Impact of Distribution Efficiency on Generation and Voltage Stability

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Abstract

On-going changes in the electric utility industry are imposing ever-stricter constraints upon the operators of transmission networks. The increase in peak load and reduced power margins in the network may under certain circumstances conspire to produce brownouts, or even blackouts, especially when compounded with low probability contingencies. The challenge is also imposed on generation capacity to meet such requirements. An efficient and inexpensive way of coping with those effects is by maintaining sufficient reactive support along the feeders to provide a flat voltage profile, thus allowing deeper levels of voltage reduction when needed. The paper describes how the beneficial effects of voltage reduction allow avoiding adding new capacity to meet peak demand, but also increasing voltage stability margins.

1. Introduction

The restructuring of the power industry is creating new challenges for system operation and planning. The sound investment strategies should include interests of all partners. The operating circumstances include tighter budgets for new generation, and narrow stability and security margins during peak loads in day-to-day operation of power systems. The probability of catastrophic events, including complete system blackouts, increases significantly when operating margins are tight. Many examples of erratic system behavior have been observed in such systems, and accuracy of analytical models of system stability [6][9][10] is sometimes compromised by interaction of various subsystems (emergency control, protection) whose main purpose is to increase the system robustness against such events [7][8].

The distribution efficiency, or conservation voltage reduction program represents an effort to utilize the resources rationally for the benefit of distribution, transmission, and generation. Briefly, its design can be described as installation of series of sufficient number of capacitor banks along the distribution feeders, having purpose of maintaining a flat voltage profile along the feeders. Thus, deeper voltage reduction can be applied to a feeder, for the most distant loads are maintained at near the same voltage level as the loads at the beginning of the feeder. The benefits can be summarized as avoided generation capacity during the load peaks over a lifetime of the capacitor banks, and creation of bigger voltage stability margins, thus avoiding use of other remedial actions, such as adding reactive generation capacity, and load shedding.

The paper explains the implementation of the program, and describes an application on a test system, as well as development of a framework for a cost benefit assessment.

2. Voltage Reduction

Voltage reduction is usually associated with the practice of regulating voltage at the substation level so as to operate the feeders at the lowest acceptable voltage levels [1][2]. Under normal circumstances, the locations of customers that are the critical points in assessing how low a voltage reduction can be applied are usually at the far ends of the feeder, due to the voltage drops along the feeders.

Figure 1. Voltage profiles at the radial feeder before the reactive compensation (dashed line). After the compensation is applied, deeper reduction is possible (solid lines) before reaching the threshold (lower dotted line).
The benefits of voltage reduction are linked to the voltage sensitivity of the loads, which (depending on their structure) tend to consume less power when supplied at lower voltage levels. Additional benefits are obtained by reducing reactive requirements of the loads, which are sometimes even more dependent upon voltage than the active powers of the loads.

In the early attempts to accomplish voltage reduction [1][2], feeders were treated without any attempts to optimize the procedure: the voltage drop along the feeder imposed that whatever considerations are applied toward defining the acceptable threshold for voltage reductions, the affected customers were, in all likelihood, at the very ends of the main feeders and their laterals.

Figure 1 shows a voltage profile along a radial feeder in such a situation (dashed line). The ANSI standard [1] requires that the lowest voltage point remain within 5 percent from the nominal value (120 ± 6 V at the customer level). Prior to the application of voltage reduction [1][2], tests were performed with a large number of max/min voltmeters at the customer sites, which were deployed over a period of several months to record the variation of the voltage levels at various suspected low voltage customer sites. The results of investigation indicated that only 1.6 V of reduction was available when worst case scenarios of load variations were taken into account.

Another consideration in implementing the voltage reduction is the step of the under-load-tap-changing (ULTC) transformers, used to provide the voltage reduction. When the available depth of reduction is rather small, smaller tap steps achieve a better reduction, but at the expense of a larger number of tap actions, roughly inversely proportional to the step size [1]. The biggest problem remains the acceptable depth of the voltage reduction, which remains a relatively weak tool without adequate reactive support.

Figure 2. Voltage profile on an uncompensated radial 12-bus feeder with nominal 15.3 MW load consisting of 50 percent constant power and 50 percent impedance load.

Figure 3. With reactive compensation at buses 4, 6, 7, 11, and 12, feeder can be allowed 3.5 percent voltage reduction and still comply with ANSI requirements. Labels correspond to loading levels from Figure 2.

Figure 4. Voltage profile of the feeder at the heaviest load after 3.5 percent voltage reduction.

