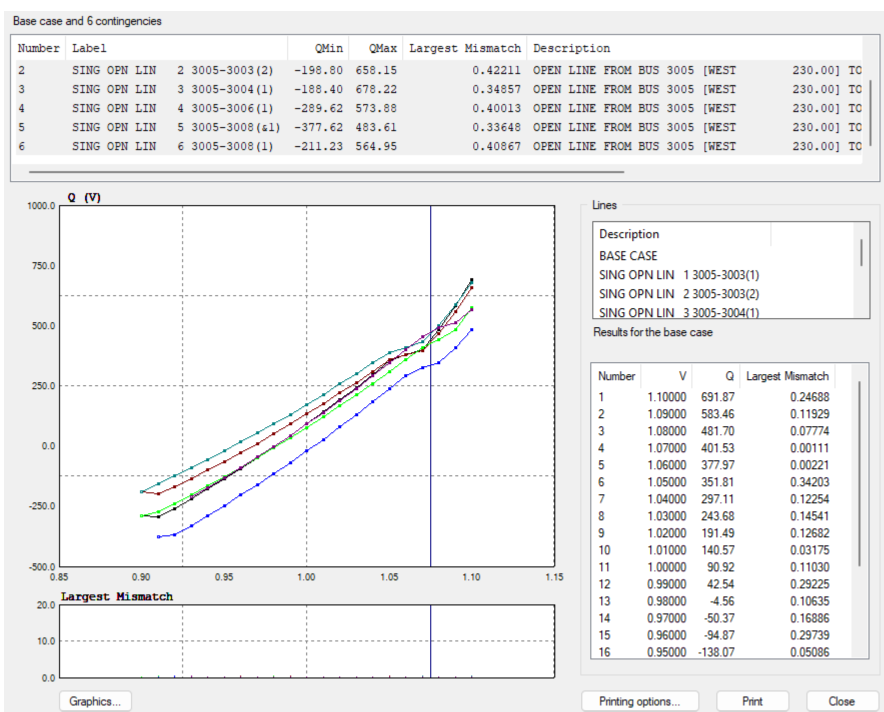

Figure 3.2: QV Curves showing Reactive power support needed for set bus voltages for Bus 3005 under Different Network Conditions for a load of 32+j6.4

The complete results of QV analysis results for every case and load obtained from PSSE is given in the Appendix B of this document.

3.3 Analysis of QV Solution for Different Network Conditions

As previously mentioned there are 7 contingency cases and 7 loads considered for this analysis. For each of the 7 network conditions for each load, the reactive power support required to maintain a voltage of 1.0 PU at the Bus 3005 is derived from the QV analysis. Table 3.1 tabulates the reactive power support required to maintain a

Study Case	Load	Load Factor	Voltage (PU)	Reactive Power (MVAR)
	32-j6.4	0.98 leading	1.0	78.117
	20-j10	0.89 leading	1.0	72.911
	41-j30.6	0.80 leading	1.0	55.152
BASE CASE	40+j0	UPF	1.0	85.613
	32+j6.4	0.98 lagging	1.0	90.917
	20+j10	0.89 lagging	1.0	92.911
	41+j30.6	0.80 lagging	1.0	116.352
	32-j6.4	0.98 leading	1.0	119.204
	20-j10	0.89 leading	1.0	113.63
	41-j30.6	0.80 leading	1.0	96.524
SING OPN LIN 1 3005-3003(1)	40+j0	UPF	1.0	126.953
	32+j6.4	0.98 lagging	1.0	132.004
	20+j10	0.89 lagging	1.0	133.63
	41+j30.6	0.80 lagging	1.0	157.724
	32-j6.4	0.98 leading	1.0	119.204
	20-j10	0.89 leading	1.0	113.63
	41-j30.6	0.80 leading	1.0	96.524
SING OPN LIN 2 3005-3003(2)	40+j0	UPF	1.0	126.953
	32+j6.4	0.98 lagging	1.0	132.004
	20+j10	0.89 lagging	1.0	133.63
	41+j30.6	0.80 lagging	1.0	157.724
	32-j6.4	0.98 leading	1.0	159.165
	20-j10	0.89 leading	1.0	153.601
	41-j30.6	0.80 leading	1.0	136.47
SING OPN LIN 3 3005-3004(1)	40+j0	UPF	1.0	166.901
	32+j6.4	0.98 lagging	1.0	171.965
	20+j10	0.89 lagging	1.0	173.601
	41+j30.6	0.80 lagging	1.0	197.67
	32-j6.4	0.98 leading	1.0	63.669
	20-j10	0.89 leading	1.0	58.437
	41-j30.6	0.80 leading	1.0	40.724
SING OPN LIN 4 3005-3006(1)	40+j0	UPF	1.0	71.183
	32+j6.4	0.98 lagging	1.0	76.469
	20+j10	0.89 lagging	1.0	78.437
	41+j30.6	0.80 lagging	1.0	101.924
	32-j6.4	0.98 leading	1.0	-34.077
	20-j10	0.89 leading	1.0	-38.488
	41-j30.6	0.80 leading	1.0	-57.639
SING OPN LIN 5 3005-3008(&1)	40+j0	UPF	1.0	-27.111
	32+j6.4	0.98 lagging	1.0	-21.277
	20+j10	0.89 lagging	1.0	-18.488
	41+j30.6	0.80 lagging	1.0	3.561
	32-j6.4	0.98 leading	1.0	77.924
	20-j10	0.89 leading	1.0	72.736
	41-j30.6	0.80 leading	1.0	54.946
SING OPN LIN 6 3005-3008(1)	40+j0	UPF	1.0	85.409
	32+j6.4	0.98 lagging	1.0	90.724
	20+j10	0.89 lagging	1.0	92.736
	41+j30.6	0.80 lagging	1.0	116.146

Table 3.1: Reactive power support required to maintain 1.0 PU at Bus 3005 for considered study cases and loads

voltage of 1.0 PU at the bus 3005 for the base case and contingencies for each considered load.

From Table 3.1, looking at the results of base case and the contingency case of single open line 1 3005 - 3008

(1), the following inferences are derived.

For the base case, to maintain a voltage of 1.0 PU at the study bus for the UPF load of 40+j0, a reactive power support of 85.613 MVAR is needed. When the load connected is having a lagging power factor, the reactive power support needed would be more than that for the UPF and when the load connected has a leading power factor, the reactive power required to maintain the 1.0 PU will be less than that is needed for the UPF load. When the 41-j30.6, 0.80 leading pf load is connected to the bus 3005, the reactive power support needed to maintain 1.0 PU is 55.152 MVAR (less than UPF load requirement) and when the load connected is 41+j30.6, 0.8 lagging pf, the reactive power support needed to maintain 1.0 PU is 116.352 MVAR (more than UPF load requirement).

