HOUR BY HOUR OPERATION OF FIXED AND SWITCHED CAPACITOR BANK CONNECTED TO A RADIAL DISTRIBUTION FEEDER

By

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ABSTRACT

This paper gives a method for selecting optimum position for fixed and switched capacitors on a radial feeder. The optimum position of capacitors (fixed and switched) are selected based on random proposal for their places on the feeder. The method also includes a selection of optimum switching time of switched capacitor which will be located at the optimum position. As the optimum location is definite, the hourly optimum operating strategy for fixed and switched capacitors located at the optimum position is obtained.

INTRODUCTION

Power capacitors have been improved tremendously over the last 30 years or so, partly due to improvements in the dielectric materials and their more efficient utilization and partly due to improvements in the processing techniques involved. Capacitor sizes have increased from the 15 - 25 KVAR range to the 200 - 300 KVAR range (capacitor banks are usually supplied in sizes ranging from 300 to 1800 KVAR). Now days, power capacitors are much more efficient than those of 30 years ago and are available to the electric utilities at a much lower cost per kilovar.

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In general, capacitors are getting more attention today than before, partly due to a new dimension added to the analysis: change-out economics [1].

Kilovars, as well as kilowatts, must be provided to the customer as part of a utility's electricity service, and the analysis of the technically most desirable and economically most attractive way to supply this reactive power requirement is one of the system planner's objectives. Where as the kilowatts can be supplied only from an energy source or power plant, kilovars are automatically produced as well as consumed by the electric network itself. This, of course, results from the inherent shunt - capacitive and series - inductive characteristics of the transmission lines. For this reason planning of the reactive power supply is subjected to a greater range of system variables [2].

A technique is developed for solving the voltampere reactive (VAR) compensation problem under uncertain operating conditions. The technique employs chance-constrained programming (CCP), and transforms the problem into a standard linear programming problem. In providing optimal allocation of VAR supports, busbars with unacceptable probability of violating voltage limits are identified and assigned appropriate chance constraints. Two cases are considered using the new technique. In the first case, capacitive compensation is evaluated for peak load conditions. Inductive compensation is considered in the second case, for light load conditions [3].

A methodology for finding the degrees of series capacitor and shunt - reactor compensation is used to increase the power transfer capability of the over - head power transmission existing rights of way and to get adequate control of steady state voltage and reactive power requirements. This methodology is based on assumed system design criteria and takes into consideration several schemes of compensation [4].

A transposition study carried out on the 654 Km Muja - Kalgoorlie 220 Kv radial transmission system are presented. Voltage control and stabilization of this network is achieved with the installation of three saturated reactor type static VAR compensators. By suitable line transposition, it is shown how voltage unbalances at the static voltage compensators locations can be reduced to ensure minimal negative phase sequence current loading on the saturated - reactors [5].

The paper presents a method for obtaining optimum positions, optimum capacitor bank sizes (fixed and switched), optimum switching time and optimum operating strategy for fixed and switched capacitor is obtained. The method is based upon Grainger and Lee equations [6, 7].

**PROBLEM FORMULATION**

- The problem here is the determination of optimum positions, optimum capacitor sizes, optimum switching time and optimum operating strategy for fixed and switched capacitors connected with radial feeder. The method for obtaining the above mentioned parameters are obtained by the following steps:
  - In the first step, a selection of random positions for fixed and switched capacitors is carried out.
  - Then, a selection of the optimum places, optimum capacitor sizes (fixed and switched), optimum switching time and optimum operating strategy are obtained. The previous parameters are determined as follows:
1) Obtain the optimum operating strategy (k) hour by hour (k) for each selected place of fixed and switched capacitors.

2) Determine the optimum switching time at which optimum switched capacitor size is minimum.

3) Obtain the sum of optimum fixed and switched capacitor sizes at each selected place and select the minimum summation.

4) Represent section numbers at which minimum summation are obtained.

The feeder under investigation consists of 9 sections and is supplied from a substation. The feeder is loaded with time-varying loads connected with it through its length at each node.

Suppose there are K sections in the physical feeder shown in Fig. 1. Choose \( r_j \), the resistance in ohms per unit length of the \( j \)th section, as the resistance in ohms per unit length of the equivalent uniform feeder. Modify the physical length \( L_i \) of the \( i \)th as follows [6, 7].

\[
L_{ui} = \frac{L_i r_i}{r_j}, \quad i = 1, 2, 3, \ldots, k
\]

Where \( L_{ui} \) is the length of the \( i \)th section of the equivalent uniform feeder.

