PERFORMANCE OF STATIC COMPENSATORS EMPLOYING SATURATED REACTORS AND SHUNT CAPACITORS

PART I: Effect of Frequency, Transformer Tapping and Temperature Variations.

BY

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ABSTRACT:

The design and operation of static compensators comprising saturated reactors and shunt capaoitors, as affected by several factors among which are the variation in system frequency, transformer tapping and temperature, are investigated. The results show that under the condition of constant voltage level at the system busbar the adequate variation in transformer tapping may result in compensating the effects of both frequency and temperature variations. Transformer taps should therefore be designed in as fine steps as possible.

Theoretical bases as well as computer investigations are included.

I. Introduction

Synchronous condensers, series and shunt capacitors, as well as linear shunt reactors have long been used in power system networks to achieve, among other benifits, higher transmission stability limits and steady-state voltage control. Synchronous condensers, however, have relatively slow response

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which decreases their influence during disturbances. The use of serios capacitors cannot, when used alone, support stability much without giving an objectionable overvoltage at light loads[1]. Linear shunt reactors, on the other hand, have a reduction effect on switching overvoltages[2], but their effectiveness, regarding steady-state voltage control, falls off rapidly when a change in transmission system throws them off centre[1]. Because of these shortcomings, static compensators employing saturated reactors[3,4], have relatively recently been introduced and greatly improved power system performance.

A static compensator (also known as static voltage stabiliser or saturated reactor compensator) consists mainly of self-saturated reactor in series with a slope-compensating capacitor and a shunt capacitor. Fig.(1) shows a simplified circuit diagram of a static compensator of this type, connected to a transmission system via a regulating transformer (which may or may not be used, depending on the value of the system voltage). A Thevenin's equivalent circuit (a voltage source behined a linear reactance) is also shown. This circuit is used to determine the total power flow to be exchanged between the system and the stabiliser. Accordingly, the equivalent circuit components are

$$X_{eq} = X_t + \frac{X_c(X_s+X_{cs})}{X_c+X_s+X_{cs}}$$

and

$$V_{eq} = V_s \frac{X_c}{X_c+ X_s + X_{cs}}$$

where

X_t = transformer leakage reactance/ph (numerically positive)

X_s = saturated reactor slope reactance/ph (numerically positive)

X_{cs} = reactance of series capacitor/ph (numerically negative)

X_c = reactance of shunt capacitor/ph (numerically negative)