For the contingency case of single open line 1 3005 - 3008 (1), to maintain a voltage of 1.0 PU at the study bus for the UPF load of 40+j0, a reactive power support of 85.409 MVAR is needed.. When the 41-j30.6, 0.80 leading pf load is connected to the bus 3005, the reactive power support needed to maintain 1.0 PU is 54.946 MVAR (less than UPF load requirement) and when the load connected is 41+j30.6, 0.8 lagging pf, the reactive power support needed to maintain 1.0 PU is 116.146 MVAR (more than UPF load requirement).

Chapter 4

Conclusion

The PV and QV analysis are carried out for various network conditions for Bus 3005. The Chapter 1 described the study system and the various network conditions considered (single line contingencies on Bus 3005 and loads of various power factors) to carry out the PV and QV analysis. In Chapter 2 the maximum incremental power that can be transferred to the sink bus 3005 was analyzed for various network conditions and load factors. In Chapter 3 the reactive power support required to maintain a voltage of 1.0 PU at the bus 3005 was analyzed for various network conditions and load factors.

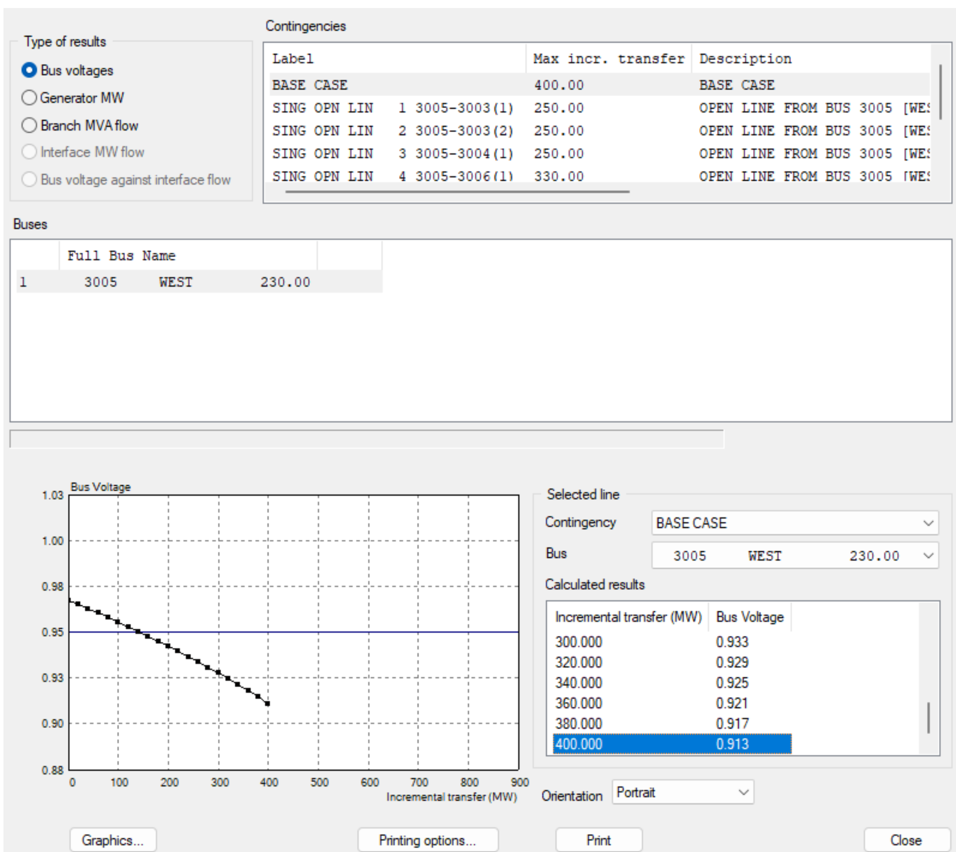

Figure 4.1: PV Results for Load Factor 0.89

To conclude this study, a special case is considered where the maximum power transfer obtained from PV analysis for a load factor of 0.89 lagging is used to estimate the load MVAR for a fictitious load. When this load is connected to the system, a QV analysis is carried out to estimate the reactive power support needed to maintain the Bus voltage of 1.0 PU for normal operating conditions. Figure 4.1 shows the PV Result obtained for the load factor of 0.89 lagging.. It can be seen that a maximum incremental transfer of 400 MW is possible from the present operating conditions. For the incremental transfer of 400 MW, the voltage at the bus is 9.13 PU, which is less than the normal operating voltage. If the 400 MW of power needed to be transferred to the system, there needs to be

