# Online Voltage Security Assessment

Report - I

April 7, 2016

## 1 Introduction

The note describes a real-time framework to monitor power system voltage stability with a handle over its assessment into near-future. It is believed that, the streaming wide-area measurement data can be utilized effectively to obtain incipient trends in dynamic quantities such as generator reactive power outputs, LTC tap movements, SVC device output which support the system voltage and are crucial indicators of system's voltage stability. In general scarcity of reactive power support near load centers is a problem. Voltage instability invariably being a mid to long term phenomenon, one can extract signatures of the same, alarm the operators and keep a hand on control actions to be taken. In the subsequent sections, an OPF based framework for obtaining a steady state solution to the network under study in real-time with trended schedules is assessed. This could also indicate effective control actions or deviations needed to find a steady operating point in the vicinity of predicted schedules. The suggested control actions can be tested in terms of their critical operating time via a transient stability analysis. In some cases, no incipient trends are observable and yet voltage collapses quickly post disturbance. As a result, one needs to also monitor both active and reactive power flows and losses over transmission lines, voltage angle separation across and type of load begin served. Monitoring transmission corridors and load areas with large industrial motors thus becomes imperative for preventing voltage instability.

## 2 Expected outcomes

- Assessment of present state of the network as voltage stable, moving towards instability or possessing risk of instability on critical disturbance
- Assessment of future state of the network with reasonable accuracy using trends in the streaming measurement data(e.g. what a bus voltage is likely to be 10 sec from now)
- Prediction of time left for certain control variable to hit its upper/lower limit based on present trends (e.g. generators hitting maximum reactive power output limits)

- Correlation between different quantities (e.g. bus 3 voltage strongly depends on gen 1 reactive power output)
- Monitoring apparent signatures of impending voltage instability (e.g. frequent LTC action over a time window, slowly increasing reactive power output of generator)
- List of possible control actions in case of contingencies or control schedules and their approximate magnitude (e.g. how much generator terminal voltage should change from current operating point to increase load bus voltage)
- Approximate time frame of the most effective control actions such as critical clearing time for faults, load shedding, capacitor switching through transient stability analysis

# 3 Mechanisms of Voltage Instability

One needs to be concerned about possible voltage instability in general, if

- The system has generating centers and load centers placed physically far apart
- The transmission system to load centers is highly stressed with voltage angle difference across exceeding 25-30 deg. with large reactive power losses
- Generators are operating near their reactive power output limits
- A contingency has resulted in depressed voltages throughout the network
- Load-side transformer tap action has been on for some time
- Load areas have large induction motor loads

# 4 Study Framework

## 4.1 Trend Extraction

Noise added time-domain transient stability output data obtained from ETAP 14.0.0 is used as streaming WAMS data with reporting rate of 40 samples/sec. A 1-5 second moving window is used to obtain a trend using Hordrik-Prescott(HP) filtering. It also captures discrete level-shifts in data from LTC action, over-excitation limiter operation and alike. The variables monitored are

1. Bus voltage magnitudes and angles
2. Generator reactive power output
3. Line real and reactive power flows (sending and receiving end)

Other quantities that can be inferred or trended using above are

1. LTC tap positions (from load bus voltage trend)

2. SVC output (from connected bus voltage trend)
3. Generator field current (from generator's reactive power output)

The table shown below indicates the parameters used in filtering and trending for HP filter. Given the data itself is noisy with a known noise level, the estimates will have proportional variability (needs to be quantified). As a result four to five successive windows are considered for getting an estimate (as mean).

Table 1: Filtering parameters(one instance)

| **Parameter** | **Range** |
|---|---|
| lambda for filter | 5-100 |
| Window size | 5 sec = 125 samples |
| Prediction start time | 15 sec |
| Predict for | 30th sec |
| window 1 | 10-15 sec |
| window 2 | 11-16 sec |
| window 3 | 12-17 sec |
| window 4 | 13-18 sec |

## 4.2 Minimum Control Variable Deviation Optimization

Quantities such as bus voltage magnitude, generator reactive power output, generator field current are trended upto 10 seconds in future. The optimization problem is fed with these schedules as initial operating points and a steady state operating point in proximity is sought for. We try to minimize the deviations from these predicted schedules. If we intend to investigate if steady state operation is possible in a post-contingency conditions, selected control variable constraints are modeled as soft constraints by introducing appropriate slack variables. Non-zero slack variables thus suggest possible control actions and their quantitative nature. As the OPF is run using predicted schedules as above, the control actions would correspond to those needed to be taken at a future state if such contingency occurs.

**Optimization Problem**

- Objective : Minimize deviations of control variables from scheduled(trended) values
- Constraints :
  1. Power balance equations
  2. Generator real power output limits (based on max mechanical input and governed by ramp rates)
  3. Generator reactive power output limit (field current limit)
  4. Generator armature current limit
  5. Steady state loadability limits

6. Line MVA ratings
7. SVC and switched shunt device limits
8. Load limits
9. LTC tap settings
10. Load bus voltage limits

## 4.3 Transient Stability Analysis

The OPF given operating point is used to initialize a transient stability run with certain expected contingencies or faults. In case a contingency constrained OPF was performed, the control actions ranked by OPF for the specific contingency are exercised for alleviating a possible transient instability in this part. Critical time of action is recorded. To minimize the running time of transient stability program, suitable modeling approximations or network reduction techniques can be employed. The following components need to be dynamically modeled in detail depending on the type of network.

1. Generators
2. Exciters
3. SVC dynamics
4. Loads mainly Induction motors
5. LTC tap movements
6. Excitation limiters

## 4.4 Transmission Line Monitoring

The reactive power transfer over a lossless transmission line is governed by the following equations. These quantities are indicative of the reactive power absorbed by the line under stressed conditions.

$$Q_s = \frac{V_s(V_s - V_r cos(\delta))}{X} \tag{1}$$

$$Q_r = \frac{V_r(V_s cos(\delta) - V_r)}{X} \tag{2}$$

$$\frac{\partial Q_r}{\partial V_r} = \frac{V_s cos(\delta) - 2V_r}{X} \qquad (-ve) \tag{3}$$

$$\frac{\partial Q_s}{\partial V_r} = \frac{-V_s cos(\delta)}{X} \qquad (-ve) \tag{4}$$

$$Q_r = Q_{r0} + \frac{\partial Q_r}{\partial V_r}\Delta V_r \tag{5}$$

$$Q_r = Q_{r0} + \frac{\partial Q_r}{\partial V_s}\Delta V_s \tag{6}$$

$Q_s$ : Sending end reactive power injected into the line
$Q_r$ : Receiving end reactive power drawn from the line
$V_s$ : Sending end voltage magnitude

$V_r$ : Receiving end voltage magnitude
$\delta$ : Angle difference between sending and receiving ends of transmission line

For a given real power transfer, this angle difference is more or less fixed. As a result, the reactive power absorbed by the line is a function of voltages at both ends. One can assume that the sending end side (source side) is stronger and is able to maintain the voltage at sending end bus near nominal or (4) is constant. In that case, how fast the receiving end voltage drops determines the additional reactive power to be supplied by load side generators or SVC devices.

