1 PowerApps Voltage Stability Solutions

An important issue in the real time system operation, monitoring and control exercise is to check whether the system is sufficiently working within the stability limits and whether the system has sufficient stability margins. The power transfer limits over transmission lines are constrained by the following factors

- The thermal overload limit – Usually this limit comes into play for short lines and this limit is usually higher than the next two limits
- The voltage drop limits – usually this limit comes into play for medium length lines. These limits are usually higher than security/stability limits and lower than the thermal limits
- These stability limits – For static or steady state operating point, this is determined by the power transfer limits as determined by the static voltage stability analysis. For normal operating conditions where system is subjected to small power impacts, these limits may be defined by the small signal stability considerations. When the system recovery subjected to contingency conditions is considered, these limits may be defined by large signal or transient stability performance of the system. The minimum power transfer limit is therefore determined from the minimum loading conditions (or power transfer limits) from these three stability considerations. Determining these stability limits usually involves numerous simulations around an operating point, based on which operators may determine safe operating limits that covers the majority of operating conditions. System frequencies, line loadings, bus voltage limits , system damping following disturbances all may be considered in determining these limits.

2 VP curve and VQ curve or PV Curve , QV curve to estimate static stability margins

These curves are generated by increasing the load power P [with constant power factor] at a given bus and performing load flow solution to determine the corresponding bus voltage. The plot of P v/s V is shown as P-V curve. A similar exercise can be done by increasing the Q load alone at the bus under consideration to obtain a plot of Q-V.

The nose point of the curve denotes the critical bus voltage and the corresponding maximum power transfer limit to the bus. The margin in MW from the operating point to this critical point denotes the MW power transfer stability margin. The MW value corresponding to the nose point also denotes power transfer limit for specified load power factor. We get a family of P-V curves for different load power factors and consequently we get different stability margins. Using this family of PV curves for different power factors, we can determine the compensation needed to improve the stability margin from an operating to point to required stability margin.

The following methods may be used to generate the PV curves at a bus of interest

1. Increase the load at the bus under consideration with constant power factor and allow this increase demand to be met by slack bus. The relevant load flow solution will provide the corresponding V coordinate of the PV curve
2. Same as 1, except that specify the generator or generators that should meet this increased demand at the load bus. Correspondingly the generation schedule is changed in the load flow. In PowerApps this is simply done by case dependent data specifications
3. Same as 1, except that the generation schedule to meet the increased demand is met by economic dispatch algorithm. The corresponding load flow solution will provide the V coordinate of the PV curve
4. Same as 1, except that the generation schedule is arrived by economic dispatch and further reactive power optimization is also performed to get optimum load flow solution. This optimum load flow solution provides the voltage point ‘V” of the PV curve.
5. The PV curve is determined by a transient stability algorithm. The increase in demand is provided as disturbance event. The sharing of this demand is realistically determined by the network characteristics and generator controllers. Once the system stabilizes the demand is further increased at the node and corresponding voltage is determined.

In all the above 5 methods of PV curve generation, the load at the given load bus is increased till either the load flow fails to converge [for methods 1 to 4] or transient stability fails to converge [for method 5]. Similar procedure is adopted for the QV curves also. Results are tabulated.

It should be noted that load flow methods are amenable for real time applications compared to stability method of 5. However, it is suggested that for real time applications , only the results from off-line simulation exercises be stored in a lookup table, rather than performing these analysis in real time environment.

It should also be noted that only the upper half of the PV or QV curve needs to be generated, there is no need to generate the bottom half as this does not serve any purpose. This is based on the assumption that the initial condition is in the upper half of the PV/QV curves.

Apart from the PV and QV curves shown in the figure 1, there is another form of QV curve for purpose of checking the suitability of the compensating device to improve voltage stability. This is shown in the figure 2. The red color plot shows the variation of load Q with respect to the bus voltage. The green color plot shows the variation of reactive power compensation with respect to the bus voltage. It can be seen from the plots that there are only two stable operating points, where the two curves intersect. Consequently the operating condition settles only to one of these two operating points , where the characteristics are intersecting. This type of QV curve is useful in determining the suitability of the compensation for the load under consideration.