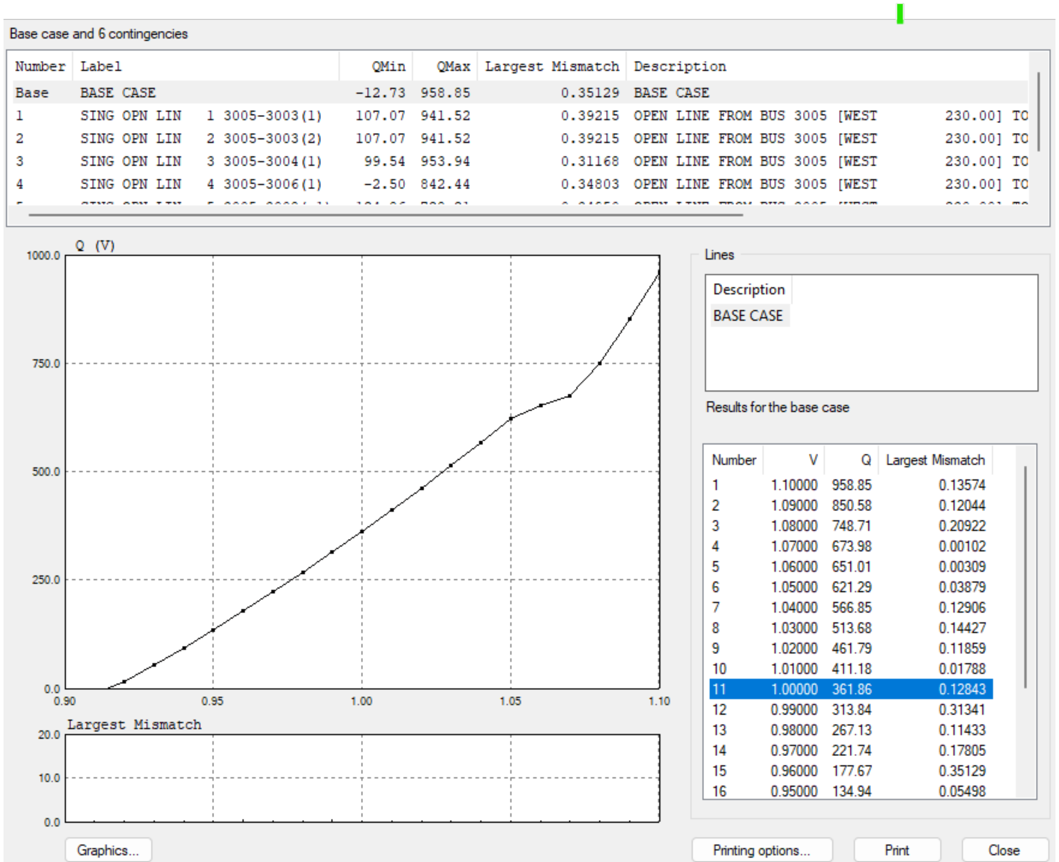

Figure 4.2: QV Results corresponding to a load of 400+j204.9 at Bus 3005

a reactive power supporting device connected at the bus. If the desired bus voltage at the bus for this transfer is chosen as 1.0 PU, a QV analysis can be carried out on the system connected with a load of 400 MW with a load factor of 0.89 lagging connected to size the reactive power supporting equipment to be connected at the bus.

```
BUS    3005      WEST        230.00 CKT     MW      MVAR      MVA   % 0.9160PU   -11.99  X--- LOSSES ---X X---- AREA -----X X---- ZONE -----X   3005
                                                                      210.69KV                MW     MVAR    5 WORLD             5 FIFTH
 TO LOAD-PQ                                400.0    204.9    449.4
 TO    3003      S. MINE     230.00  1    -209.7    -88.5    227.6                           3.66    32.91    5 WORLD             5 FIFTH
 TO    3003      S. MINE     230.00  2    -209.7    -88.5    227.6                           3.66    32.91    5 WORLD             5 FIFTH
 TO    3004      WEST        500.00  1    -263.1   -178.0    317.7  40 1.0000UN              0.48    19.54    5 WORLD             5 FIFTH
 TO    3006      UPTOWN      230.00  1     -86.9    -25.1     90.5                           0.34     2.88    5 WORLD             5 FIFTH
 TO    3008      CATDOG      230.00 &1     236.4    111.2    261.2                           2.51    20.93    5 WORLD             5 FIFTH
 TO    3008      CATDOG      230.00  1     133.0     64.0    147.6                           1.61    13.38    5 WORLD             5 FIFTH
```

Figure 4.3: Load flow results without reactive power support

```
BUS    3005      WEST        230.00 CKT     MW      MVAR      MVA   % 1.0000PU   -11.07  X--- LOSSES ---X X---- AREA -----X X---- ZONE -----X   3005
                                                                      230.00KV                MW     MVAR    5 WORLD             5 FIFTH
 TO LOAD-PQ                                400.0    204.9    449.4
 TO SHUNT                                    0.0   -361.8    361.8
 TO    3003      S. MINE     230.00  1    -206.8    -15.3    207.3                           2.57    23.15    5 WORLD             5 FIFTH
 TO    3003      S. MINE     230.00  2    -206.8    -15.3    207.3                           2.57    23.15    5 WORLD             5 FIFTH
 TO    3004      WEST        500.00  1    -270.2    -81.5    282.2  35 1.0000UN              0.32    12.94    5 WORLD             5 FIFTH
 TO    3006      UPTOWN      230.00  1     -91.4     47.6    103.1                           0.38     3.29    5 WORLD             5 FIFTH
 TO    3008      CATDOG      230.00 &1     239.5    133.7    274.3                           2.39    19.91    5 WORLD             5 FIFTH
 TO    3008      CATDOG      230.00  1     135.6     87.7    161.5                           1.63    13.59    5 WORLD             5 FIFTH
```

Figure 4.4: Load flow results with reactive power support at Bus 3005

QV results obtained by connecting a load of 400+j204.9 at the Bus 3005 is as shown in Figure 4.2. It can be seen that in order to maintain voltage of 1.0 PU at the bus a reactive power support of 361.86 MVAR is needed.

The pwer flow solution obtained at the Bus 3005 is shown with(Figure 4.3) and without(Figure 4.4 the reactive power support. It can be seen that the added reactive power support has helped to achieve the desired voltage of 1.0 PU at Bus 3005.

Appendix A

Complete PV Results

Here, the complete PV Result obtained for various load factors and network conditions are shown for reference. The maximum power transfer information shared on Table 2.1 is obtained from collating the PV result obtained for these various cases.

Load Factor 0.8 Lagging

```
               CONTINGENCY: BASE CASE      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000  160.000  180.000  200.000  220.000  240.000  260.000  280.000
3005 WEST 230.00  0.975    0.972    0.968    0.964    0.959    0.955    0.951    0.946    0.942    0.937    0.933    0.928    0.923    0.918    0.912

               CONTINGENCY: SING OPN LIN   1 3005-3003(1)      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000  160.000  170.000
3005 WEST 230.00  0.961    0.956    0.951    0.945    0.940    0.935    0.929    0.923    0.917    0.914

               CONTINGENCY: SING OPN LIN   2 3005-3003(2)      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000  160.000  170.000
3005 WEST 230.00  0.961    0.956    0.951    0.945    0.940    0.935    0.929    0.923    0.917    0.914

               CONTINGENCY: SING OPN LIN   3 3005-3004(1)      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000  160.000
3005 WEST 230.00  0.949    0.944    0.938    0.933    0.927    0.916    0.909    0.910    0.897

               CONTINGENCY: SING OPN LIN   4 3005-3006(1)      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000  160.000  180.000  200.000  220.000  240.000  260.000  270.000
3005 WEST 230.00  0.976    0.972    0.967    0.963    0.958    0.953    0.948    0.944    0.938    0.933    0.928    0.922    0.917    0.911    0.908

               CONTINGENCY: SING OPN LIN   5 3005-3008(&1)      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000  160.000  180.000  200.000  220.000  240.000  260.000  280.000
3005 WEST 230.00  0.999    0.996    0.992    0.989    0.985    0.982    0.978    0.974    0.970    0.966    0.962    0.958    0.954    0.950    0.945

               CONTINGENCY: SING OPN LIN   6 3005-3008(1)      Voltage (pu)
  MW TRANSFER->  0.000   20.000   40.000   60.000   80.000  100.000  120.000  140.000
3005 WEST 230.00  0.975    0.971    0.967    0.963    0.958    0.954    0.944    0.939
```

Figure A.1: PV Results corresponding to a base case load of 41+j30.6 and load factor of 0.8 lagging at Bus 3005

Load Factor 0.89 Lagging

CONTINGENCY: BASE CASE   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000
3005 WEST 230.00	0.981	0.978	0.975	0.972	0.969	0.966	0.963	0.960	0.957	0.954	0.951	0.947	0.944	0.940	0.937	0.933	0.929	0.925	0.921	0.917	0.913

CONTINGENCY: SING OPN LIN   1 3005-3003(1)   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	250.000
3005 WEST 230.00	0.967	0.963	0.960	0.956	0.952	0.949	0.945	0.941	0.936	0.932	0.928	0.923	0.918	0.916

CONTINGENCY: SING OPN LIN   2 3005-3003(2)   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	250.000
3005 WEST 230.00	0.967	0.963	0.960	0.956	0.952	0.949	0.945	0.941	0.936	0.932	0.928	0.923	0.918	0.916

