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

تحديد القيمة السعوية للمكثفات الثابتة والمتغيرة الموصلة على مغذى توزيع أولىمن النوع الأشعاعى

BY

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فى هذا البحث تم اختيار القيم المثلى لسعات المكثفات الثابتة والموصلة واستراتيجية التشغيل المثلى لهم والقيمة المثلى لزمن توصيل المكثفات وكذلك المكان الامثل لتوصيل المكثفات الثابتة والموصلة على مغذى توصيل اشعاعى. وقد تم عمل طريقة يمكن بواسطتها ايجاد هذة المعاملات وتتلخص فيما يلى:

١) نفرض اماكن عشوائية للمكثفات الثابتة والموصلة على المغذى.

٢) نوجد القيم المثلى لسعة المكثفات الثابتة كل ساعة تبعا لتغير الحمل.

٣) نوجد القيم المثلى لسعة المكثفات المتصلة مع تغير زمن التوصيل كل ساعة طبقا لقيمة زمن التوصيل.

٤) نوجد القيمة المثلى لزمن توصيل المكثفات الموصلة..

٥) نوجد مجموع القيم المثلى للمكثفات الثابتة والموصلة عند كل موضع ومنها نحصل على اقل مجموع.

وطبقا للخطوة الاخيرة يتم تحديد المكان الامثل للمكثفات على المغذى وكذلك زمن التوصيل الامثل للمكثفات الموصلة وايضا استراتيجية التشغيل المثلى للمكثفات الثابتة والموصلة على المغذى.

ABSTRACT

This paper gives 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 positions 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 - 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 in 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 reasons 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 unacceptably which 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, a[illegible]ing 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 imbalances at the static voltage capacitors 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, 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 (hour by hour) 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 places 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 it's length at each node.

Suppose there are K sections in the physical feeder shown in fig.(1). Chose r_j, the resistance in ohms per unit length of the ith section, as the resistance in ohms per unit length of the equivalent uniform feeder. Modify the physical length L_i of the ith as follows [6, 7].

$$L_{ui} = \frac{L_i r_i}{r_j} \qquad i = 1, 2, 3, \quad k \tag{1}$$

Where L_{ui} is the length of the ith section of the equivalent uniform feeder.
L_u, the total length of the equivalent uniform feeder is defined by:

$$L_u = \sum_{i=1}^{k} \frac{L_i \cdot r_i}{r_j} \tag{2}$$

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

$$r = \sum_{i=1}^{k} L_i r_i \tag{3}$$

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]:

$$f(x) = \frac{I(x)}{I_s} \tag{4}$$

$$F(x) = \sum f(\tau) \qquad x \le \tau \le 1 \tag{5}$$

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 I(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) a 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..........,n. The per unit bank sizes (at normal primary voltage) are denoted by I_{ci}, i = 1, 2,... .n. Therefore, in the following analysis, I_{ci}, will in general represent the per unit reactive current of the ith 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) be represented by using the following set notation.

Let M and N be the sets of idices 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]:

$$LP = 3\left[\int_0^1 (I_s F(x)^2 \, rdx - (\int_0^{h_n} (I_s F(x) - \sum_{i=1}^{N} I_{cj})^2 rdx + \sum_{i=1}^{n-1} \int_{h_{i-1}}^{h_i} (I_s F(x) - \sum_{j=1}^{i} I_{cj})^2 rdx + \int_{h_1}^{1} (I_s F(x))^2 rdx)\right] \quad (6)$$

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

$$LE = 3\int_0^{T_s} (I_s(t)F(x))^2 rdx - (\int_0^{h_n} (I_s(t)F(x) - \sum_{j=1}^{n} I_{cj})^2 rdx + \sum_{i=1}^{n-1} \int_{h_{i-1}}^{h_i} (I_s(t)F(x) - \sum_{j=1}^{i} I_{cj})^2 rdx + \int_{h_i}^{1} I_s(t)F(x))^2 rdx))dt \quad (7)$$

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 them given by:

$$S = K_p LP + K_e LE - K_{cf} \sum_{\substack{i=1 \\ i \in M}}^{n} I_{ci} - K_{cs} \sum_{\substack{i=1 \\ i \in N}}^{n} I_{ci} \quad (8)$$

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 I_c:

[H] [I_c] = [D]