\( L_u \), the total length of the equivalent uniform feeder is defined by:

\[
L_u = \sum_{i=1}^{k} L_i r_i
\]

Divide each section length \( L_{ui} \) of the equivalent feeder by \( L_u \) to yield a normalized equivalent uniform feeder of unity length and uniform resistance

\[
r = \frac{1}{\sum_{i=1}^{k} L_i r_i}
\]

ohms per normalized unit length

We now define a normalized reactive current density function, \( f(x) \), and a normalized feeder reactive current function, \( F(x) \), as follows [6, 7]:

\[
f(x) = \frac{I(x)}{I_S}, \quad x \leq x \leq 1
\]

\[
F(x) = \sum f(x) \quad x \leq x \leq 1
\]

Where \( I_S \) is the reactive current injected into the feeder at the substation, \( x \) is the distance measured along the normalized equivalent uniform feeder from the same end and \( f(x) \) is the reactive current density at \( x \).

To provide the most general solution procedures so that distribution engineers can apply the solution techniques to design problems of different nature, the following notation is used throughout the study. As shown in Fig. 1, fixed and/or switched banks are consecutively numbered from the end of the feeder toward the substation.

The locations are measured from the substation and are represented by \( h_i \), \( i = 1, 2, \ldots, n \). The per unit bank sizes (at normal primary voltage) are denoted by \( I_{ci} \), \( i = 1, 2, \ldots, n \). Therefore, in the following analysis, \( I_{ci} \) will in general represent the per unit reactive current of the \( i \)th capacitor bank, or equivalently, its per unit kVAR rating on a base equal to the...
maximum value of the reactive load in the feeder. The type of each capacitor, which is not
specified in Fig.1, may be represented by using the following set notation.

Let M and N be the sets of indices of fixed and switched capacitor banks, respectively. For
example, if the ith bank is a switched one, it will be represented as \( i \in N \). Let LP denote the
peak power and energy loss reductions which result from the capacitor’s placement. Then LP is
given by [6,7]:

\[
LP = 3 \left( \int_0^{l_1} (I_s F(x))^2 \, dx - \left( \int_0^{l_1} (I_s F(x) - \sum_{i=1}^{N} l_{i,j})^2 \, dx \right) \right)
\]

(6)

\[
= \sum_{i=1}^{a=1} \sum_{j=1}^{n=1} \left( \int_0^{l_i} (I_s F(x) - \sum_{j=1}^{n} l_{i,j})^2 \, dx + \int_0^{l_i} (I_s F(x))^2 \, dx \right)
\]

The energy loss reduction can be written in the form of:

\[
LE = 3 \int_0^{T} (I_s(t) F(x))^2 \, dx - \left( \int_0^{T} (I_s(t) F(x) - \sum_{j=1}^{n} l_{i,j})^2 \, dx \right)
\]

(7)

\[
= \sum_{i=1}^{a=1} \sum_{j=1}^{n=1} \left( \int_0^{l_i} (I_s(t) F(x) - \sum_{j=1}^{n} l_{i,j})^2 \, dx + \int_0^{l_i} (I_s(t) F(x))^2 \, dx \right) dt
\]

Where \( I_s(t) \) is the time-varying reactive load current over a load cycle of duration \( T \) at
the substation end of the normalized equivalent uniform feeder of resistance \( r \) ohms per unit
length, and its variation shown in Table 1. The net savings function to be maximized is then
given by:

\[
S = K_p LP + K_e LE - K_{of} \sum_{i=1}^{n} l_{i} - K_{cs} \sum_{i=1}^{n} l_{i}
\]

(8)

OPTIMUM BANK SIZES

If the locations of the fixed and switched banks are known, and if the switching time of
the switched banks is predetermined, the bank sizes can be determined by solving the following
set of linear equations for \( l_i \):

\[
[H][l_c] = [D]
\]

Where \( [l_c] = [l_{c,1}, l_{c,2}, \ldots, l_{c,n}]^T \) is the n dimensional column vector to be determined.

and the n x n matrix \( H \) and the n dimensional column vector \( D \) are given as follows:

For \( i \geq 1 \),
\[ H_{ij} = \begin{cases} h_i (K_p + K_e T) & \text{if both } i, j \in M \\ h_i (K_p + K_e T_s) & \text{otherwise} \end{cases} \] (9)

and for \( i < j \)

\[ H_{ij} = \begin{cases} h_j (K_p + K_e T) & \text{if both } i, j \in M \\ h_j (K_p + K_e T_s) & \text{otherwise} \end{cases} \] (10)

\[ D_k = \left( K_p + K_e T_L f \right) \int_0^{h_k} P(x) dx - \frac{K_{cf}}{2f} \quad \text{if } k \in M \]

The constants \( K_p, K_e, K_{cf}, K_{cs} \) and \( T \) are chosen as follows:

\( K_p = 0.329 \) kW / day, \( K_e = 1.5 \) Pt / kWh, \( K_{cf} = 3.5 \) / three-phase KVAR

\( K_{cs} = 5.6 \) / three-phase KVAR, \( T = 24 \) hours

\( L_f, L_{3f} \) are the daily load factors

The feeder under study is represented in Fig.(1). It consists of nine sections with different areas and lengths. The data for each section is demonstrated in the same figure.

**GIVEN DATA**

The given data are as follows:

1) Daily load curves at each node of the feeder are illustrated in table(1).
2) Fixed capacitor cost per three-phase KVAR, \( K_{cf} \).
3) Switched capacitor cost per three-phase KVAR, \( K_{cs} \).
4) Cost of KW per day, \( K_p \).
5) Cost of energy / day, \( K_e \).
6) Locations of fixed and switched capacitor banks, \( h_i \).
7) Durations of switched capacitor banks, \( T_s \).
FLOW CHART

The hour by hour fixed and switched capacitor sizes are determined by using the following steps:

1. Read load data for different cases and hours through the day period and风机 data.
2. Select the new working time.
3. Calculate the peak load at the hour.
4. Calculate the aggregated load current at each hour.
5. Obtain the peak value of the reactive current load and the moment where it occurs.
6. Calculate the load factor and switched load factor.
7. Calculate the normalized reactive current density function for each case and each hour (eq. 2).
8. Calculate the optimum fixed and switched capacitor sizes at this hour.
9. Change the time and repeat the calculations.
10. Change the working time and repeat the calculations for each hour.

Computer program steps
RESULTS

The problem is programmed for different values of a switching time, $T_s$, and different locations of a fixed and switched capacitors on the feeder. Results of calculations are represented in the family of curves. These curves illustrate the optimum fixed and switched capacitor sizes.

Fig. 2 illustrates optimum size of fixed and switched capacitor against time. The fixed capacitor is located at section 2 where switched capacitor locates at section 5 on the feeder. The switching time for switched capacitor is being 4 hours. From the figure, the maximum size of fixed capacitor bank (operates all time) and switched capacitor (operates only switching time which is equal 4 hours in this case) are obtained and represent in table (3). Figures 3 to 9 give also the relationships between fixed capacitor size and time as well as switched capacitor size and switching time. The positions of capacitors (fixed and switched) on the feeder as well as switching time are changed. Figures 1 to 9 illustrate also the values of fixed and switched capacitors as well as the instants at which they happened. The figures represent the optimum operating strategy for fixed and switched capacitors located at the definite modes for each hours.

Fig. 10 represents the switched capacitor size, located at section 4, against switching time. The switching time has values 3, 6, 9, 12 and 15 hours. The instants at which switched capacitor has a maximum value is 23. At this instant the load takes approximately its maximum value.

Fig. 11 gives the relationships between switched capacitor size and the switching time. The relation is approximately linearly decreased from $T_s = 3$ to $T_s = 11$ hours from $T_s = 11$ to 12 hours it is linear and rapidly increased. Then, the switched capacitor size is slowly decreased when $T_s = 12$ to 14 hours. The behaviour of switching capacitor size against switching time at instants 23 and 24 are similar. The recommendation obtained from this figure is that the best selection of switching time is in the range from 3 to 11 hours. In this range, the switching capacitor size takes a small value and it has a lower value at $T_s = 11$ hour.

Table 3 represents that for all instants from 8 to 24 hr the minimum size of switching capacitor obtained with switching time 11 hours. The table gives also the positions of fixed and switched capacitors $N_s$ and $N_t$ on the feeder, switching time, maximum size of fixed and switched capacitors. The table illustrates also the summation of maximum values of fixed and switched capacitors. The selection of the best position of fixed and switched capacitors on the feeder is the one at which the previous summation has minimum value. The table shows that the location of fixed capacitor is at section 4 when the position of switched capacitor is at section 8. The operating time of switched capacitor positioned at section 8 on the feeder is 11 hours as advised from fig. 11.