Both the above sensitivities ((3),(4)) are negative under normal operating conditions. As a result, for dropping receiving end voltage, the

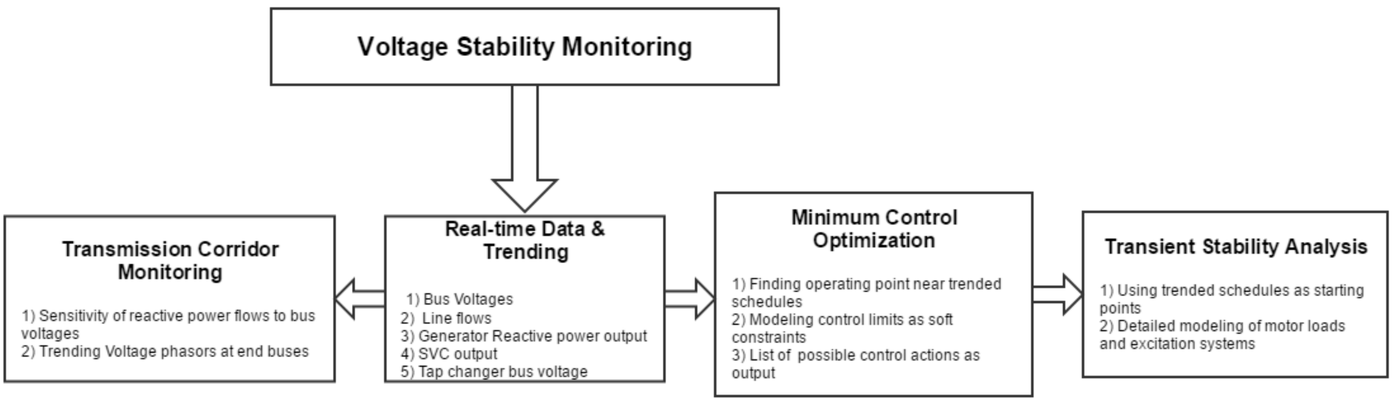
- $\Delta V_r < 0, \quad Q_{r0} > 0 \quad \Rightarrow \quad Q_r > Q_{r0}, \quad Q_s > Q_{s0}$
- $\Delta V_r < 0, \quad Q_{r0} < 0 \quad \Rightarrow \quad Q_r > Q_{r0}, \quad Q_s > Q_{s0}$
- In both cases, the rate at which reactive power is injected at either ends of the line needs to be greater than these two sensitivities, i.e

$$\frac{\partial Q_{svc}}{\partial V_r} > \frac{\partial Q_r}{\partial V_r} \tag{7}$$

$$\frac{\partial Q_{svc}}{\partial V_r} > \frac{\partial Q_s}{\partial V_r} \tag{8}$$

- One can monitor these sensitivities to decide how fast the absorption of reactive power is increasing on the line or how fast the reactive power of nearby SVCs needs to be pumped to arrest the drop in voltage.

# 5 Operating Chart



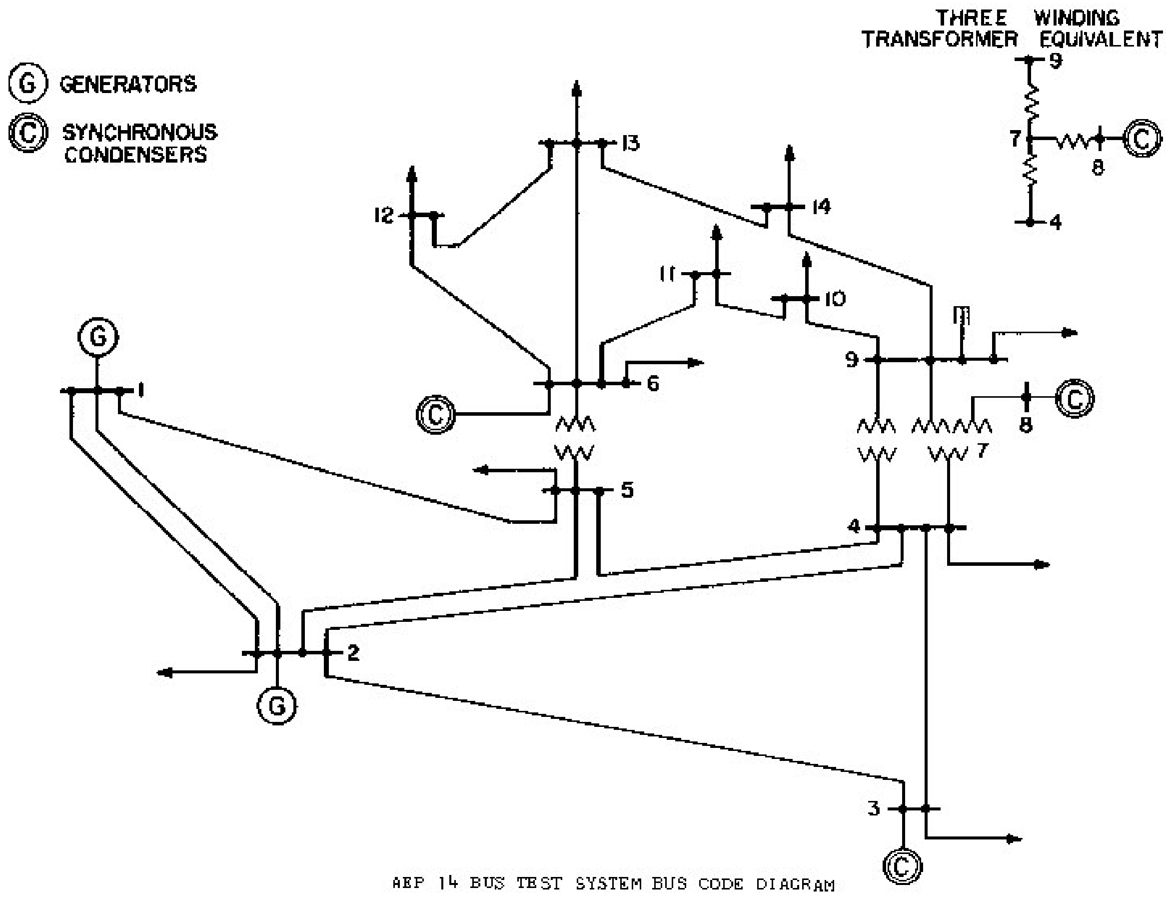

# 6 Running Time Estimate

* Needs to be understood

# 7 Test-system Results

Three systems with distinct signatures of voltage instability are considered for the study. The first two systems in their original form are tweaked a little to obtain slightly weaker systems with larger power transfers between load and generation centers.