It is obvious that an improvement in voltage reduction can only be achieved with addition of reactive support along the feeders and laterals, which would allow for flatter voltage profiles and consequently, deeper levels
of voltage reduction (Figure 1). Such effects is shown in Figure 2, where a 15.4 MW radial feeder model consisting of 12 loads (each 50% constant power and 50% impedance) was subjected to load variations causing the last customer voltage drop to 0.94 pu. With additional reactive support \[4][5][6] of 3 MVAR added to buses 4, 6, 7, 11, and 12, voltage profile has greatly improved (Figure 3) and allowed 3.5 percent voltage reduction without violating ANSI requirements.

![Figure 5. Voltage profile of a compensated feeder at different levels of supply voltage.](image)

![Figure 6. Feeder consumption vs. supply voltage. Load is 50 percent constant power and 50 percent impedance.](image)

3. Aspects of Implementation

Implementation of the system relies upon capacitor controllers that maintain the controlled points of the feeder at the pre-set voltage levels. The issue of placement of the capacitor banks can be resolved in a number of ways [3-5], by using optimization techniques, or approached heuristically, depending on the primary objectives of the implementation: loss reduction, voltage control, minimization of reactive support (investment), etc. One can approach the issue of placement by using voltage sensitivity analysis and introduce capacitor banks step-by-step until the objectives are met.

Once the capacitor banks are installed (say, in blocks of 4 x 300 kVAR) on the feeder, time delays should be set, as well as voltage set-points for their operation. The operation may be designed to be revenue-neutral, by setting the nominal supply voltage lower to offset the reduction in losses achieved by adding reactive support.

Effects of voltage reduction have been experimentally found to depend on the type of customers who dominate the feeder [1], and among the various estimates that the authors have found, the following formula can be entertained

\[
\eta = \frac{\Delta P}{P} = 0.7 + 0.5 \cdot N_{RSC} \ \%/V \quad (1)
\]

where \( \eta \) represents percentage load power reduction per 1 volt of load reduction, while \( N_{RSC} \) is a fraction of residential and small business customers on a feeder. Thus, \( \eta \) varies between 0.7% and 1.2% as \( N_{RSC} \) varies between 0 and 1. If the feeder has 50 percent residential and small commercial customers, the effects of voltage reduction are estimated to be 0.95 percent per volt of reduction.

4. Framework for Cost Benefit Analysis

Assuming for a moment that the sole intended impact of the voltage reduction is to avoid generation capacity during peak load, a simple cost benefit structure can be proposed. The following information is needed:
• If the life of the installation on the utility feeder is estimated to be \( W \) years, than the revenue based on avoided generating capacity is estimated to be \( X \) dollars per kW of load reduction obtained by using the reactive support-enhanced system.

• The fuel savings from avoided capacity are estimated to be \( Y \) dollars per kW over the same estimated lifetime of installation.

• Revenue due to saved transmission capacity during load reduction is estimated to be \( Z \) dollars per kW.

The estimated benefit

\[ B = X + Y + Z \]  

(2)

reflects all of the above effects: the total avoided capacity estimated to be obtained with voltage reduction at peak power conditions should be multiplied with \( B \) to obtain the total estimated benefit from the proposed installation.

The total cost associated with the project is the DEP installation and maintenance cost \( C \). It can be expressed as \( D \) dollars per MW of peak load power under which the savings are calculated. As a feeder ranking procedure, one can select the ratios of estimated \( B/C \) and thus select the most suitable candidate feeders for implementation based on that criterion. Based on similar considerations, \( B/C \) ratios are estimated to range from below 1.0 (unsuitable for implementation) to 4.9 (ideal candidates, which will return almost five times the investment into their efficiency) [11].

We propose to include the benefits of using voltage reduction in voltage stability enhancement of the transmission network, which should have an effect of improving the benefit-to-cost ratio entertained above.

5. Voltage Stability Effects

Voltage stability in power networks has been studied extensively over many years [6-10]. Kwatny [12] observed the sensitivities of the system variables to the change in the system’s parameters. These sensitivities become very large when a bifurcation point occurs in the parameter space. The qualitative structure of the system changes for any small variation of the parameter vector \( \lambda \). The system model assumes dynamics of the synchronous machines and constant \( PQ \) loads, i.e.

\[ g_1(\delta, \dot{\delta}, \theta, V) = 0 \]

\[ g_2(\delta, \theta, V, \lambda) = 0 \]

where \( g_1 \) describes real power balance and additional state equations of the generators and \( g_2 \) describes real and reactive power balance of the loads. The parameter vector \( \lambda \) represents the change in load power demands.