Where $I_c = [I_{c1}, I_{c2}, \ldots I_{cn}]^t$ is the n dimensional column vector to be determined.

and the n * n matrix H and the n dimensional column vector D are given as follows:

For $i \geq j$,

$$H_{ij} = \begin{cases} h_i(K_p + K_e T) & \text{if both i, and } j \in M \\ h_i(K_p + K_e T_s) & \text{otherwise} \end{cases} \quad (9)$$

and for $i < j$

$$H_{ij} = \begin{cases} hj(K_p + K_e T) & \text{if both i, and } j \in M \\ hj(K_p + K_e T_s) & \text{otherwise} \end{cases} \quad (10)$$

$$D_k = \begin{cases} (K_p + K_e T . L_f) \int_0^{h_k} I_s F(x) dx - \frac{K_{cf}}{2r} \text{......if } . k \in M \\ \\ (K_p + K_e T_s L_{fs}) \int_0^{h_k} I_s F(x) dx - \frac{K_{cf}}{2r} \text{...if } . k \in M \end{cases} \quad (11)$$

The canstants K_p, K_e, K_{cf}, K_{cs} and t are chosen as follows:
K_p = o.329 / kw / day , K_e = 1.5 pt / kwh , K_{cf} = \$3.5 / three - phase KVAR
K_{cs} = \$6 / three - phase KVAR , T = 24 . hours

L_f: is the daily load factor
L_{fs}: is switched load factor

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.

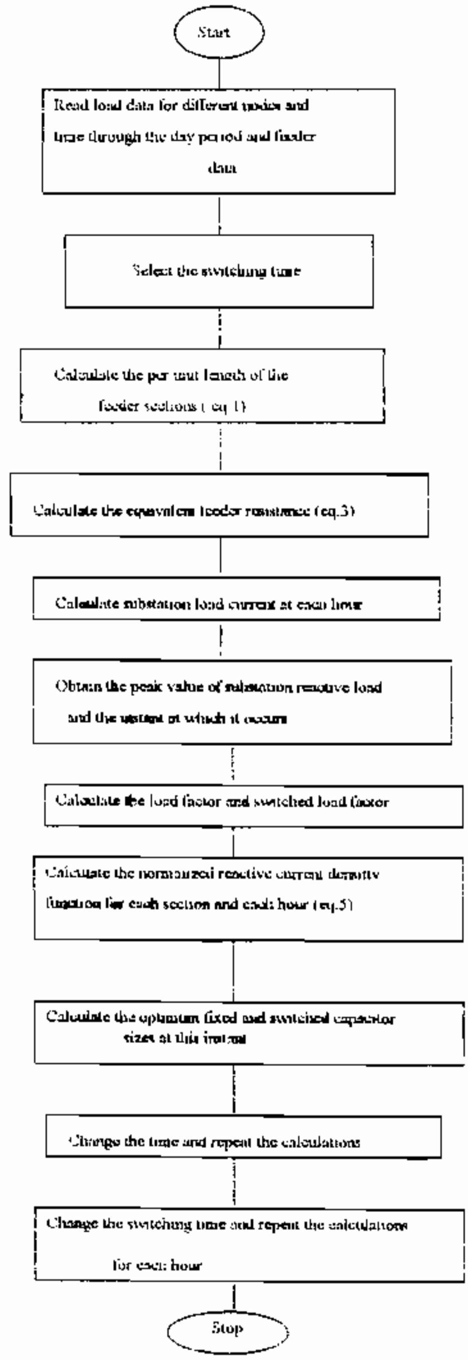
GIVEN DATA

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) Duration of switched capacitor banks, T_s.

FLOW CHART

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



Computer programe steps

RESULTS

The problem is programmed for different values of a switching tme, T_S, and differeut 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 ixed 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 houres in this case) are obtained and represent in table (3). Figures 3 to 9 give also the relationshipes 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 2 to 9 illusrate also the values of fixed and switched capacitors as well as the instants at which they happned. The figures represent the optimum operating strategy for fixed and switched capacitors located at the definite nodes for each houres.

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 houres. 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 relationshipe between switched capacitor size and the switched time. The relation is approximately linearely decreased from T_s = 3 to T_s = 11 houres from T_s = 11 to 12 houres it is linear and rapidaly increased. Then, the switched capacitor size is slowly decreased when T_s = 12 to 17 houres. The behaviours of switching capacitor size against switching tim at instants 23 and 24 are similiar. The recomindation obtained from this figure is that the best selection of switching time is in the range from 3 to 11 houres. In this range, the switching capacitor size takes a small values and it has a lower value at T_s = 11 houre.