1. **IEEE 14 bus test system (modified) - Initially a relatively strong system but a contingency renders it weak**




   (a) One external grid (G1) and one local generation (G2)
   (b) Three synchronous condensors (G3,G6,G8)
   (c) One LTC transformer (Bus14) and a nearby SVC device(Bus14)
   (d) Lumped loads modeled as constant power loads
   (e) The lines 1-2, 1-5, 2-5, 2-3, 2-4 are loaded heavily and carry power to the load centers

The table below shows variables for major lines transporting power from generation to load

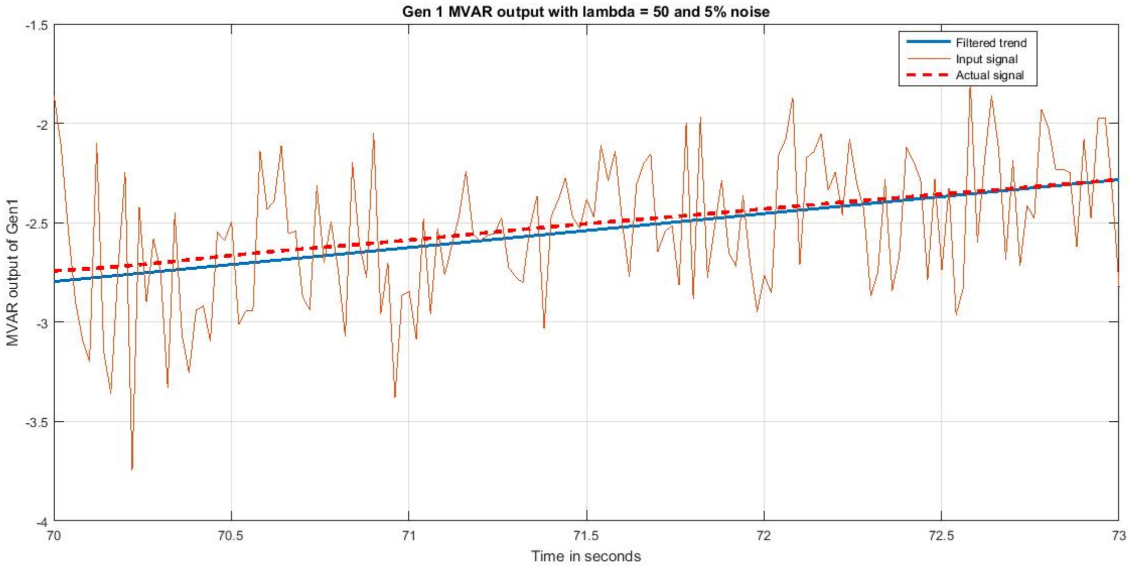
Table 2: Power flow Results for major lines after outage of 1-5 at 10 sec

| Line 2-3 | From end | To end | Loss/difference |
|---|---|---|---|
| $Q_{2-3}$ (MVar) | -0.39 | 9.34 | 9 |
| $P_{2-3}$ (MW) | 85.5 | -82 | 5 |
| V (pu) | 1.033 | 1.00 | 0.03 |
| $\delta$ (deg) | -14 | -23 | 9 |
| | | | |
| Line 1-2 | From end | To end | Loss/difference |
| $Q_{1-2}$ (MVar) | -18 | 39 | 22 |
| $P_{1-2}$ (MW) | 225 | -216 | 9 |
| V (pu) | 1.06 | 1.03 | 0.03 |
| $\delta$ (deg) | -7 | -14 | 7 |
| | | | |
| Line 2-4 | From end | To end | Loss/difference |
| $Q_{2-4}$ (MVar) | -4 | 11.1 | 8 |
| $P_{2-4}$ (MW) | 81 | -77 | 4 |
| V (pu) | 1.03 | 1 | 0.03 |
| $\delta$ (deg) | -7 | -22 | 15 |

a) We need to monitor lines with large angle difference or large real power transfer(lines 1-2, 2-3).
b) Bus 2 has a generator connected which has run out of reactive power capability. The reactive power needed to support the generator bus is being provided by the connected lines.
c) The voltage of regulated bus and gen2 reactive output continue to fall gradually due to decay of field current.

The next figures show trending in the reactive power output of Gen 1.In the first case, the trend coincides well with the actual trend, while in the other, the trend will induce some underestimation. It can be seen that the underlying trends are close to linear in nature and linear(first order) trending is likely to suffice for estimation. Also the trending under tap changing is depicted for a different network case.

Figure 1: Trending in Bus voltage and Gen reactive power output



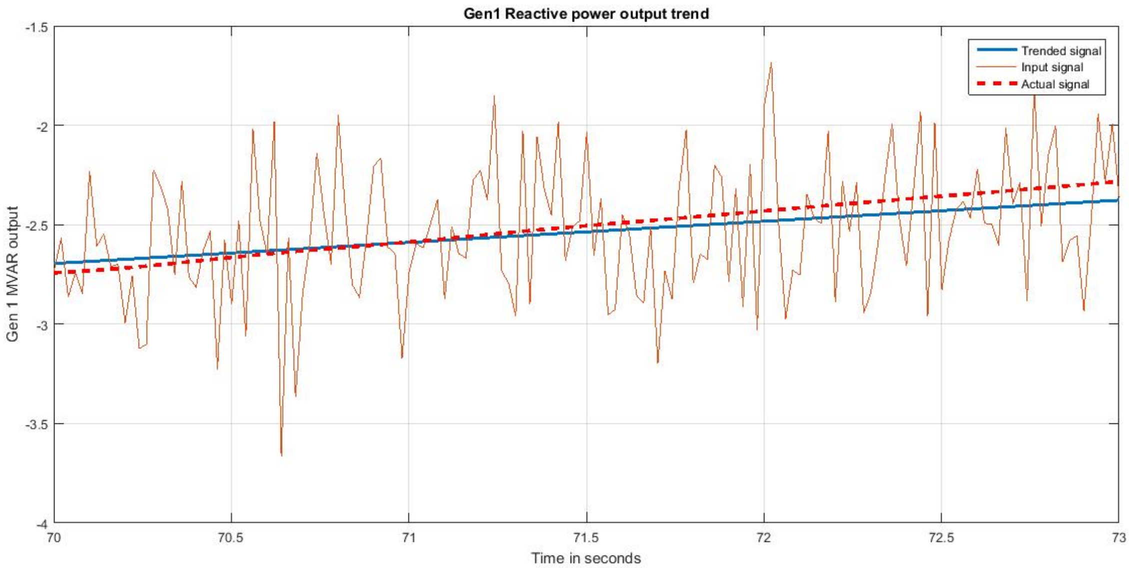
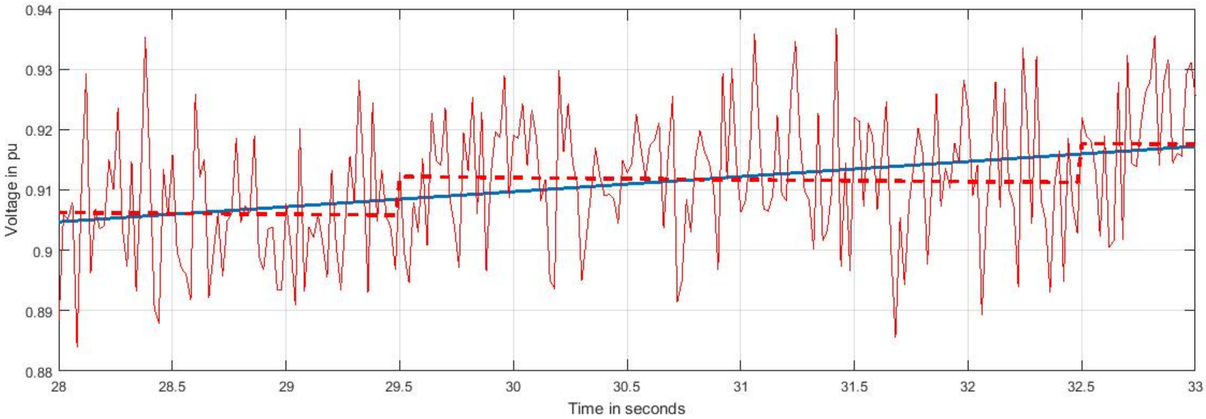



Figure 2: Trending under tap action




The table below shows results of HP filter based trending. These results correspond to predictions made for time t=80 sec. The prediction begins at t=66 sec with 3 sec windows and goes on for 5 successive windows. Each window has 150 samples(1 sample/20 msec). The measurements are assumed to have 1-5% noise.