For the fixed value of \( \lambda \), its equilibrium points are solutions of the system

\[ g_1(\delta, \theta, V) = 0 \]

\[ g_2(\delta, \theta, V, \lambda) = 0 \]

If \( g = [g_1, g_2]^T \) is linearized around an equilibrium point, and if we introduce \( d\xi = [\delta, \theta]^T \) the following relationship holds

\[ g_1 \xi + g_V V + g_\lambda \lambda = 0 \]

In the matrix form it is given by

\[ \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{bmatrix} d\xi \\ dV \end{bmatrix} = \begin{bmatrix} g_1 \xi \\ g_2 \lambda \end{bmatrix} d\lambda \]

Singularity of the Jacobian matrix on the left side of the above equation implies the bifurcation, and shows that it is accompanied with infinite sensitivity of the elements of the state vector with respect to changes in loading parameters \( \lambda \).

By applying voltage reduction described in the previous sections to the feeders (composite loads) of the power network, we are improving stability margins on two accounts:

• Active powers of the loads are reduced by virtue of voltage reduction, which may, or may not be deployed, depending on the circumstances.

• Reactive powers of the loads are offset by reactive support. Load power factors are normally kept between 0.99 lagging and 0.99 leading when reactive support is deployed to help voltage reduction. This is normally much better than the situations encountered without support.

6. Simulations and Experiments

The effects of distribution efficiency-enhanced power systems have been investigated for voltage stability improvements in well known power system models (39-bus system of New England and IEEE 118-bus system).
System models were investigated in a normal operating state (base case), and close to voltage stability boundary, modeled by progressively increasing system loads through a common multiplier $k$. Systems were also modified for this analysis by setting reactive capability limits to the system generators, and modeling the distribution efficiency the following way:

- Loads are assumed to be constant power (which both minimize the effects of voltage reduction on active power, and maximize the danger from the voltage stability standpoint).
- Reactive power impact of the loads was modeled to impose power factors ranging from 0.99 lagging to 0.99 leading by virtue of reactive support present on the feeders.

The results are shown in the following pictures:

**Figure 7.** Voltage profile for 39 IEEE bus system in normal operating state and close to the stability boundary ($k=1.634$).

**Figure 8.** Sensitivity (in MVAr/MW) of the total generated reactive power w.r.t. active power of the critical (most demanding) load buses in the operating regime close to stability boundary limit ($k=1.634$) for 39-bus system, without support of distribution efficiency.

**Figure 9.** Reactive power generation of the 39-bus system in the base case ($k=1$), close to voltage stability limit ($k=1.634$), and against the reactive capability limits $Q_{\text{max}}$ (black bars). No distribution efficiency support is deployed.

**Figure 10.** Voltage profiles for 39-bus system in the operating states close to the stability boundary when distribution efficiency support is deployed, allowing load power factor to be between 0.99 lagging ($k=1.8$) and leading ($k=2.46$).

**Figure 11.** Load bus sensitivities for 39-bus system with distribution efficiency support in service, and in the operating states close to voltage stability boundary limits. Compare with Figure 8.
Figure 12. Reactive power margins for generator units of 39-bus system in the operating states close to stability boundary. Distribution efficiency deployed. Compare with Figure 9.

Figure 13. Voltage profile for 118 IEEE bus system in normal operating state and close to the stability boundary (buses with smallest voltage magnitudes are presented, and ordered in increasing voltages for the operating regime close to voltage stability boundary).

Figure 14. The sensitivities of the generated reactive power w.r.t. active power of the most critical load bases in the operating regime close to stability boundary limit (k= 2.08) for 118 IEEE bus system. No distribution efficiency.

Figure 15. Reactive power productions for 118 IEEE bus system in the base case (k= 1), close to stability limit (k= 2.08) and against reactive capability limits $Q_{\text{max}}$ (black bars). No distribution efficiency is deployed.

Figure 16. Voltage profile for 118 IEEE bus with distribution efficiency, in the operating states close to the stability boundary for load power factor 0.99 lagging (k= 2.18) and leading (k= 2.22). Compare with Figure 12.

Figure 17. Sensitivities of the generated reactive power with respect to active load powers for 118 IEEE bus system with distribution efficiency in service, and in the operating states close to stability boundary limits.
The cost-benefit analysis based on that effect indicates that application of efficiency program can provide savings equal to two to three times the investment costs just on account of avoided generation capacity. Additional benefits are possible by using the system as an enhancement for voltage stability.

8. References