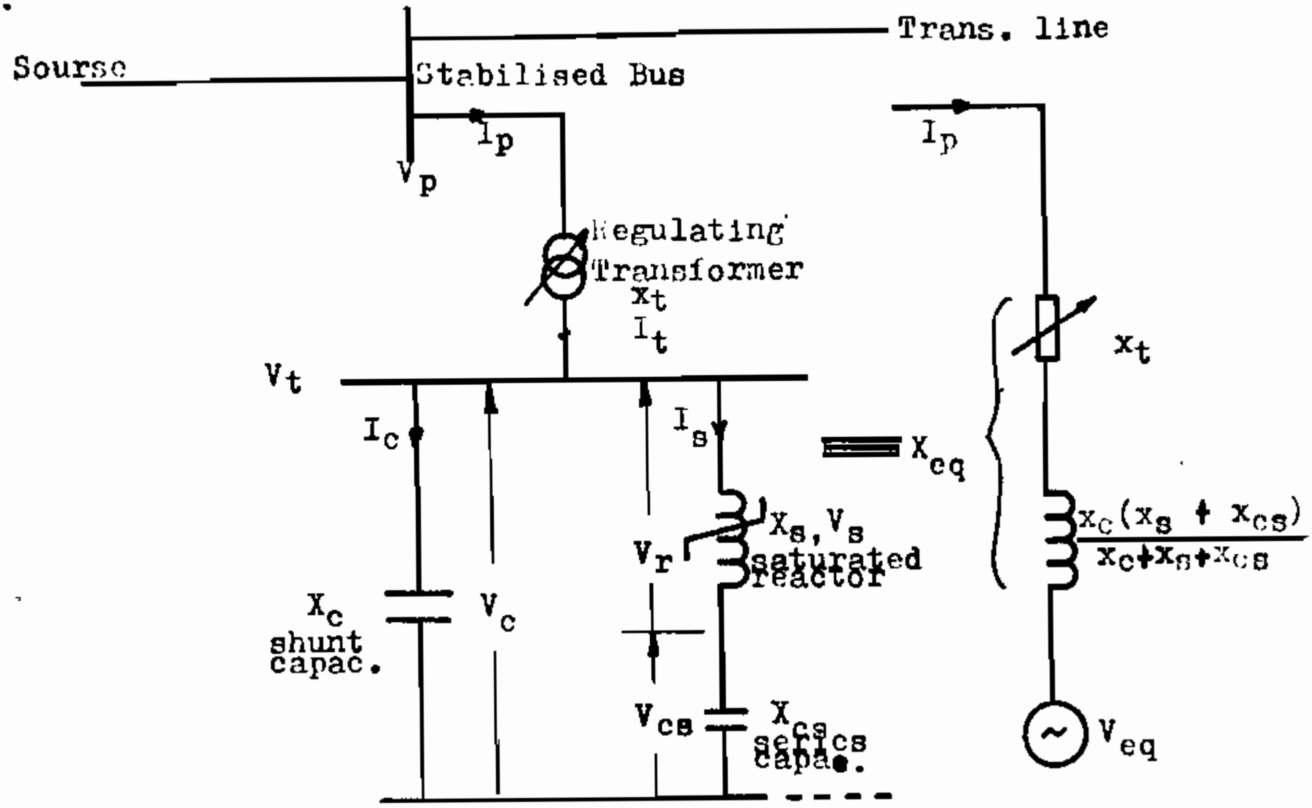

Fig.(1): Static compensator components and equivalent circuit

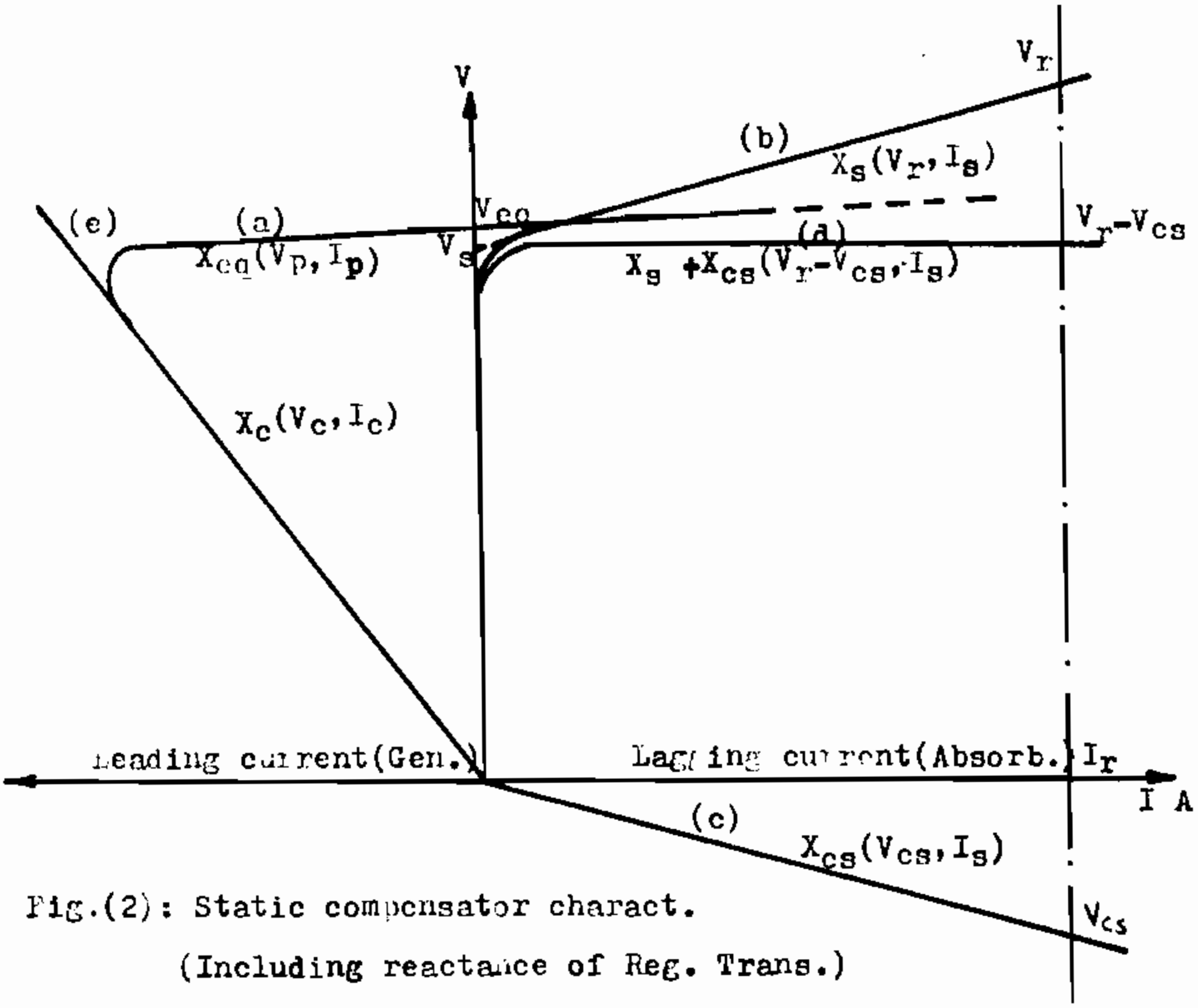

Fig.(2): Static compensator charact.

(Including reactance of Reg. Trans.)

V_s = saturation reference voltage

Fig.(2) shows how the voltage-current characteristics of the components of the stabiliser make up a composite characteristic, curve (a).

The voltage change across the saturated reactor, curve(b), from zero to the rated current is V_r-V_s, where V_r is the voltage across the reactor at current, I_r. So, if a tighter control of system voltage is required a slope compensating capacitor, curve (c), is added in series with the saturated reactor. This results in reducing the natural reactance of the saturated reactor from X_s to $X_s + X_{cs}$, giving curve (d). Such a combination can only absorb reactive power. Shunt capacitor, curve (e), enables the compensator to supply reactive power. If the system busbar voltage is less than the saturation reference voltage, V_s, of the saturated reactor, the reactor draws virtually no current and only the shunt capacitor is effective.

It is therefore obvious that, a static compensator of this type is capable of generating as well as absorbing reactive power. Thus voltage and reactive power control are achieved when such a compensator is applied to power system networks. In fact, it has been stated[3,5-9] that several static compensators incrporating saturated reactors, are now in service for different purposes[3-10] in various parts of the world. These purposes range from stabil/stabilisation of long-distance transmission lines[4,5,6,8,10], voltage control at load and generation points[3,7], reduction of voltage flicker[9], to increasing capabilities of long AC lines[8,11].