CONTINGENCY: SING OPN LIN   3 3005-3004(1)   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	250.000
3005 WEST 230.00	0.955	0.952	0.948	0.944	0.940	0.936	0.932	0.928	0.918	0.913	0.908	0.904	0.898	0.896

CONTINGENCY: SING OPN LIN   4 3005-3006(1)   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	330.000
3005 WEST 230.00	0.982	0.979	0.975	0.972	0.969	0.966	0.962	0.959	0.955	0.952	0.948	0.944	0.940	0.937	0.932	0.928	0.924	0.917

CONTINGENCY: SING OPN LIN   5 3005-3008(&1)   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000
3005 WEST 230.00	1.004	1.001	0.999	0.997	0.994	0.992	0.989	0.987	0.984	0.981	0.978	0.976	0.973	0.970	0.967	0.964	0.961	0.958	0.955	0.951	0.948

CONTINGENCY: SING OPN LIN   6 3005-3008(1)   Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000
3005 WEST 230.00	0.980	0.977	0.974	0.971	0.968	0.965	0.962	0.959	0.956	0.952	0.944	0.940

Figure A.2: PV Results corresponding to a to a base case load of 20+j10 and load factor of 0.89 lagging at Bus 3005

```
                                              Load Factor 0.98 Lagging

             CONTINGENCY: BASE CASE     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000 600.000 620.000
3005 WEST 230.00  0.981   0.980   0.978   0.977   0.975   0.973   0.972   0.970   0.968   0.967   0.965   0.963   0.961   0.959   0.957   0.955   0.953   0.951   0.949   0.946   0.944   0.942   0.939   0.937   0.934   0.931   0.929   0.926   0.923   0.920   0.917   0.914

             CONTINGENCY: SING OPN LIN   1 3005-3003(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000
3005 WEST 230.00  0.967   0.965   0.963   0.961   0.959   0.957   0.955   0.952   0.950   0.948   0.945   0.942   0.940   0.937   0.934   0.931   0.928   0.925   0.921   0.918

             CONTINGENCY: SING OPN LIN   2 3005-3003(2)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000
3005 WEST 230.00  0.967   0.965   0.963   0.961   0.959   0.957   0.955   0.952   0.950   0.948   0.945   0.942   0.940   0.937   0.934   0.931   0.928   0.925   0.921   0.918

             CONTINGENCY: SING OPN LIN   3 3005-3004(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000
3005 WEST 230.00  0.956   0.954   0.952   0.950   0.947   0.945   0.943   0.940   0.938   0.936   0.933   0.930   0.922   0.919   0.915   0.912   0.910   0.907   0.903   0.899

             CONTINGENCY: SING OPN LIN   4 3005-3006(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000
3005 WEST 230.00  0.982   0.981   0.979   0.977   0.975   0.974   0.972   0.970   0.968   0.966   0.964   0.962   0.960   0.957   0.955   0.953   0.951   0.948   0.946   0.943   0.941   0.938   0.935   0.932   0.929   0.921   0.918

             CONTINGENCY: SING OPN LIN   5 3005-3008(&1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000 600.000 620.000
3005 WEST 230.00  1.004   1.003   1.002   1.001   1.000   0.998   0.997   0.996   0.995   0.993   0.992   0.990   0.989   0.987   0.986   0.984   0.983   0.981   0.979   0.978   0.976   0.974   0.972   0.970   0.968   0.966   0.964   0.962   0.960   0.958   0.956   0.954

             CONTINGENCY: SING OPN LIN   6 3005-3008(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 370.000
3005 WEST 230.00  0.980   0.979   0.977   0.976   0.974   0.973   0.971   0.969   0.967   0.966   0.964   0.962   0.960   0.958   0.956   0.954   0.946   0.944   0.941   0.940
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Figure A.3: PV Results corresponding to a base case load of 32+j6.4 and a load factor of 0.98 lagging at Bus 3005

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                                              UPF Load Factor

             CONTINGENCY: BASE CASE     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000 600.000 620.000 640.000 660.000
3005 WEST 230.00  0.982   0.982   0.981   0.980   0.980   0.979   0.978   0.977   0.976   0.976   0.975   0.974   0.973   0.972   0.971   0.970   0.969   0.967   0.966   0.965   0.964   0.962   0.961   0.960   0.958   0.957   0.955   0.954   0.952   0.950   0.949   0.947   0.945   0.943

             CONTINGENCY: SING OPN LIN   1 3005-3003(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000
3005 WEST 230.00  0.969   0.968   0.967   0.966   0.965   0.964   0.962   0.961   0.960   0.959   0.957   0.956   0.954   0.953   0.951   0.949   0.947   0.946   0.944   0.942   0.940   0.937   0.935   0.933   0.930   0.928   0.925   0.922

             CONTINGENCY: SING OPN LIN   2 3005-3003(2)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000
3005 WEST 230.00  0.969   0.968   0.967   0.966   0.965   0.964   0.962   0.961   0.960   0.959   0.957   0.956   0.954   0.953   0.951   0.949   0.947   0.946   0.944   0.942   0.940   0.937   0.935   0.933   0.930   0.928   0.925   0.922

             CONTINGENCY: SING OPN LIN   3 3005-3004(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000
3005 WEST 230.00  0.957   0.956   0.955   0.954   0.953   0.952   0.951   0.950   0.948   0.947   0.946   0.944   0.943   0.941   0.940   0.938   0.931   0.929   0.927   0.925   0.923   0.927   0.925   0.917   0.915   0.912   0.916   0.914   0.905   0.902

             CONTINGENCY: SING OPN LIN   4 3005-3006(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000 600.000 620.000 640.000 660.000
3005 WEST 230.00  0.983   0.983   0.982   0.981   0.980   0.980   0.979   0.978   0.977   0.976   0.975   0.974   0.973   0.972   0.971   0.969   0.968   0.967   0.965   0.964   0.963   0.961   0.960   0.958   0.957   0.955   0.953   0.951   0.950   0.948   0.946   0.944   0.942   0.939

             CONTINGENCY: SING OPN LIN   5 3005-3008(&1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000 600.000 620.000 640.000 660.000
3005 WEST 230.00  1.006   1.005   1.005   1.005   1.004   1.004   1.003   1.003   1.002   1.002   1.001   1.001   1.000   0.999   0.999   0.998   0.997   0.997   0.996   0.995   0.994   0.993   0.992   0.991   0.991   0.990   0.989   0.987   0.986   0.985   0.984   0.983   0.982   0.980

             CONTINGENCY: SING OPN LIN   6 3005-3008(1)     Voltage (pu)
  MW TRANSFER->  0.000  20.000  40.000  60.000  80.000 100.000 120.000 140.000 160.000 180.000 200.000 220.000 240.000 260.000 280.000 300.000 320.000 340.000 360.000 380.000 400.000 420.000 440.000 460.000 480.000 500.000 520.000 540.000 560.000 580.000 600.000
3005 WEST 230.00  0.982   0.981   0.980   0.980   0.979   0.978   0.977   0.977   0.976   0.975   0.974   0.973   0.972   0.971   0.970   0.969   0.968   0.967   0.965   0.964   0.963   0.961   0.960   0.959   0.957   0.956   0.954   0.947   0.946   0.944   0.942
```