Figure 3: Prediction results-1

| Variable | Predicted | Actual |
|---|---|---|
| V1 | 1.0552 | 1.05889 |
| V2 | 1.022287 | 1.02818 |
| V3 | 0.99726 | 0.998793 |
| V4 | 0.987618 | 0.993909 |
| V5 | 1.001716 | 0.993039 |
| V6 | 1.049434 | 1.05367 |
| V7 | 1.052129 | 1.05733 |
| V8 | 1.10315 | 1.10107 |
| V9 | 1.046964 | 1.0547 |
| V10 | 1.053736 | 1.0395 |
| V11 | 1.030347 | 1.0395 |
| V12 | 1.03579 | 1.03106 |
| V13 | 1.017785 | 1.01583 |
| V14 | 0.985812 | 0.988109 |
| V15 | 0.957745 | 0.951782 |
| Qg1 | -1.23529 | -1.2412 |
| Qg2 | 34.70154 | 39.3698 |
| Qg3 | 34.43547 | 35.3155 |
| Qg4 | 28.59583 | 28.7478 |
| Qg5 | 29.50337 | 27.3401 |
| Pg1 | 280.389 | 286.277 |
| Pg2 | 40.88255 | 40.747 |
| Pg3 | 0.710079 | 0.7112 |
| Pg4 | 0.715755 | 0.7112 |
| Pg5 | 0.708563 | 0.7112 |

| Variable | Predicted | Actual |
|---|---|---|
| Delta1 | -6.86738 | -6.9156 |
| Delta2 | -14.1038 | -14.0718 |
| Delta3 | -23.8545 | -23.56 |
| Delta4 | -22.5965 | -22.2193 |
| Delta5 | -20.9836 | -20.8385 |
| Delta6 | -29.1336 | -29.1005 |
| Delta7 | -27.2421 | -27.1926 |
| Delta8 | -27.586 | -27.1754 |
| Delta9 | -29.9362 | -29.725 |
| Delta10 | -29.4581 | -30.2178 |
| Delta11 | -30.0055 | -29.9428 |
| Delta12 | -30.24 | -30.4355 |
| Delta13 | -30.748 | -30.8022 |
| Delta14 | -31.8488 | -32.3492 |
| Delta15 | -35.839 | -36.4 |
| Ifd1 | 1.152176 | 1.157 |
| Ifd2 | 1.915556 | 1.908 |
| Ifd3 | 1.664181 | 1.658 |
| Ifd4 | 2.504603 | 2.511 |
| Ifd5 | 2.449576 | 2.461 |

The table below indicates an estimate of time left for various control variables to hit lower/upper steady-state limit from the present moment expecting the first order trend to continue.

Figure 4: Prediction results-2

| Variable | Limit | Current point | Time to limit |
|---|---|---|---|
| **V15** | 0.9 | 0.92 | 0.13 |
| | | 0.96 | -0.75 |
| | | 0.95 | -4.58 |
| | | 0.97 | -1.58 |
| | | 0.95 | 2.16 |
| **Q1** | 5 | -2.83 | 4.88 |
| | | -2.72 | 5.24 |
| | | -2.60 | 5.82 |
| | | -2.43 | 5.19 |
| | | -2.29 | 5.04 |
| **Q4** | 40 | 28.52 | -2.16 |
| | | 28.44 | -6.30 |
| | | 28.27 | -3.48 |
| | | 28.93 | 0.92 |
| | | 28.88 | 1.66 |

| | | | **V15** | | |
|---|---|---|---|---|---|
| **Time(sec)** | **69** | **70** | **71** | **72** | **73** |
| 1 | 0.91 | 0.96 | 0.95 | 0.98 | 0.94 |
| 2 | 0.89 | 0.97 | 0.95 | 0.98 | 0.94 |
| 3 | 0.87 | 0.98 | 0.95 | 0.99 | 0.94 |
| 4 | 0.85 | 0.99 | 0.95 | 0.99 | 0.94 |
| 5 | 0.83 | 0.99 | 0.96 | 1.00 | 0.94 |
| 6 | 0.81 | 1.00 | 0.96 | 1.00 | 0.93 |
| 7 | 0.80 | 1.01 | 0.96 | 1.01 | 0.93 |
| 8 | 0.78 | 1.02 | 0.96 | 1.01 | 0.93 |
| 9 | 0.76 | 1.02 | 0.96 | 1.01 | 0.93 |
| 10 | 0.74 | 1.03 | 0.96 | 1.02 | 0.93 |

| | | | **Q1** | | |
|---|---|---|---|---|---|
| **Time(sec)** | **69** | **70** | **71** | **72** | **73** |
| 1 | -2.67 | -2.57 | -2.47 | -2.28 | -2.14 |
| 2 | -2.51 | -2.43 | -2.34 | -2.14 | -2.00 |
| 3 | -2.35 | -2.28 | -2.21 | -2.00 | -1.85 |
| 4 | -2.19 | -2.13 | -2.08 | -1.85 | -1.71 |
| 5 | -2.03 | -1.98 | -1.94 | -1.71 | -1.57 |
| 6 | -1.87 | -1.84 | -1.81 | -1.57 | -1.42 |
| 7 | -1.71 | -1.69 | -1.68 | -1.43 | -1.28 |
| 8 | -1.55 | -1.54 | -1.55 | -1.28 | -1.13 |
| 9 | -1.39 | -1.39 | -1.42 | -1.14 | -0.99 |
| 10 | -1.22 | -1.25 | -1.29 | -1.00 | -0.84 |