Table 3 represents that for all instants from 8 to 24 hr the minimum size of switching capacitor obtained with switching time 11 houres. The table gives also the positions of fixed and switched capacitors N_F and N_s on the feeder, switching time, maximum size of fixed and switched capacitors. The table illustrates also the summation of maximum values of fixed aud 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 where the position of switched capacitor is at section 8. The operating time of switched capacitor posioned at section 8 on the feeder is 11 houres as noticed from fig.11.

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

CONCLUSIONS

This paper gives the method for obtaing 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 Graiuer aud Lee equations. In the first, a selection of random positions for fixed and swiched 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:

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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 places and select the minimum summation.
4) Represent section numbers at which minimum summation are obtained.

By using the above mentioned method on the radial feeder under invistigation, 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 houres and the optimum operating strategy for fixed and switched capacitors is obtained.

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1	1	2	3	4	5	6	7	8	9
2	Cu	Al	Cu	Cu	Cu	Cu	Cu	Cu	Cu
3	300	336	2/0	2	2	2	4	4	4
4	.63	.88	1.7	.81	2.3	1.05	1.5	3.5	3.9
5	.2	.28	.44	.86	.86	.86	1.37	1.37	1.37
6	.14	.29	.866	.81	2.3	1.05	2.38	5.56	6.15
7	.01	015	.044	.041	.117	.054	.122	.284	.316

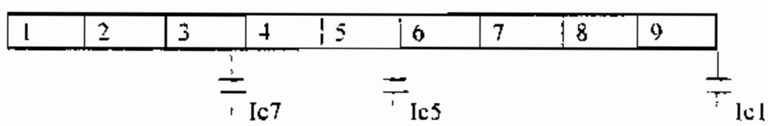

Fig.(1) Representation of feeder sections and its data

1- Section number 2- Cable materials
3- Cross Sectional areas mm ^{2} 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 $*10^{-3}$

	1	2	3	4	5	6	7	8	9
1	0.19	0.3	0.45	0.064	**0.112**	0.19	0.134	0.188	0.03
2	0.19	0.296	0.27	0.064	**0.112**	0.19	0.134	0.188	0.03
3	0.19	0.292	0.33	0.06	**0.112**	0.19	0.066	0.188	0.03
4	0.19	0.292	0.33	0.056	**0.112**	0.19	0.066	0.194	0.03
5	0.19	0.306	0.24	0.056	**0.112**	0.19	0.682	0.194	0.03
6	0.19	0.314	0.24	0.06	0.112	0.19	0.082	0.312	0.03
7	0.17	0.37	0.15	0.08	0.112	0.17	0.098	0.232	0.03
8	0.24	0.36	0.15	0.068	0.124	0.24	0.098	0.24	0.48
9	0.26	0.34	0.15	0.058	0.124	0.26	0.168	0.198	0.084
10	0.27	0.33	0.225	0.06	0.124	0.27	0.172	0.198	0.84
11	0.29	0.286	0.3	0.06	0.124	0.29	0.198	0.19	0.096
12	0.29	0.316	0.3	0.06	0.12	0.29	0.2	0.178	0.096
13	0.29	0.316	0.3	0.06	0.12	0.29	0.2	0.178	0.096
14	0.29	0.328	0.3	0.06	0.112	0.29	0.192	0.224	0.102
15	0.33	0.348	0.33	0.056	0.12	0.33	0.18	0.224	0.078
16	0.33	0.356	0.33	0.064	0.12	0.33	0.194	0.226	0.078
17	0.31	0.404	0.36	0.08	0.12	0.31	0.234	0.228	0.072
18	0.31	0.536	0.54	0.096	0.168	0.31	0.222	0.228	0.042
19	0.35	0.544	0.0585	0.12	0.168	0.35	0.212	0.36	0.036
20	0.35	0.544	0.6	0.128	0.168	0.35	0.212	0.36	0.036
21	0.35	0.484	0.585	0.12	0.168	0.35	0.192	036	0.042
22	0.3	0.442	0.6	0.108	0.152	0.3	0.182	0.324	0.042
23	0.3	0.398	0.585	0.92	0.152	0.3	0.136	0.252	0.036
24	0.19	0.3	0.45	0.064	0.112	0.19	0.134	0.188	0.03