Figure A.4: PV Results corresponding to a base case load of 40+j0 and a UPF load factor at Bus 3005

Load Factor 0.8 Leading

CONTINGENCY: BASE CASE Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	0.989	0.991	0.994	0.996	0.998	1.001	1.003	1.005	1.008	1.010	1.012	1.014	1.016	1.018	1.020	1.022	1.024	1.026	1.028	1.030	1.032	1.034	1.035	1.037	1.039	1.040	1.042	1.044	1.045	1.047	1.048	1.050	1.051	1.053	1.054

CONTINGENCY: SING OPN LIN 1 3005-3003(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	0.976	0.979	0.982	0.985	0.988	0.990	0.993	0.995	0.998	1.000	1.002	1.005	1.007	1.009	1.011	1.013	1.015	1.017	1.019	1.021	1.023	1.025	1.026	1.028	1.030	1.031	1.033	1.034	1.036	1.037	1.039	1.040	1.041	1.042	1.044

CONTINGENCY: SING OPN LIN 2 3005-3003(2) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	0.976	0.979	0.982	0.985	0.988	0.990	0.993	0.995	0.998	1.000	1.002	1.005	1.007	1.009	1.011	1.013	1.015	1.017	1.019	1.021	1.023	1.025	1.026	1.028	1.030	1.031	1.033	1.034	1.036	1.037	1.039	1.040	1.041	1.042	1.044

CONTINGENCY: SING OPN LIN 3 3005-3004(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	0.965	0.968	0.971	0.974	0.977	0.980	0.983	0.985	0.988	0.991	0.993	0.996	0.998	1.001	1.003	1.005	1.007	1.010	1.012	1.014	1.016	1.018	1.020	1.022	1.024	1.026	1.028	1.030	1.031	1.033	1.035	1.036	1.038	1.040	1.041

CONTINGENCY: SING OPN LIN 4 3005-3006(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	0.991	0.993	0.996	0.999	1.002	1.004	1.007	1.009	1.012	1.014	1.017	1.019	1.021	1.024	1.026	1.028	1.030	1.032	1.034	1.036	1.038	1.040	1.042	1.044	1.046	1.048	1.050	1.052	1.053	1.055	1.057	1.058	1.060	1.062	1.063

CONTINGENCY: SING OPN LIN 5 3005-3008(&1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	1.012	1.014	1.017	1.020	1.022	1.025	1.027	1.030	1.032	1.034	1.037	1.039	1.041	1.044	1.046	1.048	1.050	1.052	1.054	1.056	1.058	1.060	1.062	1.064	1.067	1.072	1.077	1.081	1.085	1.086	1.087	1.089	1.090	1.091	1.092

CONTINGENCY: SING OPN LIN 6 3005-3008(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
3005 WEST 230.00	0.988	0.991	0.993	0.996	0.998	1.001	1.003	1.006	1.008	1.010	1.013	1.015	1.017	1.019	1.021	1.023	1.025	1.027	1.029	1.031	1.033	1.035	1.037	1.038	1.040	1.042	1.043	1.045	1.047	1.048	1.050	1.051	1.053	1.054	1.056

Figure A.5: PV Results corresponding to a base case load of 41-j30.6 and load factor of 0.8 leading at Bus 3005

Load Factor 0.89 Leading

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	0.985	0.986	0.988	0.989	0.991	0.992	0.994	0.995	0.996	0.998	0.999	1.000	1.001	1.002	1.003	1.005	1.006	1.007	1.008	1.009	1.010	1.011	1.012	1.012	1.013	1.014	1.015	1.016	1.016	1.017	1.018	1.018	1.019	1.019	1.020	1.021

CONTINGENCY: SING OPN LIN 1 3005-3003(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	0.972	0.974	0.975	0.977	0.979	0.980	0.982	0.983	0.984	0.986	0.987	0.988	0.989	0.990	0.991	0.992	0.993	0.994	0.995	0.996	0.997	0.998	0.998	0.999	0.999	1.000	1.001	1.001	1.001	1.002	1.002	1.002	1.002	1.003	1.003	1.003

CONTINGENCY: SING OPN LIN 2 3005-3003(2) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	0.972	0.974	0.975	0.977	0.979	0.980	0.982	0.983	0.984	0.986	0.987	0.988	0.989	0.990	0.991	0.992	0.993	0.994	0.995	0.996	0.997	0.998	0.998	0.999	0.999	1.000	1.001	1.001	1.001	1.002	1.002	1.002	1.002	1.003	1.003	1.003

CONTINGENCY: SING OPN LIN 3 3005-3004(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	0.961	0.963	0.964	0.966	0.968	0.969	0.971	0.972	0.974	0.975	0.977	0.978	0.979	0.981	0.982	0.983	0.984	0.985	0.987	0.988	0.989	0.990	0.990	0.991	0.992	0.993	0.994	0.995	0.995	0.996	0.997	0.997	0.998	0.998	0.999	0.999

CONTINGENCY: SING OPN LIN 4 3005-3006(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	0.986	0.988	0.990	0.991	0.993	0.995	0.996	0.998	0.999	1.001	1.002	1.003	1.005	1.006	1.007	1.008	1.010	1.011	1.012	1.013	1.014	1.015	1.016	1.017	1.018	1.019	1.020	1.020	1.021	1.022	1.023	1.023	1.024	1.025	1.025	1.026

CONTINGENCY: SING OPN LIN 5 3005-3008(&1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	1.008	1.010	1.011	1.013	1.015	1.016	1.018	1.019	1.021	1.022	1.024	1.025	1.027	1.028	1.029	1.031	1.032	1.033	1.035	1.036	1.037	1.038	1.039	1.040	1.041	1.042	1.043	1.044	1.045	1.046	1.047	1.048	1.049	1.050	1.051	1.051

CONTINGENCY: SING OPN LIN 6 3005-3008(1) Voltage (pu)

MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000	700.000
3005 WEST 230.00	0.984	0.986	0.988	0.989	0.991	0.992	0.994	0.995	0.996	0.998	0.999	1.000	1.001	1.003	1.004	1.005	1.006	1.007	1.008	1.009	1.010	1.011	1.012	1.013	1.014	1.015	1.015	1.016	1.017	1.018	1.018	1.019	1.020	1.020	1.021	1.021

Figure A.6: PV Results corresponding to a base case load of 20-j10 and to a load factor of 0.89 leading at Bus 3005