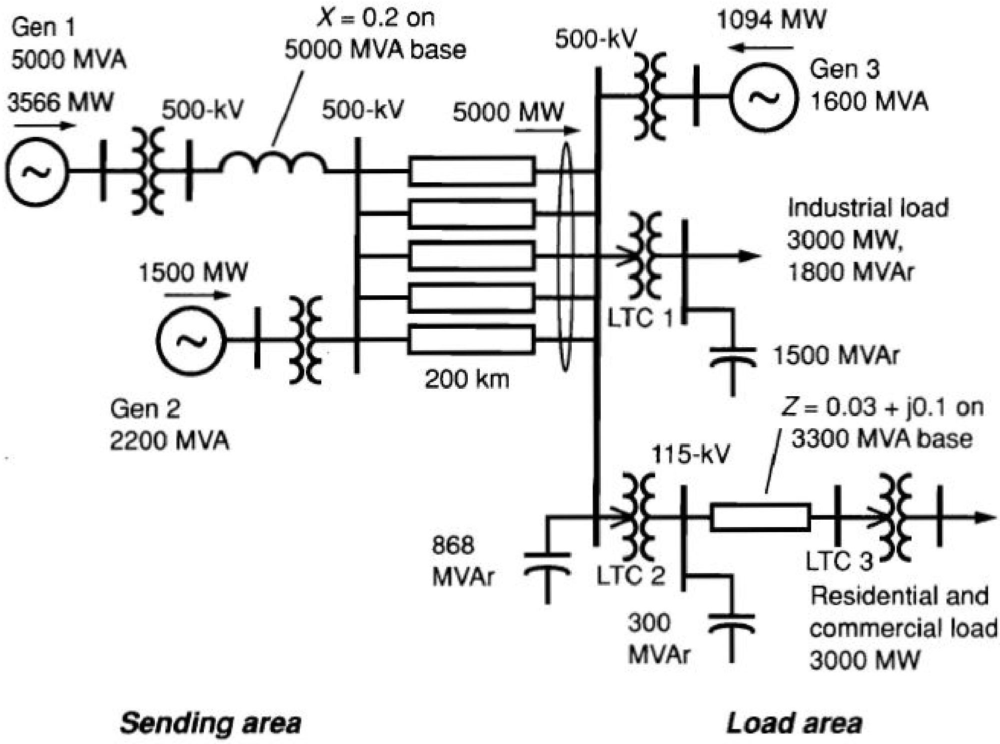
The following table shows the output of the optimization problem. The results are obtained with a maximum deviation of 5% allowed from the initial guess (prediction) obtained post-smoothing. The magnitudes of control variables' deviation gives a sense of quality of estimates. Also, this indicates a possibility of having a stable operating point in the vicinity of predicted values of control variables. The optimization problem was solved in GAMS using CONOPT solver.

Figure 5: Optimization Problem Results

| Control Variable Bus | Control Variable | Min Limit | Predicted Value | OPF Value | Max Limit | Deviation from Prediction |
|---|---|---|---|---|---|---|
| 'B1' | Pg | 0.00 | 303.61 | 282.75 | 332.40 | 20.86 |
| 'B6' | Qg | -6.00 | 30.34 | 24.00 | 24.00 | 6.34 |
| 'B3' | Qg | 0.00 | 40.58 | 36.07 | 40.00 | 4.51 |
| 'B2' | Qg | -40.00 | 36.92 | 32.65 | 50.00 | 4.27 |
| 'B2' | Pg | 0.00 | 41.06 | 36.95 | 140.00 | 4.11 |
| 'B1' | Qg | -20.00 | -1.33 | -2.00 | 10.00 | 0.67 |
| 'B6' | Pg | 0.00 | 0.71 | 0.36 | 1.00 | 0.36 |
| 'B8' | Pg | 0.00 | 0.71 | 0.36 | 1.00 | 0.36 |
| 'B3' | Pg | 0.00 | 0.71 | 0.36 | 1.00 | 0.36 |
| 'B8' | Qg | -6.00 | 24.10 | 24.00 | 24.00 | 0.10 |
| 'B6' | Vg | 0.90 | 1.07 | 1.04 | 1.10 | 0.03 |
| 'B1' | Vg | 0.90 | 1.03 | 1.04 | 1.10 | -0.01 |
| 'B3' | Vg | 0.90 | 0.98 | 0.99 | 1.10 | -0.01 |
| 'B8' | Vg | 0.90 | 1.10 | 1.09 | 1.10 | 0.01 |
| 'B2' | Vg | 0.90 | 1.02 | 1.02 | 1.10 | 0.01 |
| 'B2' | Pl | 17.36 | 26.04 | 21.70 | 26.04 | 0.00 |
| 'B3' | Pl | 75.36 | 113.04 | 94.20 | 113.04 | 0.00 |
| 'B4' | Pl | 38.24 | 57.36 | 47.80 | 57.36 | 0.00 |
| 'B5' | Pl | 6.08 | 9.12 | 7.60 | 9.12 | 0.00 |
| 'B6' | Pl | 8.96 | 13.44 | 11.20 | 13.44 | 0.00 |
| 'B9' | Pl | 23.60 | 35.40 | 29.50 | 35.40 | 0.00 |
| 'B10' | Pl | 14.40 | 21.60 | 18.00 | 21.60 | 0.00 |
| 'B11' | Pl | 5.60 | 8.40 | 7.00 | 8.40 | 0.00 |
| 'B12' | Pl | 4.88 | 7.32 | 6.10 | 7.32 | 0.00 |
| 'B13' | Pl | 21.60 | 32.40 | 27.00 | 32.40 | 0.00 |
| 'B15' | Pl | 24.00 | 36.00 | 30.00 | 36.00 | 0.00 |
| 'B14' | Bs | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

The next set of results follow from the transient stability analysis initiated with trended real and reactive power outputs of generators. The analysis follows the same contingency as above (line 1-5, ckt2).

2. **A reduced Kundur BPA 10 bus voltage stability test system - A stressed system to with large power transfer over a corridor. Loss of a line leads to voltage instability**




- Gen 1(external grid, 5000 MVA), Gen 2 (1000 MVA) and Gen 3(1000 MVA)
- Load at bus 7 (1500 MW, 500 MVar), load at bus 9 (1000 MW)
- Capacitor bank at bus 6(700 MVar)
- LTC transformer between bus 8-9

(a) Generator reactive power output

| | Qgen | Qmax |
|---|---|---|
| Gen1(source side) | 200 | Inf |
| Gen2(source side) | 475 | Inf |
| Gen3(Load side) | 530 | 600 |

(b) The transfer of real and reactive power over the lines between 5-6 holds key to the system stability.

(c) It can be observed that the line absorbs large amount of reactive power from both ends. The reactive power transfer over a transmission line is governed by equations (1-8)

Table 3: Power flow Results for Transmission corridor

| Line 5-6 | From end | To end | Loss/difference |
|---|---|---|---|
| $Q_{5-6}$ (MVar) | 654 (into line) | 240(into line) | 830 |
| $P_{5-6}$ (MW) | 1750 | 1700 | 50 |
| V (pu) | 1.03 | 0.95 | 0.08 |
| $\delta$ (deg) | -3.08 | -33.3 | 30 |

(d) With the designated real power transfer, the angle difference $\delta_{sr}$ is almost constant over the period.

(e) The time-domain simulation with outage of one of the lines of the transmission corridor resulted in further depressed voltages.

(f) It was tried to obtain possible control actions and steady state operating point using the optimization program with minimum control variable deviation. The list of control actions is shown in the table below as suggested by OPF.

(g) As indicated in (7-8) the reactive power compensation from both sides needs to increase very fast to cover for increased absorption by the line.