Table(1) Load-Time characteristics at different nodes

8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	H/T
–	–	–	–	–	–	–	–	–	–	—	—	—	—	792	1700	618	3
–	–	–	–	–	–	–	–	–	–	—	—	—	716	749	1582	518	4
–	–	–	–	–	–	–	–	–	–	—	—	725	675	703	1473	544	5
–	–	–	–	–	–	–	–	–	–	—	657	683	637	663	1377	511	6
–	–	–	–	–	–	–	–	–	–	607	628	653	610	632	1300	486	7
–	–	–	–	–	–	–	–	–	324	590	613	636	595	613	1243	470	8
–	–	–	–	–	–	–	–	271	328	579	604	626	587	602	1198	[illegible]	9
–	–	–	–	–	–	–	276	277	331	570	597	618	580	592	1159	[illegible]	10
–	–	–	–	–	–	254	281	282	334	561	590	610	574	[illegible]	1124	440	11
–	–	–	–	–	713	748	790	801	867	1120	1234	1257	1210	[illegible]	1796	822	12
–	–	–	–	731	710	747	786	798	862	1105	1220	1242	1196	1145	1758	809	13
–	–	–	721	727	704	743	782	794	855	1090	1204	1225	1181	1129	1720	796	14
–	–	867	717	722	698	739	776	788	848	1073	1188	1208	1165	1112	1684	783	15
–	800	872	710	718	697	733	769	781	839	1057	1171	1190	1148	1095	1650	770	16
677	804	874	705	709	684	726	671	773	830	1041	1183	1173	1132	1070	1614	757	17

Table(2) Switched capacitor size, locates at node 4, in KVAR against time with different switching time.

Nf	2.	4	3	4	2	4	2	3
Ns	5	8	7	8	5	8	5	7
Ts	4	3	3	11	10	11	7	8
Cfmax.	3389	3444	1900	1514	3200	1582	3300	2143
Csmax	444	417	1100	771	375	800	400	893
Cfmax + Csmax	3833	3861	3000	2285	3575	2382	3700	3036

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

Nf: Location of fixed capacitor.
Ns: Location of switched capacitor.
Ts. Switching time.
Cfmax, Csmax : are the maximum capacitances of fixed and switched capacitor.

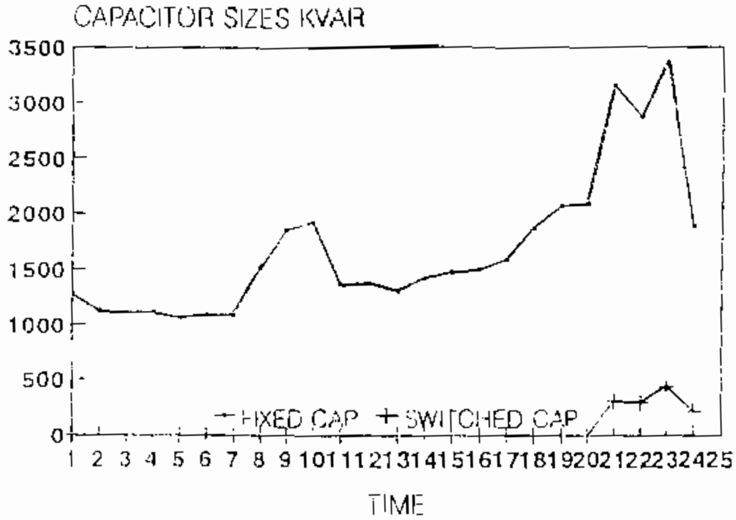

Fig.(2) Optimum size of fixed and switched capacitor banks located at sections No. 2 and 5 for switching time 3 hours.