3 The Sensitivity Analysis and other Voltage Collapse Proximity Indicators

From PV curves or from repeated load flow solutions or from load flow jacobian at the point of solution as used in optimal power flow, the following sensitivities can be computed. These sensitivities can be used as measure of proximity of the bus to the voltage collapse point. These measures are approximate and varies from bus to bus. i.e. the same sensitivity level at two buses do not indicate same voltage stability margin in terms of MW load or MVAR load. Thus the operator needs to formulate the basis for these sensitivities based on his experience with the system analysis. The advantage of the sensitivity methods is that it takes only few seconds to compute the same at an operating point as against the time taken for PV/QV curves.

1. The change in the terminal voltage magnitude of a bus for a given change in the active power loading of the bus $\frac{\Delta V}{\Delta P}$
2. The change in the terminal voltage magnitude of a bus for a given change in the reactive power loading of the bus $\frac{\Delta V}{\Delta Q}$

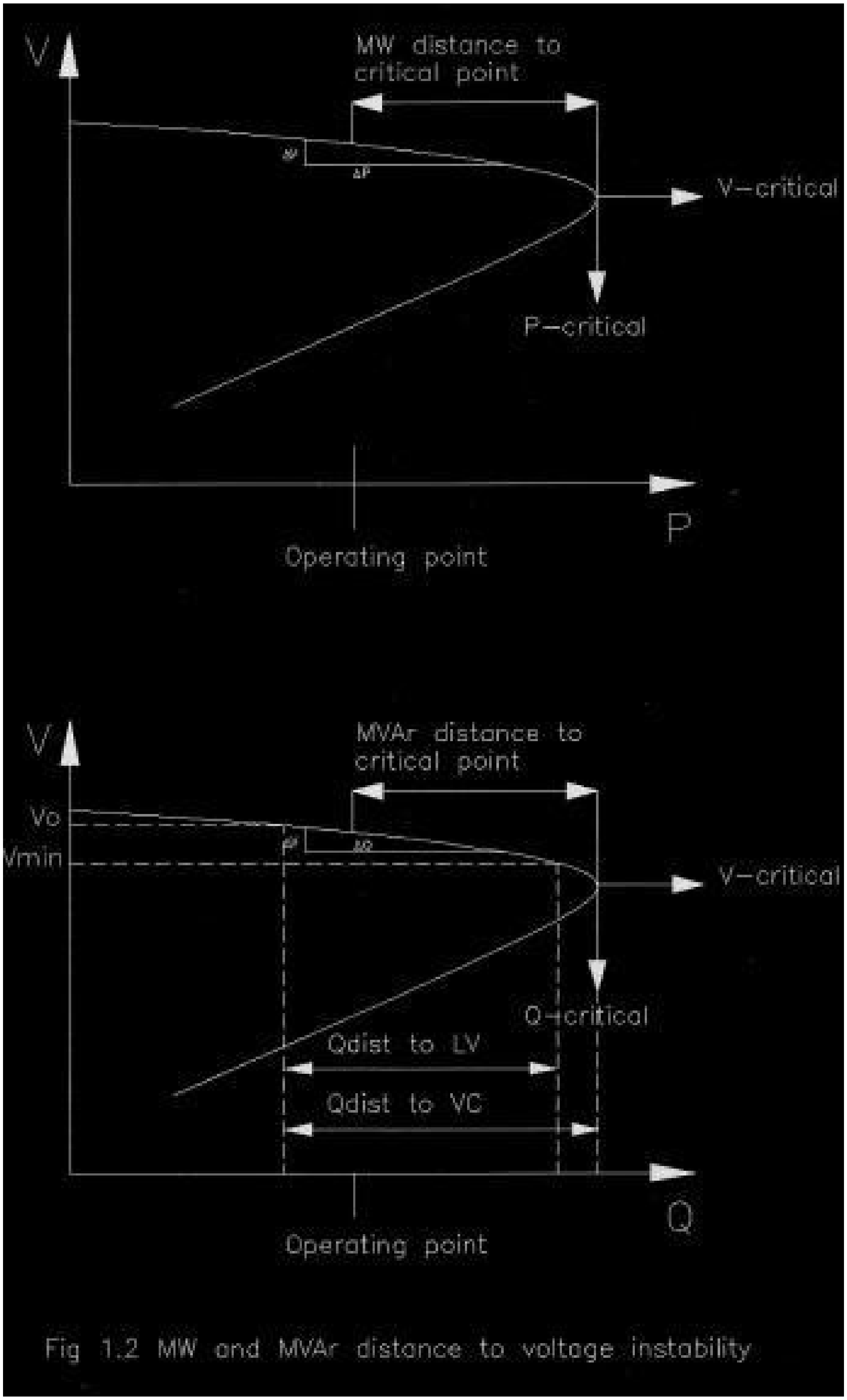
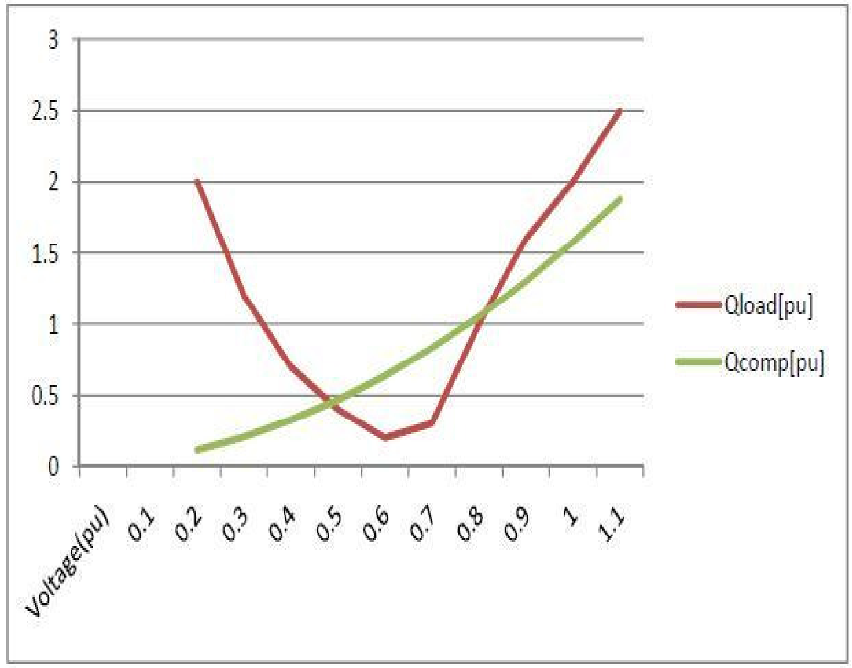