Because of their relatively new applications, however, these kinds of voltage stabilisers require more investigations in order to achieve better design data and more practical operation characteristice. The present investigation entails the use of a computer program, especially developed by the authers, to take care for the non-linear characteristics of the compensator under practical operating conditions.

2. Purpose of Study:

The purpose of this study is to investigate and evaluate the influence of some practical factors on the performance, under steady-state operation, of the static compensators employing saturated reactors and series and shunt capacitors. These factors are:

a) The change in system frequency, Δf

b) The change in tap-position of the regulating transformer, Δn

c) The change in the value of ambient temperature, ΔT

Both of the saturation reference voltage, V_s, and the slope reactance, X_s, will be affected by the change in system frequency. Affected also by the change in system frequency are the transformer reactance, X_t, the reactances of the series and the shunt capacitors, X_{cs} and X_c respectively. X_t as well as other system parameters (e.g. V_t) are also affected by the change in transformer tapping. Only capacitive reactance values are considered to be subjected to the change in ambient temperature, because of the nature of the dielectric.

The equations to determine the exact effects are given in the next section.

3. Program Description:

The program used for this investigation is written and developed in Fortran IV for the purpose of determining the performance of static compensators employing saturated reactors, under normal conditions and under the conditions of frequency, transformer tapping and temperature variations. The circuit diagram upon which this program is designed, is shown in Fig(3). It should be noticed that a resistive element has been added to each branch so that, the power (watt) loss, if any, can easily be represented for any branch. The magnetising impedance of the saturated reactor is also represented by a branch which is connected in parallel with the slope impedance and the saturation reference voltage of the reactor. Regulating transformer taps are considered to be on the system (primary) side.