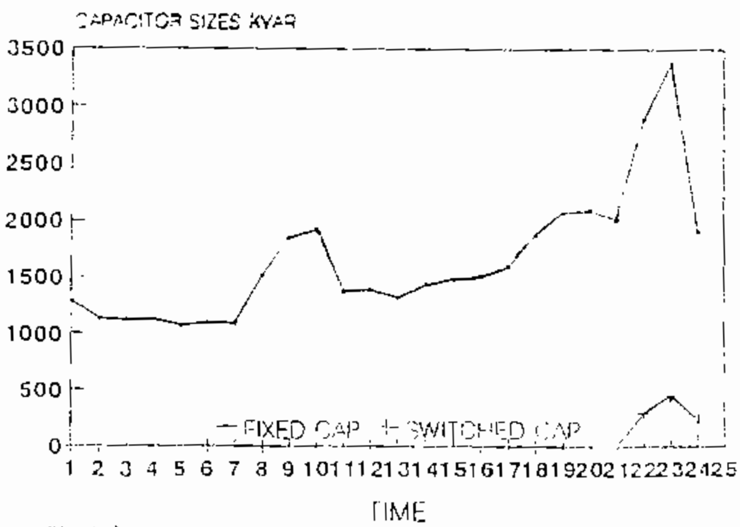

Fig.(3) Optimum size of fixed and switched capacitor banks located at sections No. 4 and 8 for switching time 3 hours.

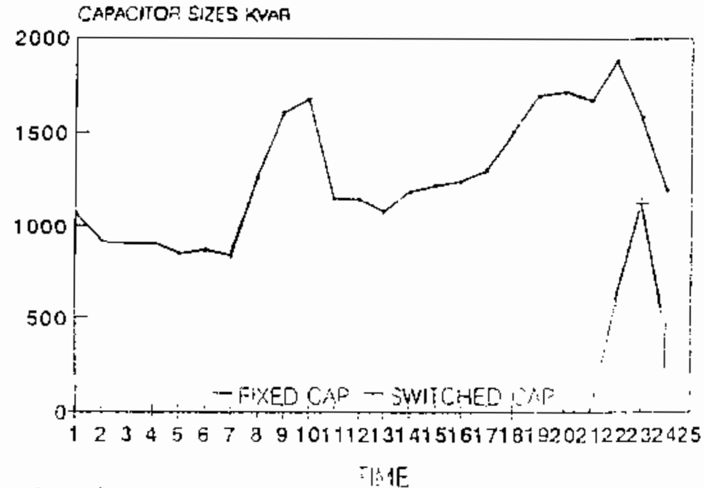

Fig.(4) Optimum size of fixed and switched capacitor banks located at sections No. 5 and 7 for switching time 3 hours.

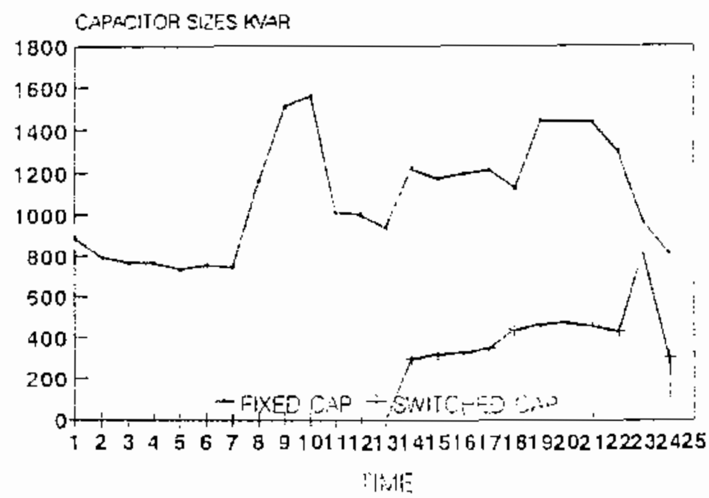

Fig.(5) Optimum size of fixed and switched capacitor banks located at sections No. 4 and 8 for switching time 11 hours.