Load Factor 0.98 Leading

CONTINGENCY (Voltage (pu))	MW TRANSFER->	0.000	20.000	40.000	60.000	80.000	100.000	120.000	140.000	160.000	180.000	200.000	220.000	240.000	260.000	280.000	300.000	320.000
CONTINGENCY: BASE CASE	3005 WEST 230.00	0.984	0.984	0.984	0.984	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.984
CONTINGENCY: SING OPN LIN 1 3005-3003(1)	3005 WEST 230.00	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.970	0.970	0.970	0.969	0.969	0.968	0.968	0.967
CONTINGENCY: SING OPN LIN 2 3005-3003(2)	3005 WEST 230.00	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.970	0.970	0.970	0.969	0.969	0.968	0.968	0.967
CONTINGENCY: SING OPN LIN 3 3005-3004(1)	3005 WEST 230.00	0.959	0.959	0.960	0.960	0.960	0.960	0.960	0.960	0.959	0.959	0.959	0.959	0.959	0.958	0.958	0.958	0.957
CONTINGENCY: SING OPN LIN 4 3005-3006(1)	3005 WEST 230.00	0.985	0.985	0.986	0.986	0.986	0.986	0.986	0.986	0.987	0.987	0.987	0.987	0.986	0.986	0.986	0.986	0.986
CONTINGENCY: SING OPN LIN 5 3005-3008(&1)	3005 WEST 230.00	1.007	1.007	1.008	1.008	1.009	1.009	1.010	1.010	1.010	1.011	1.011	1.011	1.011	1.012	1.012	1.012	1.012
CONTINGENCY: SING OPN LIN 6 3005-3008(1)	3005 WEST 230.00	0.983	0.984	0.984	0.984	0.984	0.984	0.984	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.984	0.984	0.984

CONTINGENCY (Voltage (pu))	MW TRANSFER->	340.000	360.000	380.000	400.000	420.000	440.000	460.000	480.000	500.000	520.000	540.000	560.000	580.000	600.000	620.000	640.000	660.000	680.000
CONTINGENCY: BASE CASE	3005 WEST 230.00	0.984	0.984	0.984	0.983	0.983	0.983	0.982	0.982	0.981	0.981	0.980	0.980	0.979	0.979	0.978	0.977	0.976	0.976
CONTINGENCY: SING OPN LIN 1 3005-3003(1)	3005 WEST 230.00	0.967	0.966	0.965	0.964	0.964	0.963	0.962	0.961	0.959	0.958	0.957	0.956	0.954	0.953	0.951	0.950	0.948	0.946
CONTINGENCY: SING OPN LIN 2 3005-3003(2)	3005 WEST 230.00	0.967	0.966	0.965	0.964	0.964	0.963	0.962	0.961	0.959	0.958	0.957	0.956	0.954	0.953	0.951	0.950	0.948	0.946
CONTINGENCY: SING OPN LIN 3 3005-3004(1)	3005 WEST 230.00	0.957	0.956	0.956	0.955	0.954	0.954	0.953	0.952	0.951	0.950	0.944	0.943	0.947	0.946	0.945	0.944	0.942	0.941
CONTINGENCY: SING OPN LIN 4 3005-3006(1)	3005 WEST 230.00	0.986	0.985	0.985	0.985	0.984	0.984	0.983	0.983	0.982	0.982	0.981	0.981	0.980	0.979	0.978	0.978	0.977	0.976
CONTINGENCY: SING OPN LIN 5 3005-3008(&1)	3005 WEST 230.00	1.012	1.012	1.012	1.012	1.012	1.012	1.012	1.012	1.012	1.012	1.012	1.011	1.011	1.011	1.011	1.010	1.010	1.010
CONTINGENCY: SING OPN LIN 6 3005-3008(1)	3005 WEST 230.00	0.984	0.984	0.983	0.983	0.983	0.982	0.982	0.982	0.981	0.981	0.980	0.979	0.979	0.978	0.977	0.977	0.976	0.975

Figure A.7: PV Results corresponding to a base case load of 32-j6.4 and to a load factor of 0.98 leading at Bus 3005

Appendix B

Complete QV Results

Here, the complete QV Result obtained for various loads and network conditions are shown for reference. The reactive power required to maintain a voltage of 1 PU at the Bus 3005 information shared on Table 2.1 is obtained from collating the QV result obtained for these various cases.

Load 41+j30.6

CONTINGENCY (Plant (MVAR))	VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
CONTINGENCY: BASE CASE	3005 WEST 230.00	717.271	608.855	507.084	427.011	403.464	377.230	322.541	269.103	216.922	166.003	116.352	67.976	20.882	-24.920	-69.423	-112.614	-154.484	-195.019	-234.204	-268.236	-263.134
CONTINGENCY: SING OPN LIN 1 3005-3003(1)	3005 WEST 230.00	683.802	583.548	489.767	419.358	403.254	383.249	335.910	289.683	244.573	200.584	157.724	115.999	75.417	35.986	-2.285	-39.385	-75.302	-110.023	-143.534	-172.833	-162.632
CONTINGENCY: SING OPN LIN 2 3005-3003(2)	3005 WEST 230.00	683.802	583.548	489.767	419.358	403.254	383.249	335.910	289.683	244.573	200.584	157.724	115.999	75.417	35.986	-2.285	-39.385	-75.302	-110.023	-143.534	-172.833	-162.632
CONTINGENCY: SING OPN LIN 3 3005-3004(1)	3005 WEST 230.00	703.828	611.862	524.314	457.827	431.999	412.105	370.392	325.708	282.024	239.343	197.670	157.007	117.359	78.730	41.126	4.551	-30.988	-65.484	-98.930	-131.318	-162.638
CONTINGENCY: SING OPN LIN 4 3005-3006(1)	3005 WEST 230.00	599.307	509.022	464.846	434.272	383.610	334.005	285.458	237.973	191.554	146.205	101.924	58.721	16.599	-24.437	-64.381	-103.229	-140.972	-177.604	-213.115	-247.497	-263.928
CONTINGENCY: SING OPN LIN 5 3005-3008(&1)	3005 WEST 230.00	508.471	431.611	372.350	348.894	315.291	260.354	206.605	154.046	102.682	52.519	3.561	-44.187	-90.716	-136.021	-180.093	-222.923	-264.501	-304.815	-343.851	-352.717	
CONTINGENCY: SING OPN LIN 6 3005-3008(1)	3005 WEST 230.00	590.325	539.088	516.452	479.973	424.321	369.885	316.669	264.680	213.925	164.411	116.146	69.140	23.403	-21.053	-64.214	-106.066	-146.593	-185.773			

Figure B.1: QV Results corresponding to a load of 41+j30.6, load factor of 0.8 lagging at Bus 3005