Figure 1 PV and QV curves from Load Flow

Voltage(pu)	Qload[pu]	Qcomp[pu]
0.1		
0.2		
0.3	2	0.117
0.4	1.2	0.208
0.5	0.7	0.325
0.6	0.4	0.468
0.7	0.2	0.637
0.8	0.3	0.832
0.9	1	1.053
1	1.6	1.3
1.1	2	1.573
1.2	2.5	1.872



Note: The system can have only two stable operating points where the characteristics of the compensating device intersects with that of the load Q characteristics

Figure 2 QV curve of the load and compensating device

3. The net change in the generator reactive power injection for a given change in the reactive power injection at the bus under consideration $\frac{\sum \Delta Q_g}{\Delta Q}$
4. The net change in the generator reactive power injection for a given change in the active power injection at the bus under consideration $\frac{\sum \Delta Q_g}{\Delta P}$

In order to have a good understanding and feel of these sensitivities, the system operator must perform numerous off-line load flow solutions and record the observations and formulate operating guidelines

3.1 Minimum Singular Value Decomposition

This method in PowerApps is derived from the references

A. P.A.Lof, T.Smed, G.Anderson, D.J. Hill, "Fast Calculation of a Voltage Stability Index" , IEEE Transactions on Power Systems, Vol.7, No.1, February 1992
B. P.A.Lof, G.Anderson, D.J.Hill, "Voltage Stability Indices for Stressed Power Systems", IEEE Transactions on Power Systems, Vol.8, No.1, February 1993

The following is the partial output extract from PowerApps voltage stability program

3.1.1 From Full Load Flow Jacobian for an Indian System

```
     MINIMUM SINGULAR VALUE OF LF JACOBIAN IS =       .0591957

-----------------------------------------------------
 CRITICAL BUS VOLTAGE RANKING BY RIGHT SINGULAR VECTOR
 -----------------------------------------------------

               1          53    .16936
               2          52    .16561
               3          16    .14831
               4          72    .14729
               5          55    .14379
```

**Bus 53 is the most critical from voltage stability point of view

3.1.2 From Reduced and Modified Jacobian for an Indian System

```
     MINIMUM SINGULAR VALUE OF THE LF REDUCED JACOBIAN IS =       .0819574

-----------------------------------------------------
 CRITICAL BUS VOLTAGE RANKING BY RIGHT SINGULAR VECTOR
 -----------------------------------------------------

               1          53    .21668
               2          52    .21020
               3          16    .18725
               4          72    .18554
               5          55    .17725
```

**Bus 53 is the most critical from voltage stability point of view

3.2 Voltage Stability Index L

This method in PowerApps is implemented from the following reference

- P.Kessel, H.Glavitsch, "Estimating the Voltage Stability of a Power System", IEEE Transactions on Power Delivery, Vol. PWRD-1, No.3, July 1986

The following is the partial extract from PowerApps voltage stability calculation for this index

```
-------------------------
VOLTAGE STABILITY INDEX L
-------------------------
  1          32    .73547
  2          56    .70498
  3          55    .69864
  4          57    .68356
  5          43    .64667
```

**Bus 32 is the most critical bus in the system from view point of the voltage stability

3.3 Voltage Stability Index 'C' developed by this Author

This method is based on the publication of this author's research work published in the following reference

Raghunatha, R and Ramanujam, R and Parthasarathy, K and Thukaram, D (1998) "*A new and fast technique for voltage stability analysis of a grid network using system voltage space.*" In: International Journal of Electrical Power & Energy Systems, 20 (5). pp. 337-344.

The following is the partial extract from the PowerApps voltage stability program for the calculation of this voltage stability index

```
------------------------------------
   RANKING BY STB INDEX AT CONST PF
STABILITY INDEX = |VG*/V...+ V*...|
------------------------------------
    1          32    .73181
    2          52    .71886
    3          55    .71803
    4          56    .71726
    5          57    .70513
```

**Bus 32 is the most critical bus in the system from view point of the voltage stability

3.4 How to use Voltage Stability Indices for Real Time Operation and Control

As compared to detailed PV curve methods, or QV curve methods that are time consuming, the voltage collapse proximity indicators or "VCPI's" is a convenient way to rank the buses from view point of the proximity of the buses to the voltage collapse. From the short listed or ranked list of the buses, we can select the buses of interest for more detailed evaluation through PV/QV curves using any one of the methods suggested in section 2.0. From the detailed analysis we will be in a position to know the quantum of the reactive power compensation needed to improve the voltage stability margin at selected buses.

4 The PowerApps OPF method for Voltage Stability Improvement

The methods of PV curves provide corrective measures needed locally at the bus under consideration. Often no corrective measures may be available at the most critical bus from view point of the voltage stability. However, PowerApps OPF solution provides a general controller solution available in the system that improves the overall system voltage stability. This algorithm was developed as part of this author's research work and is published as under

"Optimal static voltage stability improvement using a numerically stable SLP algorithm, for real time applications" by R. Raghunatha, R. Ramanujam, K. Parthasarathy , and D. Thukaram International Journal of Electrical Power & Energy Systems Volume 21, Issue 4, May 1999, Pages 289-297