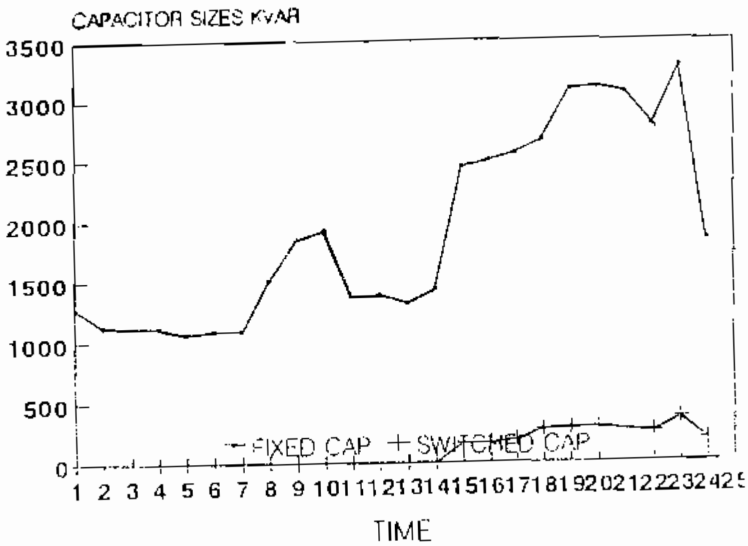

Fig.(6) Optimum size of fixed and switched capacitor banks located at sections No. 2 and 5 for switching time 11 hours.

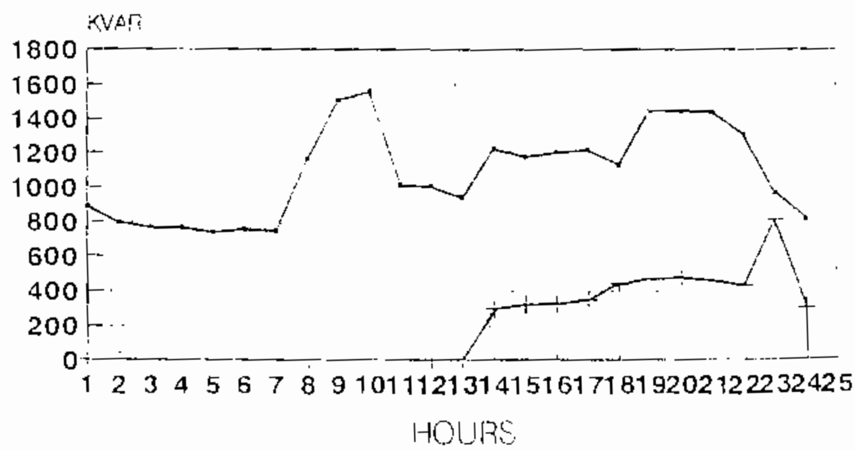

Fig.(7) Optimum size of fixed and switched capacitor banks located at sections No. 4 and 8 for switching time 11 hours.

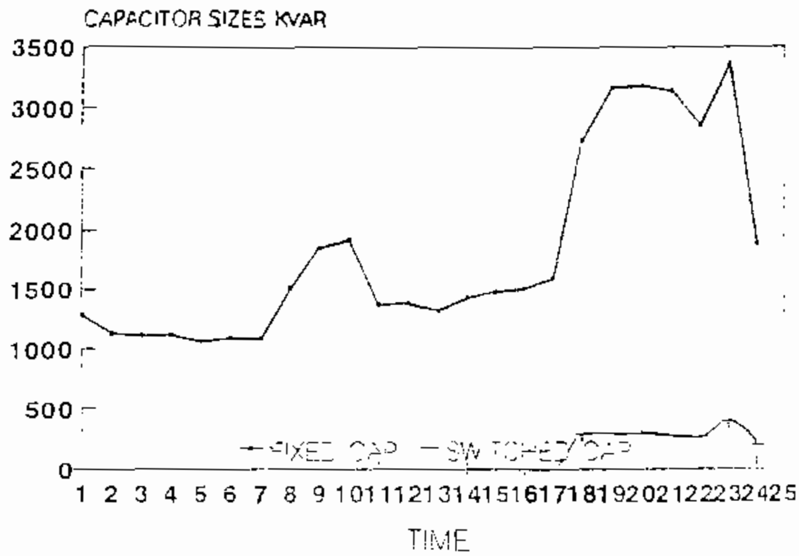

Fig.(8) Optimum size of fixed and switched capacitor banks located at sections No. 2 and 5 for switching time 7 hours.