Load 20+j10

CONTINGENCY (Plant (MVAR))	VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
CONTINGENCY: BASE CASE	3005 WEST 230.00	693.917	585.498	483.747	403.455	379.891	353.812	299.120	245.679	193.493	142.568	92.911	44.527	-2.575	-48.388	-92.901	-136.105	-177.989	-218.538	-257.740	-292.034	-286.997
CONTINGENCY: SING OPN LIN 1 3005-3003(1)	3005 WEST 230.00	659.868	559.609	465.851	395.076	378.944	359.195	311.851	265.618	220.499	176.501	133.630	91.893	51.297	11.851	-26.436	-63.554	-99.491	-134.234	-167.769	-197.496	-187.392
CONTINGENCY: SING OPN LIN 2 3005-3003(2)	3005 WEST 230.00	659.868	559.609	465.851	395.076	378.944	359.195	311.851	265.618	220.499	176.501	133.630	91.893	51.297	11.851	-26.436	-63.554	-99.491	-134.234	-167.769	-197.496	-187.392
CONTINGENCY: SING OPN LIN 3 3005-3004(1)	3005 WEST 230.00	679.982	588.006	500.490	434.012	407.561	387.620	346.348	301.659	257.969	215.282	173.601	132.930	93.273	54.634	17.019	-19.568	-55.120	-89.631	-123.093	-155.498	-186.836
CONTINGENCY: SING OPN LIN 4 3005-3006(1)	3005 WEST 230.00	575.873	485.592	441.158	410.813	360.149	310.541	261.992	214.503	168.079	122.725	78.437	35.227	-6.903	-47.948	-87.903	-126.761	-164.517	-201.161	-236.687	-271.085	-287.954
CONTINGENCY: SING OPN LIN 5 3005-3008(&1)	3005 WEST 230.00	486.366	409.522	350.151	326.693	293.193	238.266	184.525	131.975	80.620	30.464	-18.488	-66.230	-112.754	-158.055	-202.124	-244.951	-286.527	-326.840	-365.877	-374.915	
CONTINGENCY: SING OPN LIN 6 3005-3008(1)	3005 WEST 230.00	567.020	515.550	492.893	456.591	400.938	346.500	293.281	241.288	190.528	141.008	92.736	45.723	-0.023	-44.489	-87.662	-129.527	-170.068	-209.264			

Figure B.2: QV Results corresponding to a load of 20+j10, load factor of 0.89 lagging at Bus 3005

Load 32+j6.4

Plant (MVAR), bus 3005 WEST 230.00

CONTINGENCY / VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
BASE CASE	691.875	583.458	481.695	401.527	377.973	351.805	297.115	243.676	191.492	140.571	90.917	42.537	-4.560	-50.367	-94.874	-138.072	-179.948	-220.489	-259.681	-293.827	-288.753
SING OPN LIN 1 3005-3003(1)	658.153	557.897	464.125	393.557	377.441	357.547	310.206	263.976	218.862	174.869	132.004	90.273	49.685	10.247	-28.031	-65.138	-101.064	-135.795	-169.317	-198.802	-188.643
SING OPN LIN 2 3005-3003(2)	658.153	557.897	464.125	393.557	377.441	357.547	310.206	263.976	218.862	174.869	132.004	90.273	49.685	10.247	-28.031	-65.138	-101.064	-135.795	-169.317	-198.802	-188.643
SING OPN LIN 3 3005-3004(1)	678.221	586.251	498.716	432.233	406.135	386.220	344.699	300.012	256.325	213.642	171.965	131.298	91.646	53.013	15.404	-21.176	-56.721	-91.224	-124.677	-157.072	-188.400
SING OPN LIN 4 3005-3006(1)	573.876	483.593	439.305	408.831	358.168	308.561	260.013	212.526	166.105	120.753	76.469	33.263	-8.862	-49.902	-89.852	-128.704	-166.453	-203.090	-238.608	-272.997	-289.618
SING OPN LIN 5 3005-3008(&1)	483.610	406.757	347.448	323.991	290.433	235.500	181.754	129.199	77.839	27.678	-21.277	-69.022	-115.550	-160.853	-204.924	-247.753	-289.331	-329.644	-368.681	-377.622	
SING OPN LIN 6 3005-3008(1)	564.950	513.612	490.966	454.564	398.912	344.475	291.257	239.267	188.509	138.992	90.724	43.715	-2.026	-46.486	-89.653	-131.511	-172.044	-211.231			

Figure B.3: QV Results corresponding to a load of 32+j6.4, load factor of 0.98 lagging at Bus 3005

Load 40+j0

Plant (MVAR), bus 3005 WEST 230.00

CONTINGENCY / VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
BASE CASE	686.537	578.121	476.351	396.267	372.719	346.492	291.803	238.366	186.184	135.265	85.613	37.237	-9.857	-55.660	-100.163	-143.355	-185.226	-225.761	-264.947	-298.992	-293.893
SING OPN LIN 1 3005-3003(1)	653.040	552.785	459.005	388.578	372.473	352.480	305.142	258.914	213.803	169.814	126.953	85.228	44.645	5.213	-33.059	-70.159	-106.077	-140.800	-174.312	-203.632	-193.436
SING OPN LIN 2 3005-3003(2)	653.040	552.785	459.005	388.578	372.473	352.480	305.142	258.914	213.803	169.814	126.953	85.228	44.645	5.213	-33.059	-70.159	-106.077	-140.800	-174.312	-203.632	-193.436
SING OPN LIN 3 3005-3004(1)	673.071	581.104	493.557	427.071	401.213	381.316	339.625	294.940	251.256	208.575	166.901	126.238	86.589	47.960	10.355	-26.220	-61.759	-96.256	-129.703	-162.092	-193.413
SING OPN LIN 4 3005-3006(1)	568.569	478.284	434.095	403.533	352.871	303.265	254.718	207.234	160.814	115.465	71.183	27.980	-14.142	-55.179	-95.124	-133.972	-171.716	-208.348	-243.860	-278.243	-294.695
SING OPN LIN 5 3005-3008(&1)	477.797	400.937	341.671	318.214	284.617	229.680	175.931	123.373	72.010	21.847	-27.111	-74.858	-121.388	-166.693	-210.765	-253.595	-295.172	-335.486	-374.522	-383.397	
SING OPN LIN 6 3005-3008(1)	559.594	508.345	485.708	449.237	393.586	339.149	285.933	233.944	183.189	133.674	85.409	38.402	-7.335	-51.791	-94.953	-136.806	-177.333	-216.514			

Figure B.4: QV Results corresponding to a load of 40+j0, UPF load factor at Bus 3005