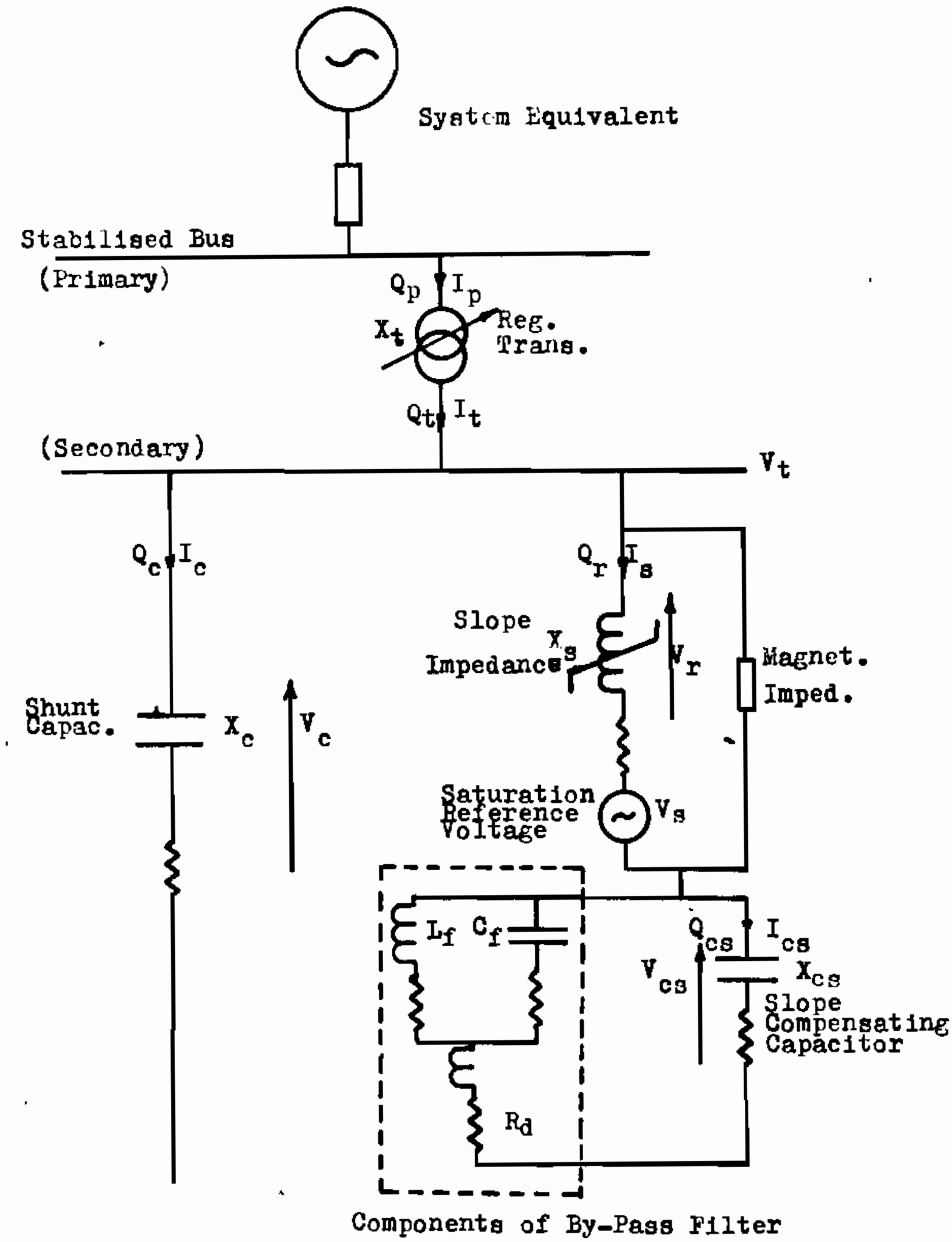

Fig.(3): A complete circuit diagram of a static compensator

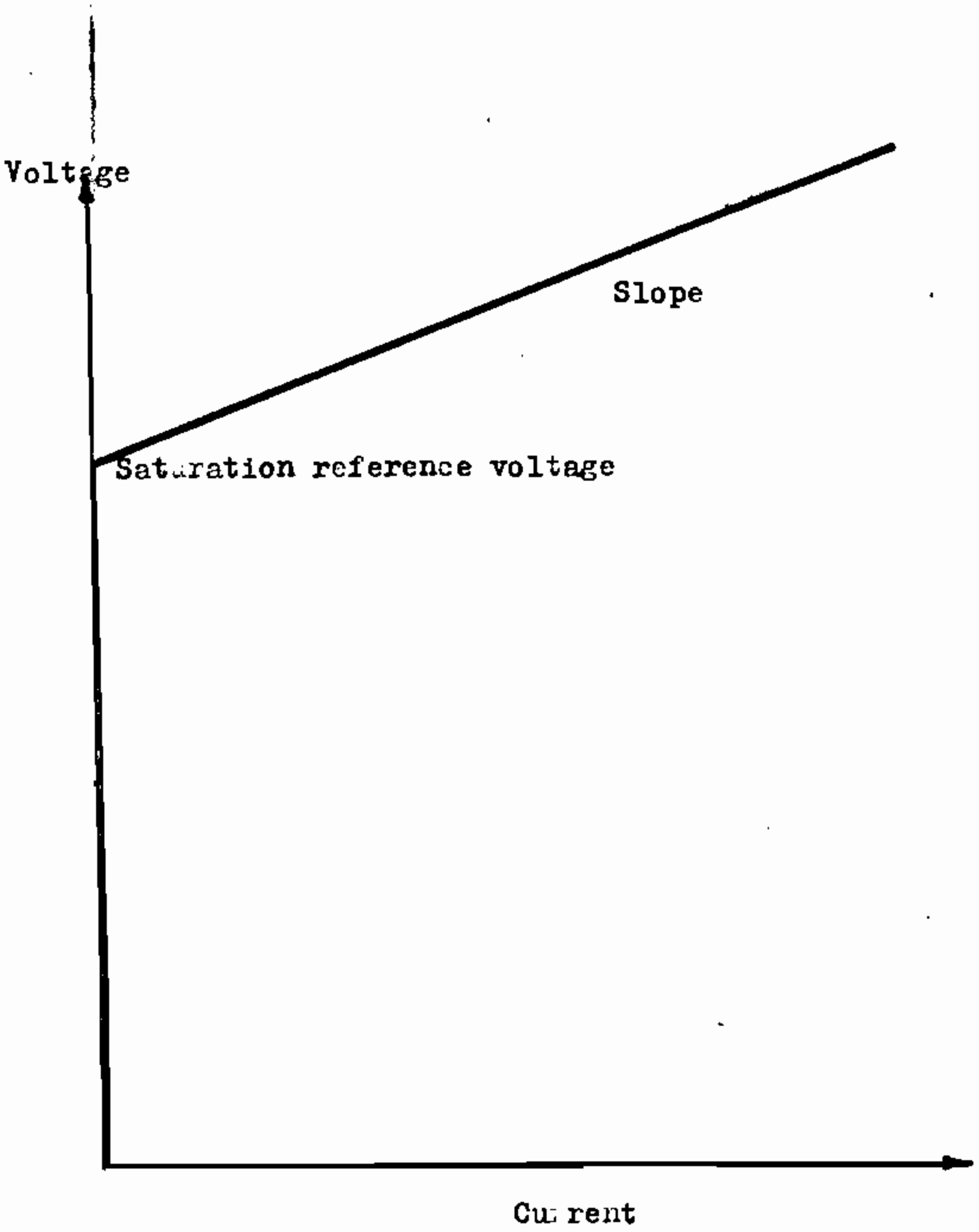

Fig.(4): Idealised saturated-reactor non-linear characteristics

Based on the previous remarks, the modified characteristics of Fig. 4 have been used in the program to represent the saturated reactor. In other words, no cosideration has been given to the curveture at the knee or to any other curvature which may exist along the actual saturation part of the characteristics. This assumption is valid from the practical point of view because the curveture is usually made as small as possible.

Fig.(5) shows a simplified flow-chart of the computer program. The variations in frequency, temperature and transformer tapping are imposed on system parameters as follows:

a) Frequency variation

For the saturation reference voltage

$$V_{s_{new}} = V_{s_{old}} \; (1 + \Delta f/f)$$

For inductive elements

$$X_{new} = X_{old} \; (1 + \Delta f/f)$$

For capacitive elements

$$X_{new} = X_{old} \,/(1 + \Delta f/f)$$

where

f is the system frequency in Hz,
$\Delta f/f$ is the p.u. change in system frequency, and
"new" and "old" subscripts denote after and before the change.

b) Temperature variation

Only capacitive elements are considered. Thus

$$X_{new} = X_{old}/(1 + \alpha \cdot \Delta T)$$

where

α is the capacitive temperature coefficient, per °C, and
ΔT is the change in temperature in °C.