Now the optimum operating strategy of fixed and switched capacitor banks is determined. Fig. 7 represents this strategy and gives the hour by hour fixed and switched capacitor banks size connected to the feeder under research. This figure gives the optimum operating strategy for fixed and switched capacitors located at sections 4 and 8 respectively. Sections 4 and 8 represent the optimum places at which fixed and switched capacitors are connected.

CONCLUSIONS

This paper gives the method for obtaining optimum locations, optimum capacitor sizes and the optimum operating strategy for fixed and switched capacitor banks connected with radial feeder. The method is based upon Grauer and Lee equations. In the first, a selection of random positions for fixed and switched capacitor is carried out. Then, a selection of the optimum places, optimum capacitor sizes ( fixed and switched ), optimum switching time and optimum operating strategy are obtained. The previous parameters are determined as follows:
1) Obtain the optimum operating strategy (hour by hour) for each section of fixed and switched capacitors.
2) Determine the optimum switching time at which optimum switched capacitor size is minimum.
3) Obtain the sum of optimum fixed and switched capacitor sizes at each section and select the minimum sum.
4) Represent section numbers at which minimum summation are obtained.

By using the above mentioned method on the radial feeder under investigation, the optimum optimum values of previous parameters which are optimum locations of fixed and switched capacitors are being at sections 4 and 8, optimum switching time is 11 hours and the optimum operating strategy for fixed and switched capacitors is obtained.

REFERENCES


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Fig. (1) Representation of feeder sections and its data

1- Section number
2- Cable materials
3- Cross sectional areas mm²
4- Section length in mile
5- Sections resistance ohm/mile
6- Section length of equivalent uniform feeder in mile
7- Normalized section length for equivalent uniform feeder.
### KVAR load at the feeder sections ×10⁻³

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*Table 1: Load-Time characteristics at different nodes*
Table (2) Switched capacitor size, located at node 4, in kVAR against different switching time.

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<tr>
<td>Cmax</td>
<td>3389</td>
<td>3444</td>
<td>1900</td>
<td>1514</td>
<td>3200</td>
<td>1582</td>
<td>3300</td>
</tr>
<tr>
<td>Cmin</td>
<td>444</td>
<td>417</td>
<td>1100</td>
<td>771</td>
<td>375</td>
<td>800</td>
<td>400</td>
</tr>
<tr>
<td>Cmax + Cmin</td>
<td>3833</td>
<td>3861</td>
<td>3000</td>
<td>2285</td>
<td>3575</td>
<td>2282</td>
<td>2700</td>
</tr>
</tbody>
</table>

Table 3: Maximum Capacitances of Fixed and Switched Capacitor Banks and Their Optimum Locations

Nr: Location of fixed capacitor.
Nt: Location of switched capacitor.
Tn: Switching time.
Cmax, Cmin: are the maximum capacitances of fixed and switched capacitor.
Fig. 2. Optimum size of fixed and switched capacitor banks located at sections A and B for switching times 1-3 hours.

Fig. 3. Optimum size of fixed and switched capacitor banks located at sections A and B for switching times 1-3 hours.
Fig. (4) Optimum size of fixed and switched capacitor banks located at sections No. 1 and 2 for switching time 1 hour.

Fig. (5) Optimum size of fixed and switched capacitor banks located at sections No. 4 and 9 for switching time 1 hour.
Fig. (6) Optimum size of fixed and switched capacitor banks located at sections No. 2 and 4 for switching time 11 hours.

Fig. (7) Optimum size of fixed and switched capacitor banks located at sections No. 4 and 6 for switching time 11 hours.
Fig. (9) Optimum size of fixed and switched capacitor banks located at sections No. 3 and 5 for switching time 7 seconds.

Fig. (10) Optimum size of fixed and switched capacitor banks located at sections No. 3 and 7 for switching time 7 hours.
Fig. 10 Switched capacitor size-time characteristic with switching times 3, 6, 9, 12, 15 hours. Fixed capacitor locates in section 3 and switched capacitor in section 4.
Fig. 11 switched capacitor size against switching time.
- fixed capacitor located at section 3 and
- switched capacitor at 4.