Load 41-j30.6

Plant (MVAR), bus 3005 WEST 230.00

CONTINGENCY / VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
BASE CASE	656.071	547.655	445.884	365.811	342.264	316.030	261.341	207.903	155.722	104.803	55.152	6.776	-40.318	-86.120	-130.623	-173.814	-215.684	-256.219	-295.404	-329.436	-324.334
SING OPN LIN 1 3005-3003(1)	622.602	522.348	428.567	358.158	342.054	322.049	274.710	228.483	183.373	139.384	96.524	54.799	14.217	-25.214	-63.485	-100.585	-136.502	-171.223	-204.734	-234.033	-223.832
SING OPN LIN 2 3005-3003(2)	622.602	522.348	428.567	358.158	342.054	322.049	274.710	228.483	183.373	139.384	96.524	54.799	14.217	-25.214	-63.485	-100.585	-136.502	-171.223	-204.734	-234.033	-223.832
SING OPN LIN 3 3005-3004(1)	642.628	550.662	463.114	396.627	370.799	350.905	309.192	264.508	220.824	178.143	136.470	95.807	56.159	17.530	-20.074	-56.649	-92.188	-126.684	-160.130	-192.518	-223.838
SING OPN LIN 4 3005-3006(1)	538.107	447.822	403.646	373.072	322.410	272.805	224.258	176.773	130.354	85.005	40.724	-2.479	-44.601	-85.637	-125.581	-164.429	-202.172	-238.804	-274.315	-308.697	-325.128
SING OPN LIN 5 3005-3008(&1)	447.271	370.411	311.150	287.694	254.091	199.154	145.405	92.846	41.482	-8.681	-57.639	-105.386	-151.916	-197.221	-241.293	-284.123	-325.701	-366.015	-405.051	-413.917	
SING OPN LIN 6 3005-3008(1)	529.125	477.888	455.252	418.773	363.121	308.685	255.469	203.480	152.725	103.211	54.946	7.940	-37.797	-82.253	-125.414	-167.266	-207.793	-246.973			

Figure B.5: QV Results corresponding to a load of 41-j30.6, load factor of 0.8 leading at Bus 3005

Load 20-j10

Contingency	VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
CONTINGENCY: BASE CASE Plant (MVAR)	3005 WEST 230.00	673.917	565.498	463.747	383.455	359.891	333.812	279.120	225.679	173.493	122.568	72.911	24.527	-22.575	-68.388	-112.901	-156.105	-197.989	-238.538	-277.740	-312.034	-306.997
CONTINGENCY: SING OPN LIN 1 3005-3003(1) Plant (MVAR)	3005 WEST 230.00	639.868	539.609	445.851	375.076	358.944	339.195	291.851	245.618	200.499	156.501	113.630	71.893	31.297	-8.149	-46.436	-83.554	-119.491	-154.234	-187.769	-217.496	-207.392
CONTINGENCY: SING OPN LIN 2 3005-3003(2) Plant (MVAR)	3005 WEST 230.00	639.868	539.609	445.851	375.076	358.944	339.195	291.851	245.618	200.499	156.501	113.630	71.893	31.297	-8.149	-46.436	-83.554	-119.491	-154.234	-187.769	-217.496	-207.392
CONTINGENCY: SING OPN LIN 3 3005-3004(1) Plant (MVAR)	3005 WEST 230.00	659.982	568.006	480.490	414.012	387.561	367.620	326.348	281.659	237.969	195.282	153.601	112.930	73.273	34.634	-2.981	-39.568	-75.120	-109.631	-143.093	-175.498	-206.836
CONTINGENCY: SING OPN LIN 4 3005-3006(1) Plant (MVAR)	3005 WEST 230.00	555.873	465.592	421.158	390.813	340.149	290.541	241.992	194.503	148.079	102.725	58.437	15.227	-26.903	-67.948	-107.903	-146.761	-184.516	-221.161	-256.687	-291.085	-307.954
CONTINGENCY: SING OPN LIN 5 3005-3008(&1) Plant (MVAR)	3005 WEST 230.00	466.366	389.522	330.151	306.693	273.193	218.266	164.525	111.975	60.620	10.464	-38.488	-86.230	-132.754	-178.055	-222.124	-264.951	-306.527	-346.840	-385.877	-394.915	
CONTINGENCY: SING OPN LIN 6 3005-3008(1) Plant (MVAR)	3005 WEST 230.00	547.020	495.550	472.893	436.591	380.938	326.500	273.281	221.288	170.528	121.008	72.736	25.723	-20.023	-64.489	-107.662	-149.527	-190.068	-229.264			

Figure B.6: QV Results corresponding to a load of 20-j10, load factor of 0.89 leading at Bus 3005

Load 32-j6.4

Contingency	VOLTAGE SETPOINT->	1.100	1.090	1.080	1.070	1.060	1.050	1.040	1.030	1.020	1.010	1.000	0.990	0.980	0.970	0.960	0.950	0.940	0.930	0.920	0.910	0.900
CONTINGENCY: BASE CASE Plant (MVAR)	3005 WEST 230.00	679.075	570.658	468.895	388.727	365.173	339.005	284.315	230.876	178.692	127.771	78.117	29.737	-17.360	-63.167	-107.674	-150.872	-192.748	-233.289	-272.481	-306.627	-301.553
CONTINGENCY: SING OPN LIN 1 3005-3003(1) Plant (MVAR)	3005 WEST 230.00	645.353	545.097	451.325	380.757	364.641	344.747	297.406	251.176	206.062	162.069	119.204	77.473	36.885	-2.553	-40.831	-77.938	-113.864	-148.595	-182.117	-211.602	-201.443
CONTINGENCY: SING OPN LIN 2 3005-3003(2) Plant (MVAR)	3005 WEST 230.00	645.353	545.097	451.325	380.757	364.641	344.747	297.406	251.176	206.062	162.069	119.204	77.473	36.885	-2.553	-40.831	-77.938	-113.864	-148.595	-182.117	-211.602	-201.443
CONTINGENCY: SING OPN LIN 3 3005-3004(1) Plant (MVAR)	3005 WEST 230.00	665.421	573.451	485.916	419.433	393.335	373.420	331.899	287.212	243.525	200.842	159.165	118.498	78.846	40.213	2.604	-33.976	-69.521	-104.024	-137.477	-169.872	-201.200
CONTINGENCY: SING OPN LIN 4 3005-3006(1) Plant (MVAR)	3005 WEST 230.00	561.076	470.793	426.505	396.031	345.368	295.761	247.213	199.726	153.305	107.953	63.669	20.463	-21.662	-62.702	-102.652	-141.504	-179.253	-215.890	-251.408	-285.797	-302.418
CONTINGENCY: SING OPN LIN 5 3005-3008(&1) Plant (MVAR)	3005 WEST 230.00	470.811	393.957	334.648	311.191	277.633	222.700	168.954	116.399	65.039	14.878	-34.077	-81.822	-128.350	-173.653	-217.724	-260.553	-302.130	-342.444	-381.481	-390.422	
CONTINGENCY: SING OPN LIN 6 3005-3008(1) Plant (MVAR)	3005 WEST 230.00	552.150	500.812	478.166	441.764	386.112	331.674	278.457	226.467	175.709	126.192	77.924	30.915	-14.826	-59.286	-102.453	-144.311	-184.844	-224.031			

Figure B.7: QV Results corresponding to a load of 32-j6.4, load factor of 0.98 leading at Bus 3005