c) Transformer-tapping variation

Assuming that the transformer p.u. turns-ratio is changed from n: 1 to $(n + \Delta n)$: 1. Then, with the voltage on the primary side held constant, the secondary voltage is given by

$$V_{new} = V_{old} \,/(n + \Delta n)$$

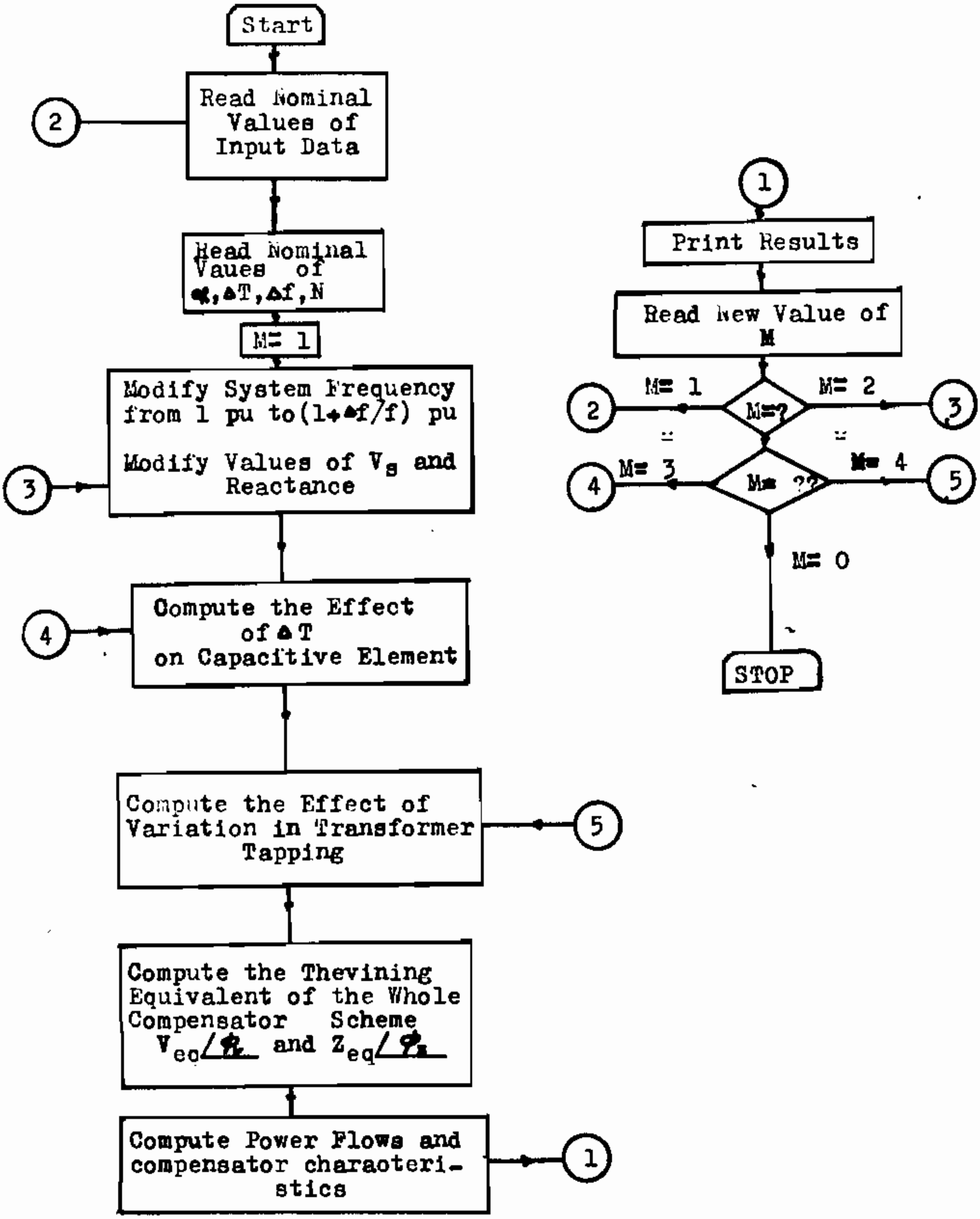

Fig.(5): A simplified flow chart of the computer program

For resistive values

$$R_{new} = R_{old} /(n + \Delta n)^2$$

For reactive values

$$X_{new} = X_{old} /(n + \Delta n)^2$$

For the combined effect cosider, as an example, the voltage V_t, at the secondary busbar of the transformer, Fig. (3), and neglecting the resistance values, the voltage equation for a 40% filter (i.e. $L_F C_F = 0.4$) may be obtained as

$$V_t = V_s(1 + \Delta f/f) + I_s \left\{ X_s(1+\Delta f/f) + \frac{X_{cs}(1+\Delta f/f)}{1.4(1+\alpha\cdot\Delta T)(1+\Delta f/f)-0.4} \right\}$$

for nominal tapping and $V_t/(n + \Delta n)$ for off-nominal tapping, where I_e is the current through the saturated reactor and X_{cs} is numerically negative, as already pointed out.

Having included the various effects of variations, the program formulates a Thevenin's equivalent circuit for the secondaryside circuit and then computes the phase angle of V_s so that no active power is dissipated in the saturated reactor. The program then proceeds to calculate the voltage at the different busbars, the load flows in the various components, and prints them out.

The program is provided by an option card which provide the user with great flexibilty to investigate the effect of varying one or more variables, during the same run.