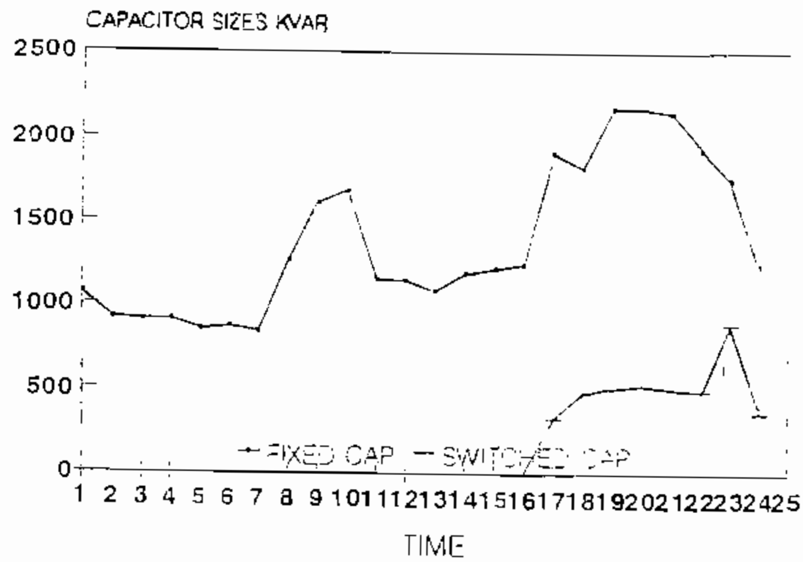

Fig.(9) Optimum size of fixed and switched capacitor banks located at sections No. 3 and 7 for switching time 8 hours.

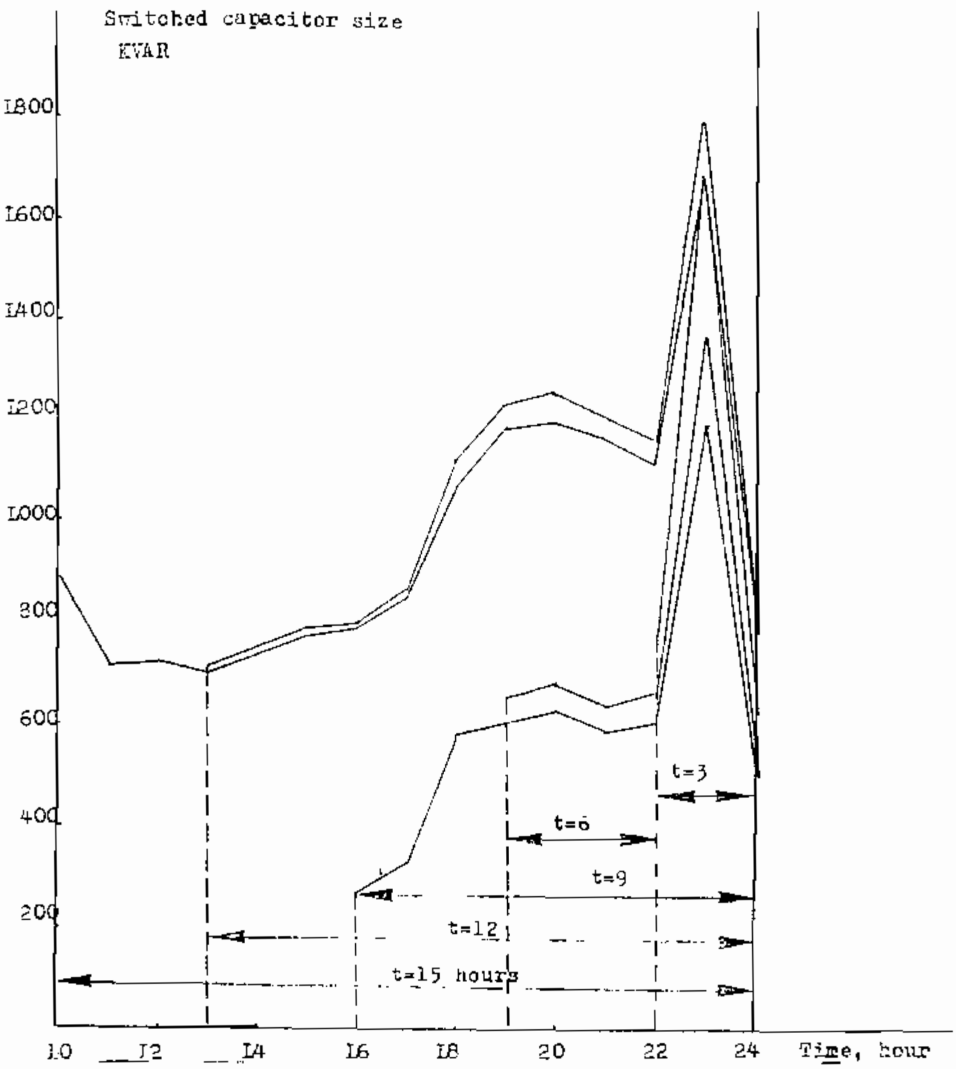

Fig.10 Switched capacitor size-time characteristic with switching time 3, 6, 9, 12, 15, hours, fixed capacitor locates at section 3 and switched capacitor at section 4.