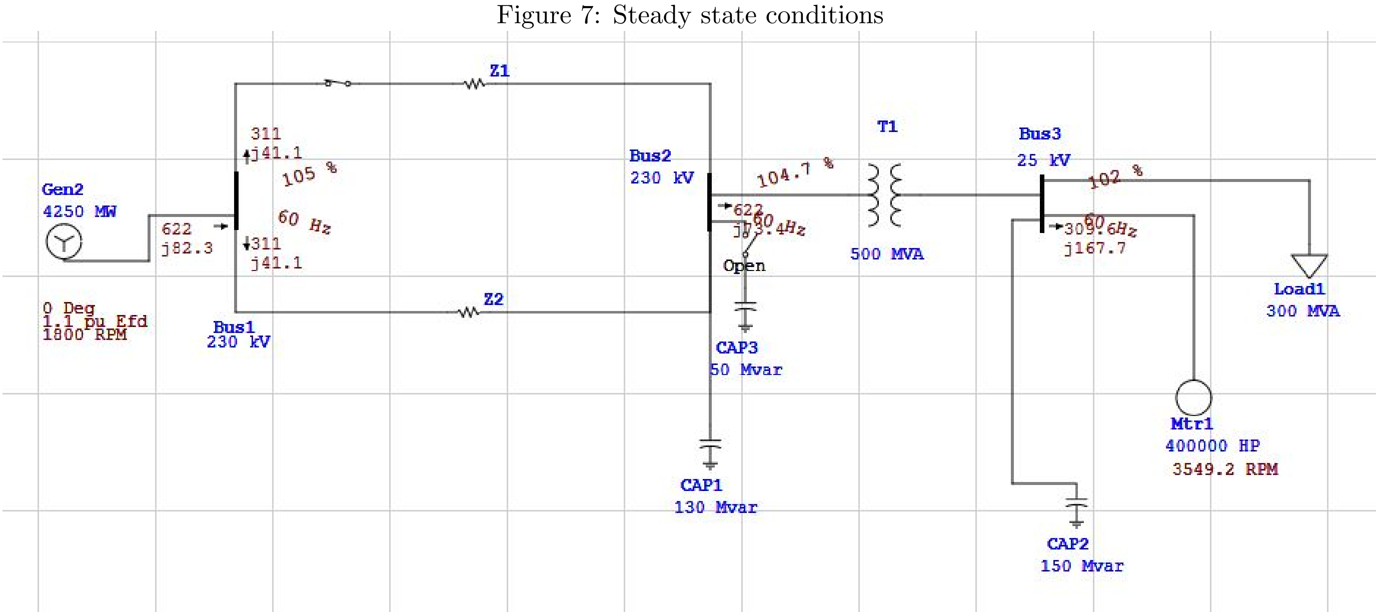
There was no apparent major trend observed in the vital system variables. Hence, the optimization problem could find a solution in the vicinity of current operating conditions. Next, the slack variable bounds were relaxed and an outage case was tried. It was able to find a stable operating point. Results are shown below. However, this does not imply that the system was transiently voltage stable. Hence, a transient voltage stability analysis also becomes imperative.

Figure 6: List of control actions

| Control Variable Bus | Control Variable | Min Limit | Predicted Value | OPF Value | Max Limit | Deviation from Prediction |
|---|---|---|---|---|---|---|
| 'B3' | Pg | 0.00 | 800.00 | 810.20 | 1000.00 | 10.20 |
| 'B6' | Bs | 560.00 | 700.00 | 709.18 | 840.00 | 9.18 |
| 'B1' | Qg | -1000.00 | 176.20 | 185.09 | 1000.00 | 8.89 |
| 'B2' | Qg | 0.00 | 441.25 | 450.06 | 800.00 | 8.81 |
| 'B3' | Qg | 0.00 | 420.29 | 424.48 | 600.00 | 4.19 |
| 'B1' | Pg | 0.00 | 947.77 | 945.92 | 1500.00 | -1.85 |
| 'B2' | Pg | 0.00 | 800.00 | 798.47 | 1200.00 | -1.53 |
| 'B3' | Vg | 0.90 | 0.97 | 1.02 | 1.10 | 0.05 |
| 'B1' | Vg | 0.90 | 1.02 | 1.07 | 1.10 | 0.05 |
| 'B2' | Vg | 0.90 | 1.03 | 1.08 | 1.10 | 0.05 |
| 'B7' | Pl | 1200.00 | 1500.00 | 1500.00 | 1800.00 | 0.00 |
| 'B9' | Pl | 800.00 | 1000.00 | 1000.00 | 1200.00 | 0.00 |
| 'B7' | Bs | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

3. **Taylor's 3 bus test system with motor dynamics - A reduced system from Test-case 2 with fast voltage collapse at the load bus**
   This system can be seen as an equivalent representation of the above 10 bus system with the load dynamics modeled in more detail. The generators 1 and 2 are combined into one large generating station and the power is transported to the load center with large motor load via a transmission corridor. Voltage dynamics of this system is governed by the motor load dynamics. A corrective action of capacitor switching is available. LTC transformer steps down voltage to distribution level. No reactive power limitations are modeled for the generator, however, the transport is limited by transmission corridor voltage stability. The figure below depicts the steady state system as modeled in ETAP.

Figure 7: Steady state conditions




- One large, remote generation (Infinite bus) at bus 1
- Large induction motor load at bus 3 (500 MVA) and 300 MW resistive load
- SVC device for voltage support at bus 3 (80% of motor reactive power)
- About 600 MW transported over the corridor

Table 4: Line 1-2 operating conditions

| | Before Collapse | During Collapse |
|---|---|---|
| Vs (pu) | 1.05 | 1.049 |
| Vr (pu) | 1.047 | 0.85 |
| Qs (MVar) | 41 | 355 |
| Qr (MVar) | -34 | 10 |
| angle difference (deg) | 18 | 35 |
| MW flow | 300 | 600 |
| $\frac{\partial Q_r}{\partial V_r}$ | -10 | -7.67 |

Following figures show the characteristics of motor load. In general, the reactive power absorbed by the motor increases as its speed decreases, brought about by drop in terminal voltage. A cyclic reduction between these two quantities could lead to stalling of motor.

After outage of one line between buses 1 and 2 and without any additional VAR support, voltage collapses.