4. Results and Discussion:

Presented below are the nominal data values of the static compensator used in this investigation. These are actual values for a static compensator produced by the G.E.C. Power Group of England. (For the definition of symbols, refer to Fig. 3). The compensator is located where the system voltage is assumed to be 232 kV. For the compensator main equipment:

Saturation reference voltage V_s = 71.12 kV

X_s = 3.85 Ω/ph (0.0935 p.u.)
X_c =-36.65 Ω/ph (-0.8902 p.u.)
X_{cs} =- 7.47 Ω/ph (-0.1814 p.u.)
X_t = 58.19 Ω/ph on primary side (0.11 p.u.)
= 4.53 Ω/ph on secondary side (0.11 p.u.)

For the by-pass filter:

X_{C_F} =-18.67 Ω/ph (-0.454 p.u.)
X_{L_F} = 18.67 Ω/ph (0.454 p.u.)
R_d = 6.54 Ω/ph (0.1587 p.u.)

Total slope reactance at compensator busbar = -3.29 Ω/ph
= -0.08 p.u.
Total slope reactance at system busbar = 15.87 Ω/ph
= 0.03 p.u.

This means that voltage at system busbar changes between 1 p.u. and 1.03 p.u. as the saturated reactor current changes between 0 and full load (about 260 MVAr). The p.u. values are based on 100 MVA base, 230 kV base for system side and, 64.17 kV base for compensator side.

Table (1) gives the results obtained under normal operating conditions, for different volt levels at the system busbar.

When the above results are plotted on a V/I graph, Fig.(6) results and shows that, for a voltage at the system less than the nominal value (232 kV), reactive power is being transfered from the stabiliser to the system. The stabiliser acts as a booster in this case. When the system busbar voltage is at the nominal value, no reactive power is being exchanged between the system and the stabiliser. The results show also that, reactive power is being absorbed by the stabiliser when the system voltage is of value above the nominal. This reactive power increases as the system voltage increases due to the 3% slope at the system busbar.

Table (1)

Variable Quantities in kV, A &MVAr	Load No.					
	(1)	(2)	(3)	(4)	(5)	(6)
V_p	223.4	225.37	232	233.29	239.93	244.95
V_t	71.12	69.65	64.73	63.76	58.82	55.08
V_r	71.12	72.68	77.92	78.94	84.2	88.17
V_{cs}	0	-3.03	-13.19	-15.18	-25.38	-33.09
$V_c (=V_t)$	71.12	69.65	64.73	63.76	58.82	55.08
I_p	-312.53	-240.81	0	47.07	288.76	471.4
I_t	-1120.18	-863.10	0	168.7	1034.98	1689.61
I_s	0	234.0	1019.51	1173.04	1961.47	2557.27
$I_{cs} (=I_s)$	0	234.0	1019.51	1173.04	1961.47	2557.27
I_c	-1120.18	1097.07	-1019.51	-1004.34	-926.49	-867.66
Q_p	-121	-94	0	19	120	200
Q_t	-158	-104.12	0	18.63	105.44	161.21
Q_s	0	29.46	137.59	160.30	286.05	390.54
Q_{cs}	0	-1.23	-23.29	-30.84	-86.22	-146.55
Q_c	-158	-132.35	-114.30	-110.92	-94.39	-82.78