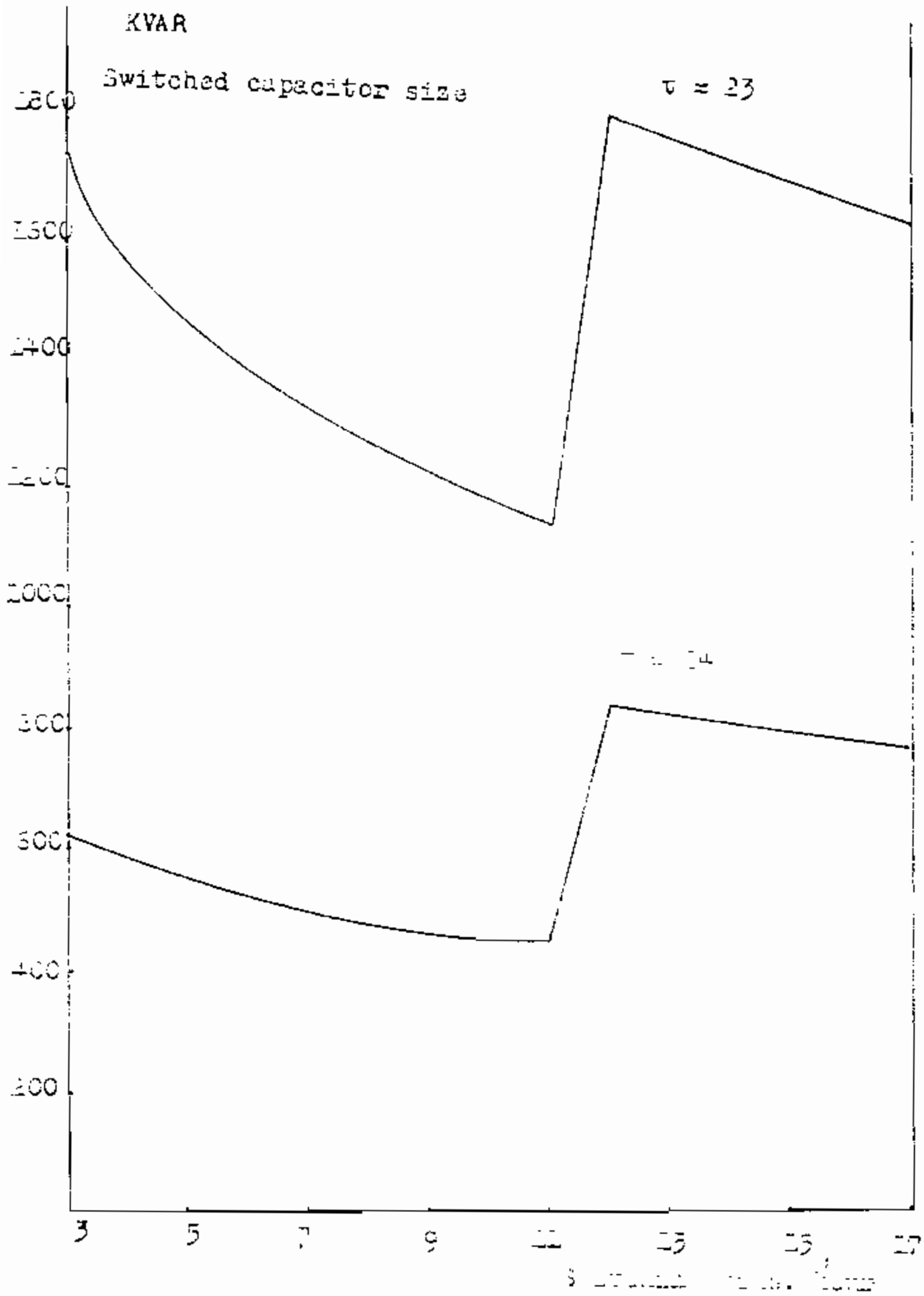

Fig.11 Switched capacitor size against switching time , fixed capacitor locates at section 3 and switched capacitor at 4.