Figure 8: Post outage collapse

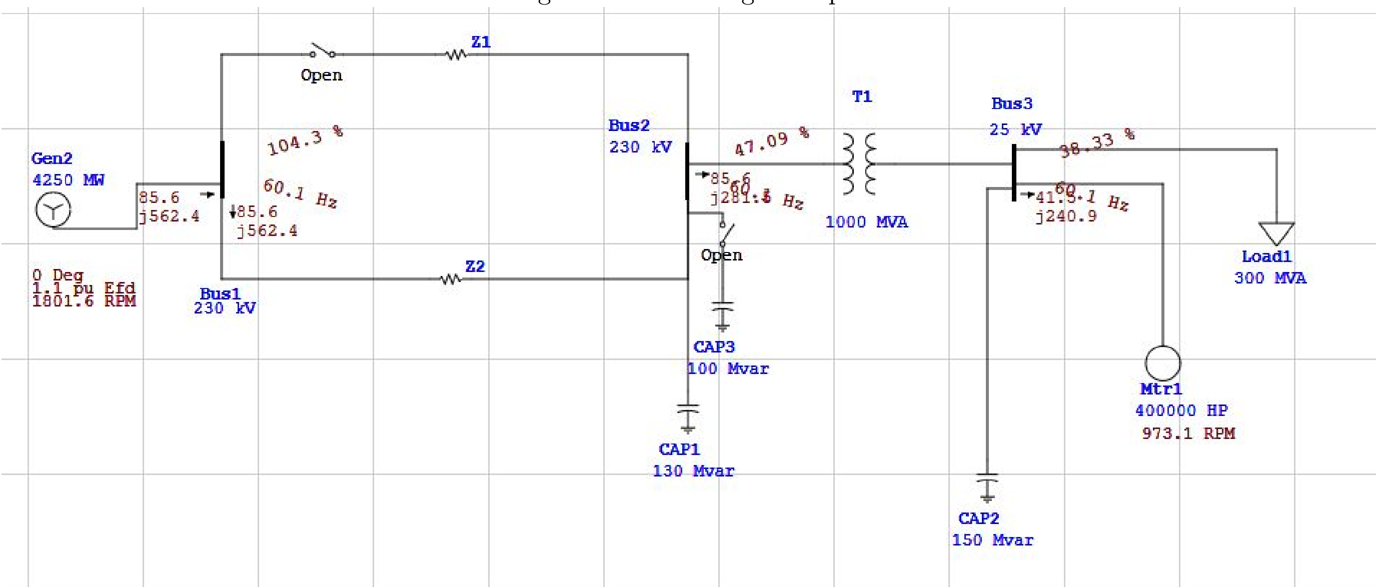
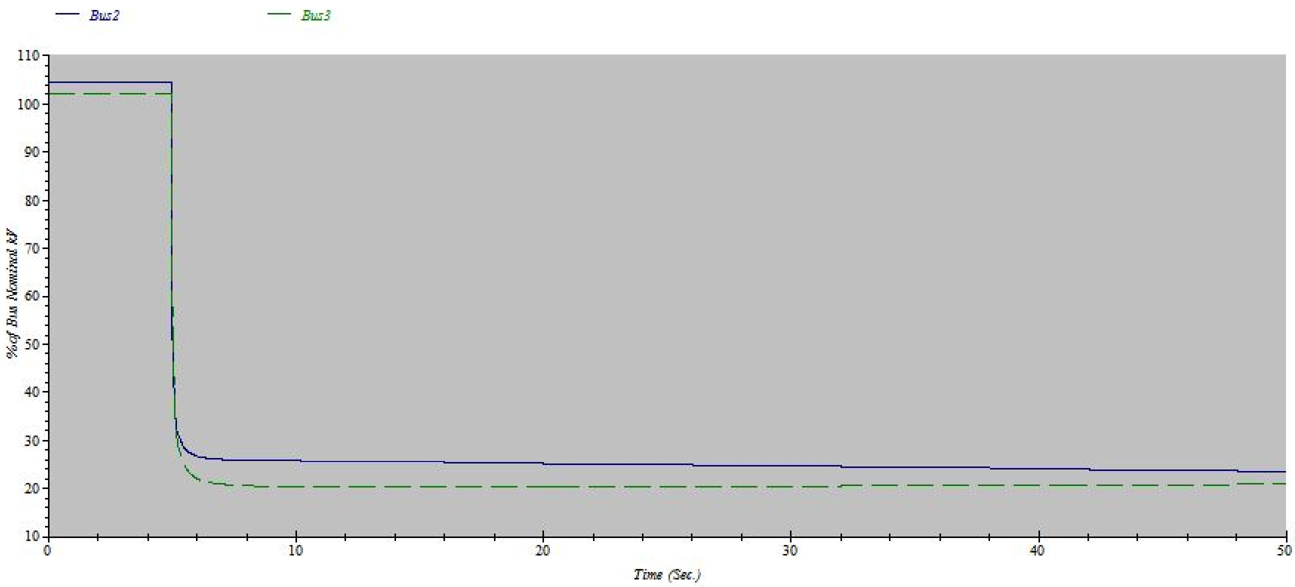


Figure 9: Fast voltage collapse at the load bus (bus 3)




It can be observed that the collapse is very fast and there is almost no time to ponder on a control action. One has to know them a-priori with their critical action times in this case. However, if one could understand that given the current operating conditions, an outage will lead to such a fast collapse, migration into one can be avoided. In this case the only control action available is switching in a shunt bank at bus 2 or load shedding. Adding 50 MVAr cap bank stabilizes the voltage for a while but is still dropping. After it drops below 0.85 pu, the motor stalls and starts drawing a more reactive power leading to fast collapse.

Figure 10: Slow voltage collapse at the load bus (bus 3) after 50 MVAr shunt support

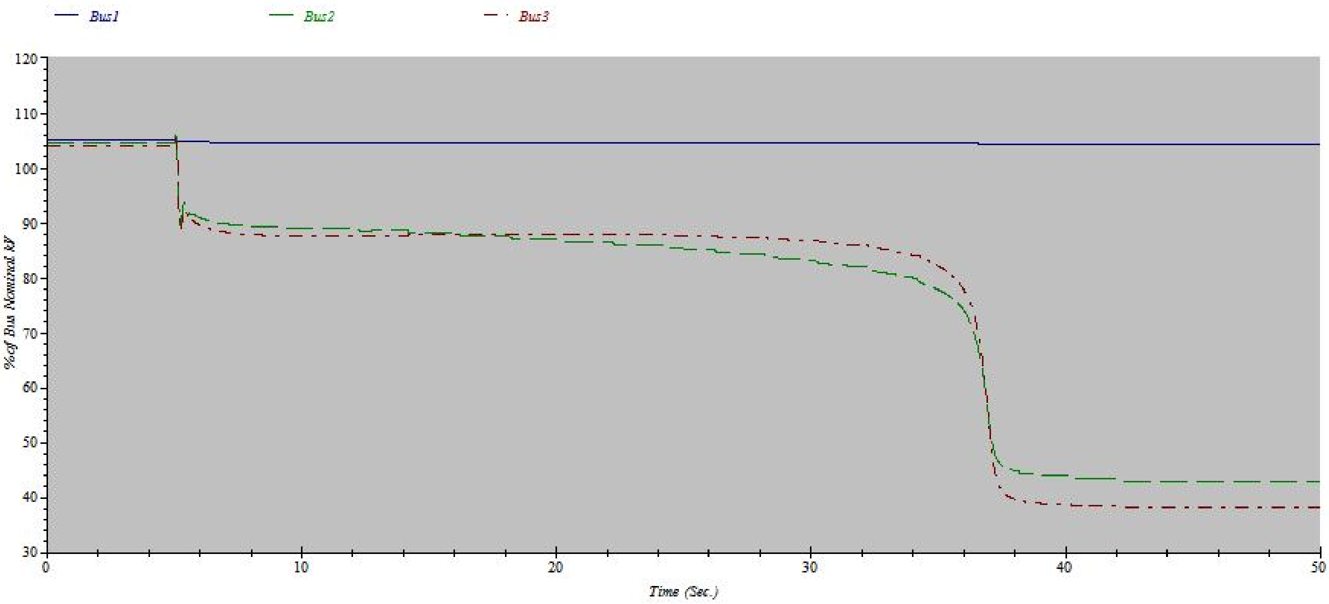
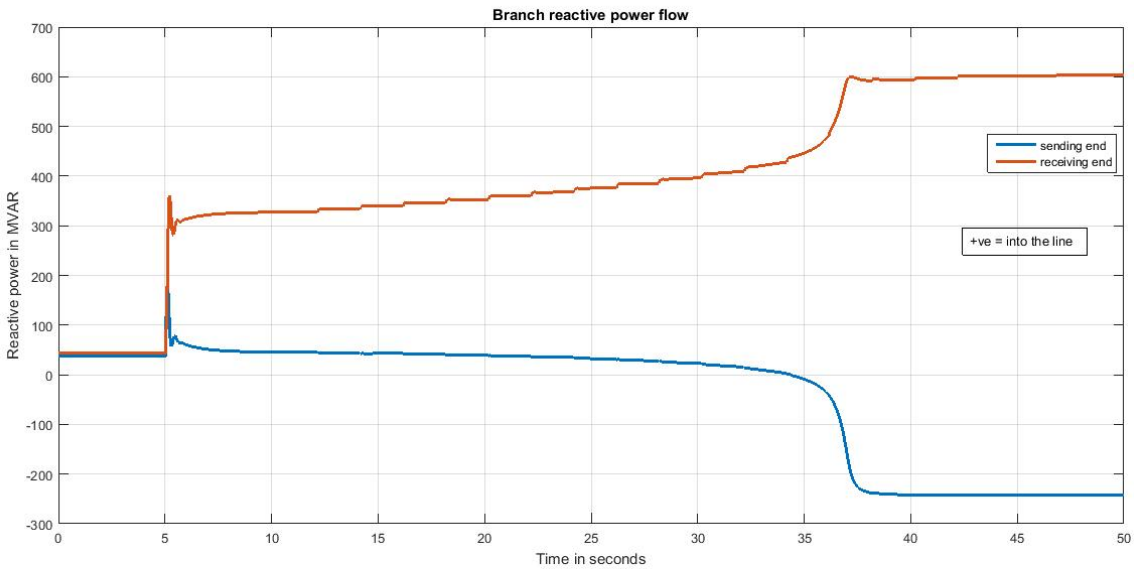