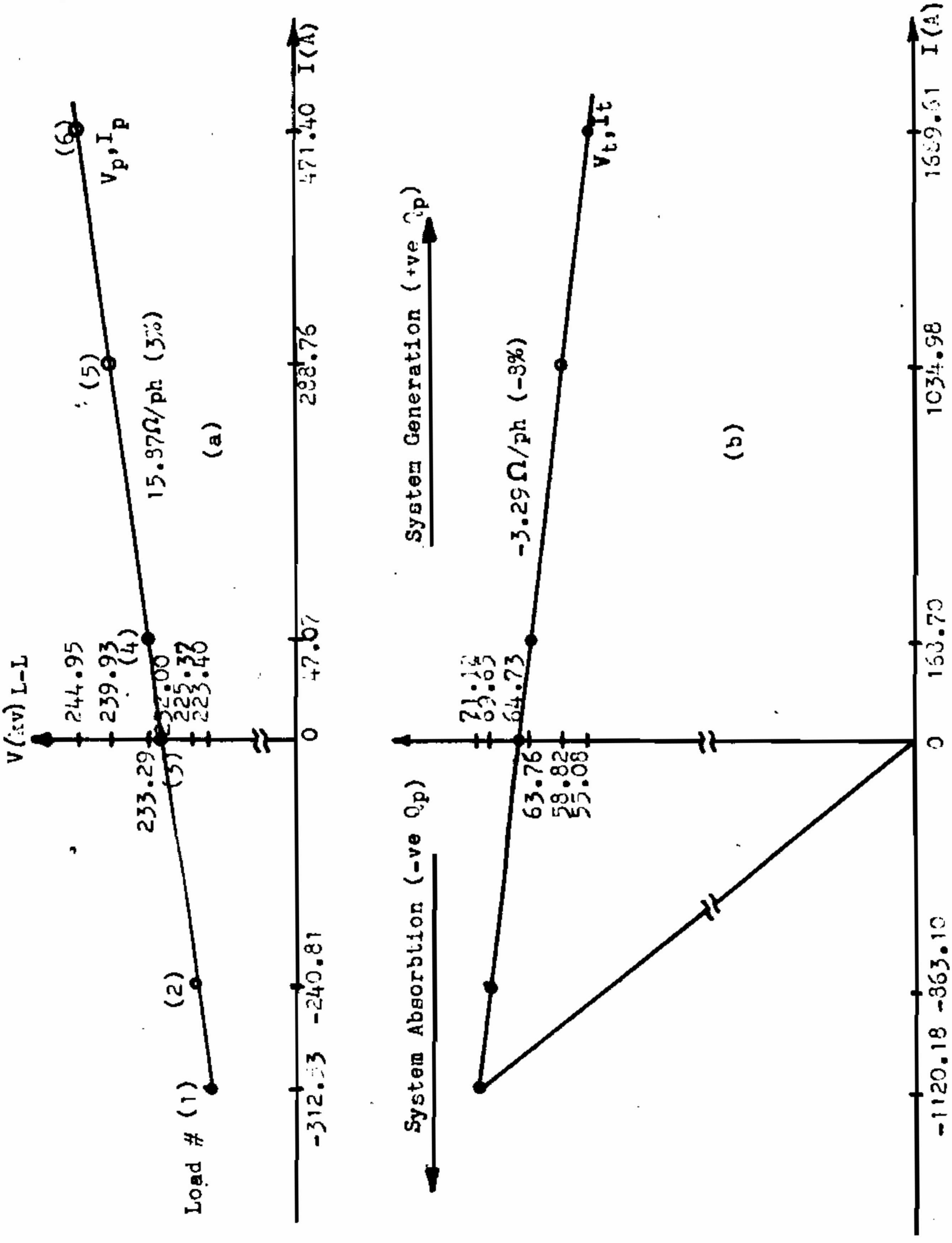

Fig.(6): Combined characteristics At (a) System Busbar
(b) Compensator Busbar

The effect of changes in system frequency, transformer tapping and temperature has been investigated for a variety of loading conditions. Results for load number (3), of Table (1), are presented here in detail. For this study, a practical value of $-6x10^{-4}$ per °C was assigned to the temperature coefficient, α. A frequency variation of ± 0.1 Hz (0.2% on 50 Hz bases), per centage tap variation of -2% and a temperature variation of ±45°C have been examined. Those results due to Δf = 0.1 Hz, Δn= -2% and ΔT = -45 °C, together with the results obtained under normal conditions, are listed in Table (2) and are represented on the V/I graphs of Fig. (7).

The results show that, for a constant voltage of 232 kV at the system busbar the decrease in temperature by 45 °C results in an increase in the voltage at compensator busbar from 64.73 kV to 65.63 kV (i.e. 1.4%). System absorbtion is increased from 0 to 12.92 MVAr. It was also found that a decrease of about 1.3% in compensator busbar voltage occurs when ΔT is an increase of 45 °C. In this case, the compensator equipment absorbed a reactive power of about 12 MVAr. The results show also that, an increase of 120.68 - 114.3 = 6.38 MVAr = 5.6% occurs in the shunt capacitor loading when ΔT = -45 °C. Shunt capacitor loading is decreased below that obtained under normal conditions when ΔT = 45 °C.

With the frequency increased by 0.1 Hz, a further increase in compensator busbar voltage, as well as in system absorbtion, occurs. In this case, it can be seen that the shunt capacitor loading has increased by a value of 122.44 - 114.30 = 8.12 MVAr = 7.1% of its loading at normal operating conditions.

However, with a change of -0.2% in transformer tapping (in addition to the changes of Δf = 0.1 Hz and ΔT =-45°C) condtions are reversed, where the voltage at the compensator busbar is decreased to 62 kV and, consequently, a reactive power of 38.85 MVAr is drawn from the system by the compensator components.

Table (2)

Variable Quantities in kV, A &MVAr	Operating Conditions			
	normal	$\Delta f=0$ $\Delta n=0$ $\Delta T=-45$ °C	$\Delta f=0.1$ Hz $\Delta n=0$ $\Delta T=-45$ °C	$\Delta f=0.1$ Hz $\Delta n=-0.2\%$ $\Delta T=-45$ °C
V_p	232	232	232	232
V_t	64.73	65.63	66.05	62
V_r	77.92	77.43	77.26	78.8
V_{cs}	-13.19	-11.80	-11.21	-16.8
$V_c\ (=V_t)$	64.73	65.63	66.05	62
I_p	0	-32.16	-47.08	96.68
I_t	0	-115.26	-168.74	346.51
I_s	1019.51	946.4	901.52	1351.16
$I_{cs}(=I_s)$	1019.51	946.4	901.52	1351.16
I_c	-1019.51	-1061.66	-1070.26	-1004.65
Q_p	0	-12.92	-18.92	38.85
Q_t	0	-13.10	-19.31	37.21
Q_r	137.54	126.92	120.64	187.41
Q_{cs}	-23.29	-19.34	-17.50	-39.31
Q_c	-114.30	-120.68	-122.44	-107.89

