하계학술대회
논문86-7-4

PERFORMANCE OF DISTRIBUTION SYSTEM REACTIVE COMPENSATION SCHEMES CONSIDERING RANDOM LOAD VARIATION

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Properly applied reactive compensation on distribution system primary feeders provides important benefits. Feeder losses are reduced, peak power requirements are reduced, system capacity is released and feeder voltage characteristics are improved. The increased cost of losses and capacity and the development of new technologies for more sophisticated distribution system control have stimulated renewed interest in the optimization of distribution system reactive compensation schemes. The recent work of Grainger, et. al., has yielded improved methods for the application of fixed and/or switched capacitor banks along primary feeders [1-3]. An idealized infinitely variable source of reactive power was proposed in[4]. It was shown that such a device realizes increased loss reduction, increased peak power reduction, improved voltage characteristics and simpler implementation and control. The analysis was extended in[5] to include multiple variable sources of reactive power.

Detailed performance data for a proposed compensation scheme under actual operating conditions is difficult to obtain. A need exists for a rigorous yet economical technique for determining performance of hypothetical compensation schemes. Computer simulation of distribution system performance is an effective means of achieving this. A load flow based technique with randomly varied loads is presented in this paper. The technique permits easy determination of virtually any operating data desired. The technique is demonstrated for 12km long, 12.5kv distribution system primary feeder with various reactive compensation schemes applied. Four cases are considered:

1. An uncompensated base case
2. Compensation with a single fixed capacitor
3. Compensation with a single idealized infinitely variable source of reactive power
4. Compensation with a practical realization of a single idealized infinitely variable source of reactive power

Accumulated feeder losses, peak power requirements, and feeder voltage profile data are compared for the four cases.

LOAD FLOW FOR A RADIAL FEEDER

For a radial feeder, the problem can be defined in terms of the variables illustrated in Figure 1. The feeder is assumed to consist of sections each described by a series resistance and series reactance. Real and reactive power, P_i and Q_i, at buses 1 through n-1 and the voltages, V_1 through V_{n-1} must satisfy the following relationships:

$$I'_i = I'_{i-1} + I_i \qquad (1)$$

Where

$$I'_i = 0 \qquad i = 0$$

$$= \frac{V_{i+1} - V_i}{r_i + jx_i} \qquad i=1 \text{ to } n-1 \qquad (2)$$

and $$I_i = \frac{P_i - jQ_i}{V_i^*} \qquad i=1 \text{ to } n-1 \qquad (3)$$

One method of solving (1-3) is to estimate a value for V_1 then calculate remaining voltages working from the end of the feeder back to the source. If the calculated voltage at the source matches the specified source voltage within some reasonable tolerance,a solution has been found. If not, an improved estimate for V_1 is obtained by multiplying the previous estimate by V_s/V_n where V_s is the desired source voltage and V_n is the calculated source voltage based on the estimate. For reasonable first estimates, convergence $(|V_s/V_n| - 1 < 10^{-4})$ occurs in 2-6 iterations.

LOAD VARIATION

A normalized load cycle curve for a desired time period, say 24 hours, is assumed. Maximum megawatt and megavar loads at each point along the feeder are specified as inputs. The time period of interest is divided into a finite number of intervals over which the real and reactive power loads at each bus are assumed to remain constant. Real and reactive load at the i^{th} bus over the k^{th} interval in time is then obtained as:

$$P_{ik} = (f_k + 0.2\, R_{ik})\, P_{max\ i} \qquad (4)$$

$$Q_{ik} = (f_k + 0.2\, R'_{ik})\, Q_{max\ i} \qquad (5)$$

where f_k is the value of the load cycle curve at the midpoint of the K^{th} time interval. R_{ik} and R'_{ik} are zero mean random variables associated with real and reactive power at bus i and for the k^{th} time interval. $P_{max\ i}$ and $Q_{max\ i}$ are specified maximum real and reactive powers at bus i.

FEEDER SIMULATION

A computer subroutine is used to generate random numbers R_{ik} and R'_{ik}. The subroutine used in this investigation generated random numbers with a Gaussian distribution. A mean of zero and standard deviation of $1/\sqrt{3}$ were specified. The real and reactive power load at each bus were determined by (4) and (5) for each 15 minute interval in a 24 hour period and assumed to remain constant over the 15 minute interval. Experience with the technique revealed that smaller time intervals increased computation time without significantly altering final results For each load condition (96 in a 24 hour period if 15 minute intervals are chosen) the load flow is solved and appropriate output data is stored. Feeder energy losses are accumulated by feeder sections and for the total feeder. Power losses, total power requirements at the source, and bus voltages are easily obtained for each 15 minute interval of the 24 hour period.

COMPARATIVE RESULTS

Analysis of the uncompensated feeder will be referred to as case 1. As shown in [5], for this particular feeder, most of the benefits of reactive compensation are realized with a single source of reactive power whether fixed or variable. Accordingly, only cases involving a single source are considered. Siting and sizing relationships for fixed or variable sources of reactive power are summarized in [5]. The optimal location for a single fixed or variable source, for the sample feeder, is found to be at bus 11 where the normalized value of the simplified reactive current distrbution curve is .4083 $(I(L_c) = .4083)$.