Figure 11: Reactive power flow on the 1-2




Increasing compensation restores voltage to a steady state value and avoids collapse. I tried to see if the OPF could find a steady state solution post outage with the shunt switched in. The formulation needs to include voltage-dependent motor dynamics to be reliable, although approximate. The table below shows calculation of sensitivities of reactive power absorbed by the line on the load side during drop in load side bus voltage. The red colored area on the left indicates time when the voltages are dropping fast, while on the right, the voltages are stable although low.

| Time(sec) | dQrdVr | dQsdVr | Vr(pu) | dVr(pu) | dQr (MVAr) | dQs(MVAR) |
|---|---|---|---|---|---|---|
| 5 | -9.96178108 | -9.1365766 | 1.04659 | | | |
| 5.02 | -9.96178108 | -9.1365766 | 1.04659 | 0 | 0 | 0 |
| 5.04 | -9.96178108 | -9.1365766 | 1.04659 | 0 | 0 | 0 |
| 5.05 | -9.96178108 | -9.1365766 | 1.06368 | 0.01709 | -17.02468387 | -15.61440938 |
| 5.051 | -10.7931103 | -8.6171087 | 1.06025 | -0.00343 | 3.702036839 | 2.955668271 |
| 5.071 | -10.9257134 | -8.4219144 | 1.04409 | -0.01616 | 17.65595279 | 13.60981364 |
| 5.091 | -10.8973621 | -8.1553751 | 1.01711 | -0.02698 | 29.40108291 | 22.00320213 |
| 5.111 | -10.698954 | -7.8614475 | 0.98327 | -0.03384 | 36.20526035 | 26.60313819 |
| 5.131 | -10.3517795 | -7.5911037 | 0.947538 | -0.035732 | 36.98897847 | 27.12453182 |
| 5.151 | -9.90304659 | -7.3877928 | 0.914472 | -0.033066 | 32.74541385 | 24.42847577 |
| 5.171 | -9.41333374 | -7.2741115 | 0.887256 | -0.027216 | 25.61932912 | 19.79722189 |
| 5.191 | -8.94005162 | -7.2507513 | 0.867363 | -0.019893 | 17.78444469 | 14.42391955 |
| 5.211 | -8.52988923 | -7.2979027 | 0.854756 | -0.012607 | 10.75363135 | 9.20046599 |
| 5.231 | -8.21021459 | -7.3875226 | 0.848361 | -0.006395 | 5.250432228 | 4.724320729 |
| 5.251 | -7.98746164 | -7.4935785 | 0.846583 | -0.001778 | 1.420170679 | 1.332358259 |
| 5.271 | -7.85308053 | -7.5955144 | 0.847719 | 0.001136 | -0.892109948 | -0.862850432 |
| 5.291 | -7.78835532 | -7.6809695 | 0.850225 | 0.002506 | -1.951761843 | -1.924850957 |
| 5.311 | -7.77220805 | -7.7428467 | 0.852858 | 0.002633 | -2.046422379 | -2.038691535 |
| 5.331 | -7.78146773 | -7.7816345 | 0.854724 | 0.001866 | -1.452021878 | -1.45205299 |
| 5.351 | -7.79929593 | -7.7978574 | 0.855276 | 0.000552 | -0.430521135 | -0.430441726 |
| 5.371 | -7.81146997 | -7.7957563 | 0.854278 | -0.000998 | 0.779584703 | 0.77801648 |
| 5.391 | -7.80815239 | -7.7808622 | 0.851753 | -0.002525 | 1.971558479 | 1.964667707 |
| 5.411 | -7.78547799 | -7.75746 | 0.847917 | -0.003836 | 2.986509355 | 2.975761645 |
| 5.431 | -7.74126774 | -7.7316702 | 0.843098 | -0.004819 | 3.730516922 | 3.725891879 |
| 5.451 | -7.67869929 | -7.7063007 | 0.837675 | -0.005423 | 4.164158622 | 4.179126878 |

| Time(sec) | dQrdVr | dQsdVr | Vr(pu) | dVr(pu) | dQr (MVAr) | dQs(MVAR) |
|---|---|---|---|---|---|---|
| 5.811 | -6.27462492 | -7.6756488 | 0.759957 | -0.004518 | 2.834875538 | 3.46785813 |
| 5.831 | -6.19156106 | -7.6762674 | 0.755342 | -0.004615 | 2.85740543 | 3.542597408 |
| 5.851 | -6.10607877 | -7.6775344 | 0.750634 | -0.004708 | 2.874741884 | 3.614583182 |
| 5.871 | -6.01833505 | -7.6793657 | 0.745833 | -0.004801 | 2.889402659 | 3.686863461 |
| 5.891 | -5.92832102 | -7.6817702 | 0.740933 | -0.0049 | 2.904877301 | 3.764067407 |
| 5.911 | -5.83593835 | -7.6847368 | 0.735925 | -0.005008 | 2.922637926 | 3.848516205 |
| 5.931 | -5.74102428 | -7.688264 | 0.730796 | -0.005129 | 2.944571355 | 3.943310625 |
| 5.951 | -5.6433433 | -7.6923501 | 0.725534 | -0.005262 | 2.969527243 | 4.047714641 |
| 5.971 | -5.54210617 | -7.6975654 | 0.720124 | -0.00541 | 2.998279436 | 4.164382863 |
| 5.991 | -5.43817666 | -7.7027722 | 0.714554 | -0.00557 | 3.029064398 | 4.290444142 |

# 8 Further Questions

1. Increasing robustness of prediction
2. Other possible signatures obtainable from data trending
3. Total time required for the algorithm
4. Capturing sudden actions like excitation limiting
5. Accuracy of load models
6. Network reduction/equivalencing for faster computational speed