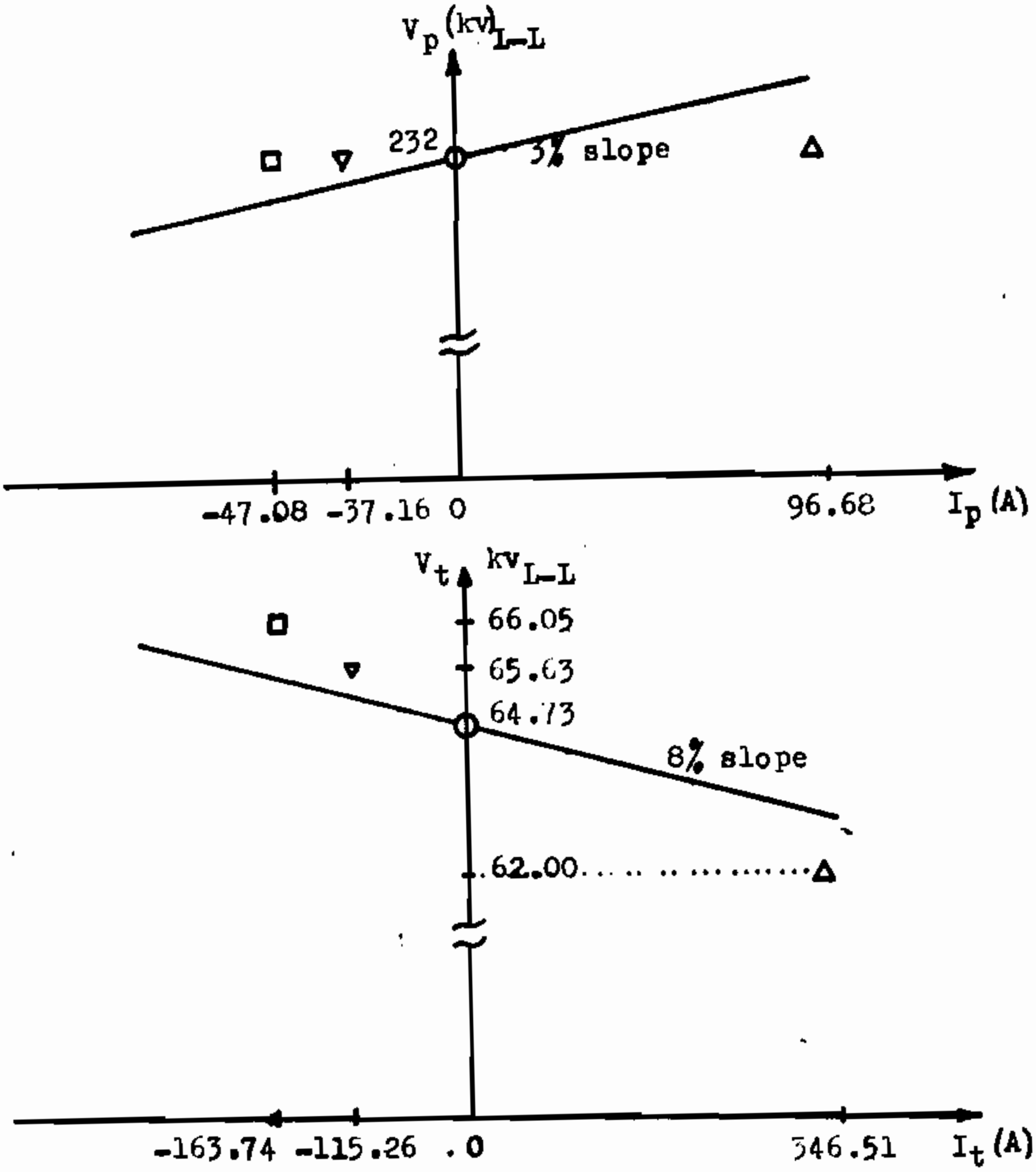

Fig.(7): Effect of frequency, transformer tapping and temperature variations on compensator operation.

○ normal condition, Δf=Δn=ΔT= 0.

▽ Δf=0., Δn=0., ΔT= -45°.

□ Δf=0.1 HZ, Δn=0., ΔT= -45°.

△ Δf=0.1 HZ, Δn= -.02 pu, ΔT= -45°

It should therefore be noted that the effect of tap change is more appreciable than those in frequency or in temperature. It can also be seen that a negative change in transformer tapping will have an opposite effect on compensator characteristics to those caused by a positive change in frequency or a negative change in temperature. A positive change in transformer tapping will, however, result in an increase in the loading of the shunt capacitor.

The investigation has also shown that, for a change in frequency between 0.1 Hz and -0.1 Hz the saturation reference voltage, V_s, is changed between 71.12 kV and 71 kV(about $\pm 0.17\%$ of its nominal value of 71.12 kV). Saturated reactor slope reactance, X_s, will vary between 3.86 Ω/ph and 3.84 Ω/ph($\pm 0.26\%$ of its nominal value). This will inversely affect the value of current drawn by the reactor and the series capacitor.

With respect to the current, and cosequently the reactive power, in the series capacitor it can be seen that these will decrease as temperature is decreased or as the frequency is increased. The effect of reducing transformer tapping will result in increasing both the current and the reactive power in the series capacitor. The investigation has also shown that series capacitor current (or loading) is decreased as f is increased or as T or n are decreased, and is increased as f is decreased or as T or n are increased. (T is the ambient temperature.)

Although only one operating condition has been presented in detail, similar effects have been observed under other operating conditions. This can be expected, for the voltage profiles at both system and compensator busbars are linear.

5. Conclusions:

A program for determining the behaviour of a static compensator employing saturated reactor and shunt capacitor, under normal conditions and under the conditions of frequency, transformer tapping and temperature variations, has been presented. The results obtained show that, increasing the frequency by a small margin or decreasing the temperature by a large amount will result in increasing the system reactive power absorbtion by an appreciable value, if the system voltage is to remain unaltered. Opposite effect on system absorbtion will result when the transformer tapping is reduced.

The effect on compensator characteristic due to the change in transformer tapping is more pronounced than those effects due to frequency or temperature variations. Moreover, appropriate change in transformer tapping may result in canceling out the effects of both frequency and temperature variations. Transformer tapping should, for this reason, be designed in as fine steps as possible.

If however no regulating transformer is present (in which case the compensator is directly connected to the system) the design rating of both shunt and series capacitors should be adequately increased. A value of about 10% in both rating would be reasonable. However, this warrant further investigations.

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