The size of an optimal fixed capacitor (case 2) depends on the reactive current load factor and on the relative costs of

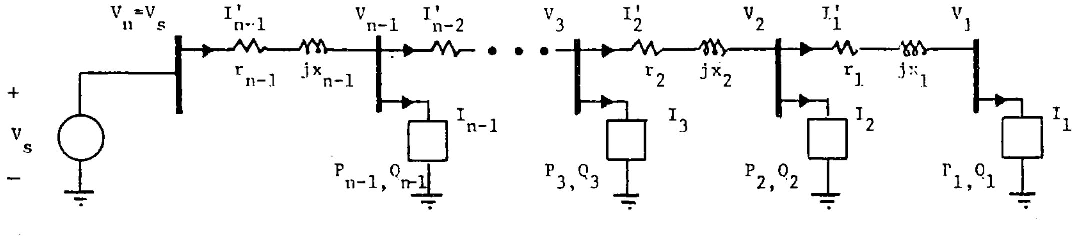

Fig. 1. Load Flow Formulation for a Radial Feeder.

energy and peak power [4,5]. In the cases considered here, the reactive current load factor was taken to be the same as the load factor of the load cycle curve.

The cost of energy was taken as ₩35/kwh and the cost of capacity (peak power) was taken as ₩657,000/kw per year [7]. With these assumptions, the optimally sized fixed capacitor bank, as described in [4, 5], is 2.24 Mvar. In terms of the notation introduced in [4,5] m = 1 and F_{avg} = o,4453.

A variable source of reactive power (case 3) is operated in such a way as to supply compensation based on the instantaneous reactive power consumption at its location, i.e., bus 11. A capability to continuously monitor reactive power consumption and control the source is required and assumed.

The load flow solution procedure described earlier lends itself quite well to the simulation.

A practical realization (case 4) of the idealized variable source of reactive power is described in [4] where it is referred to as a suboptimal strategy. In essence, the maximum reactive compensation required of an idealized variable source is divided arbitrarily into n discrete amounts of compensation realized by switching capacitors at bus 11. If five discrete values are used (n=5), the suboptimal strategy requires 5 switching fixed capacitor banks to realize a total compensation .

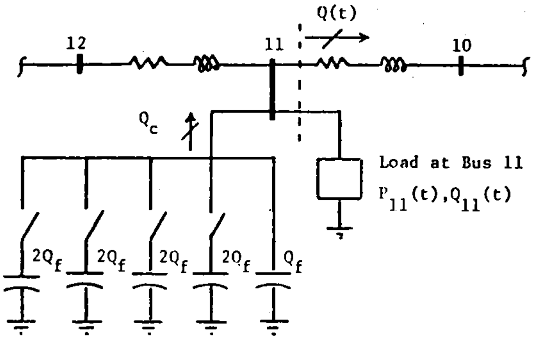

Fig. 2. A practical Realization of the Idealized Infinitely Variable Source of power (Case 4).

The load flow solution procedure described earlier also lends itself well to the simulation of the setup shown in Figure 2.

Sample output data related to power, energy and capacity are summarized in Table 1 for the four cases considered. As shown in Table.1, the more dramatic reductions are those computed only on the basis of reactive current. Power, capacity and energy computed on a total current basis are easily determined by the method and yield a more meaningful perspective. For this particular 24 hour run, the practical realization of the idealized variable source performed nearly as well as the variable source with respect to energy losses for the 24 hour period but peak power losses and peak capacity required were somewhat higher than expected. This is due to the reduced compensation provided by capacitors at peak load when voltage effects are considered.

The total load energy served in the 24 hour period, excluding all losses, was 66.426 MWH. Using data from Table 1, the variable source is seen to realize an energy savings over the fixed source of:

$$\frac{1113.1 - 938.9}{66,426} \times 100 = 0.262\%$$

The corresponding figure for the practical realization of the variable source is 0.244%

Performance index (P.I) reductions predicted by the simple expressions or curves presented in [4] and [5] compare favorably to the reductions determined using the detailed simulation procedure presented in this paper. Table 2 summarizes results where $P.I._2$ is the performance index reduction for case 2, $P.I._3$ for case 3, etc.

Table 1 shows that the simpler techniques described in [4] and [5] can be used to identify the most promising reactive compensation schemes. The calculated ratios of performance index reductions shown in Table 2 are based on total peak power and total energy losses whereas the techniques of [4] and [5] treat effects of reactive current only. Agreement is good because the P.I. terms are primarily due to reactive current effects.

TABLE 1

Sample Output Data for Cases 1 Through 4

	Peak Capacity Required At Source (MVA)	Peak Power Losses (kW)	Energy Losses In 24 Hour Period (kWh)	Energy Losses in 24 Hour Period Due to Reactive Current (kWh)
Case 1 Uncompensated feeder	8.4449	208.72	1406.7	481.0
Case 2 Single Fixed Capacitor	7.2209	203.76	1113.1	202.3
Case 3 Single Idealized Variable Source of Reactive Power	6.8062	182.16	938.9	31.0
Case 4 Practical Realization of Idealized Variable Source of Reactive Power	7.0006	190.8	951.1	43.2

TABLE 2

Performance Index Reduction Ratios

	Predicted	Calculated by Detailed Simulation
$\frac{P.I._3}{P.I._2}$	1.19	1.30
$\frac{P.I._4}{P.I._3}$	0.98	0.93

CONCLUSTONS

Computer simulation of distribution system primary feeder behavior is an effective and economical means of evaluating reactive compensation schemes. Results of the detailed simulation procedures presented compare favorably with earlier predicted performance characteristics and add considerable insights and perspective. The load flow solution procedure presented permits examination of various control strategies with regard to actual implementation. For the cases considered, five easily determined discrete values of switched capacitances provide performance comparable to that of the idealized variable source of reactive power.

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