PERFORMANCE OF STATIC COMPENSATORS EMPLOYING SATURATED REACTORS AND SHUNT CAPACITORS

PART II: Harmonics produced by the compensator due to unbalances in system voltage and shunt capacitor impedance.

BY

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ABSTRACT:

The manufacturing of three-phase capacitor banks does not always result in the capacitive reactance to be exactly the same on all phases. Also, due to actual operating and loading conditions of power systems, it is liable that unbalance occurs in the voltage of the power system to which the compensator is connected.

Using experimental model, this paper investigates the values of harmonics produced in the system current due to unbalances in both system voltage and shunt capacitor impedance. The results show that third harmonic currents are most pronounced in both cases of unbalance. Harmonic filters are therefore necessary to eliminate these harmonics.

1. INTRODUCTION:

In a previous paper[1], the effects on steady state peformance of the static compensator due to the variations in frequency, transformer tapping, and ambient teperature were investigated. The investigation was carried out using a computer program[1] developed for this purpose. The theory and operation of the network stabilizer were also included.

Earlier static compensators have employed saturated reactors of the single-phase type. The harmonic currents normally associated with this type of saturated reactor have led to the development of the Twin-Tripler type of polyphase saturated reactor[2]. This involves six equal cores wound so that there is flux displacement of 30° between the cores to eliminate all odd harmonics excluding eleventh and thirteen harmonics. This reactor arrangement is outlined in Fig. (1).

To completely eliminate all self-produced harmonics, the Treble-Tripler type of a.c. saturated reactors[3] was recently introduced. This polyphase, multi-core, multi-winding saturated

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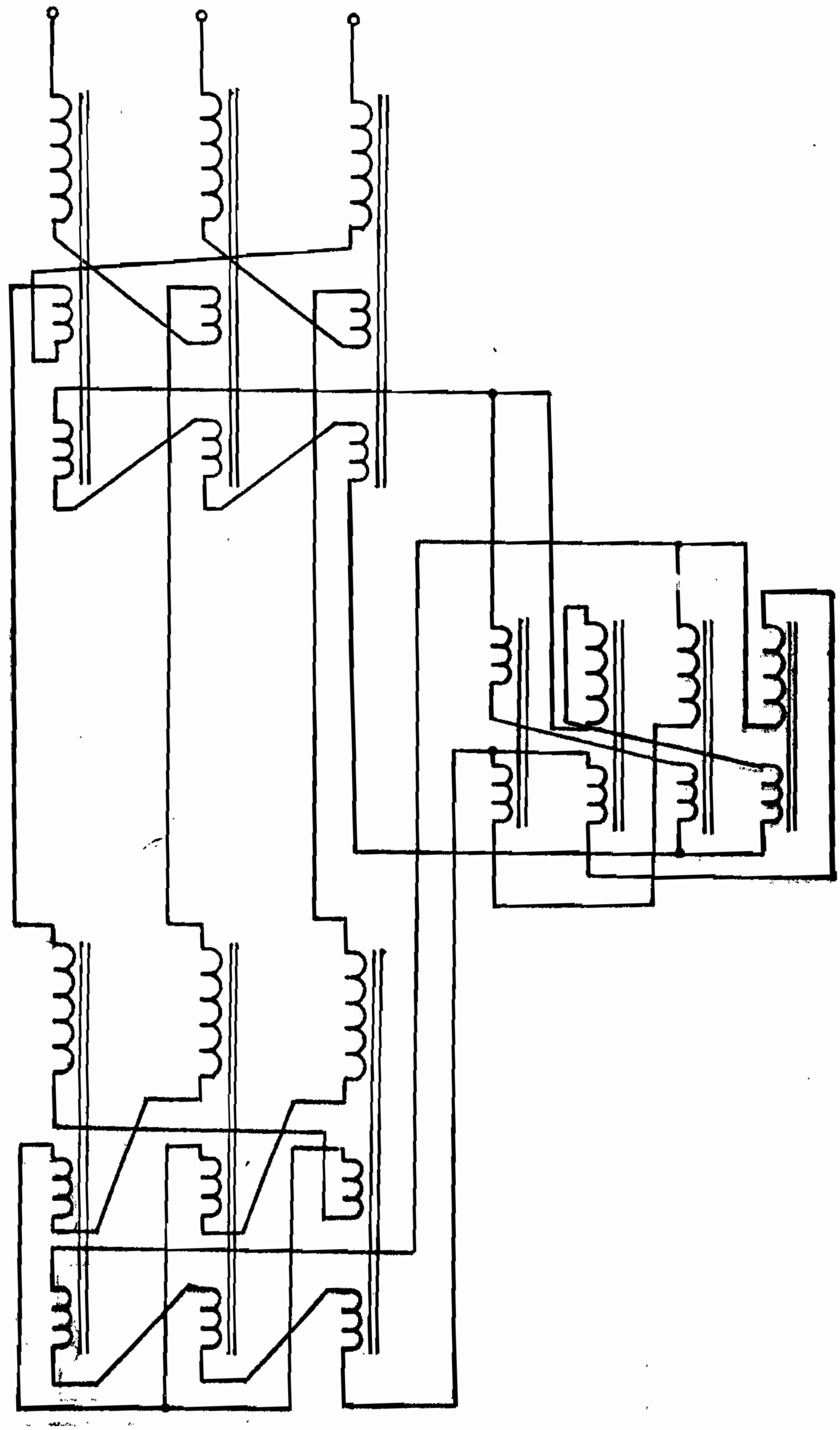


Fig. 1 : Twin Tripler design of polyphase series connected multicore saturated reactor, with auxiliary saturated reactor operating at treble frequency.

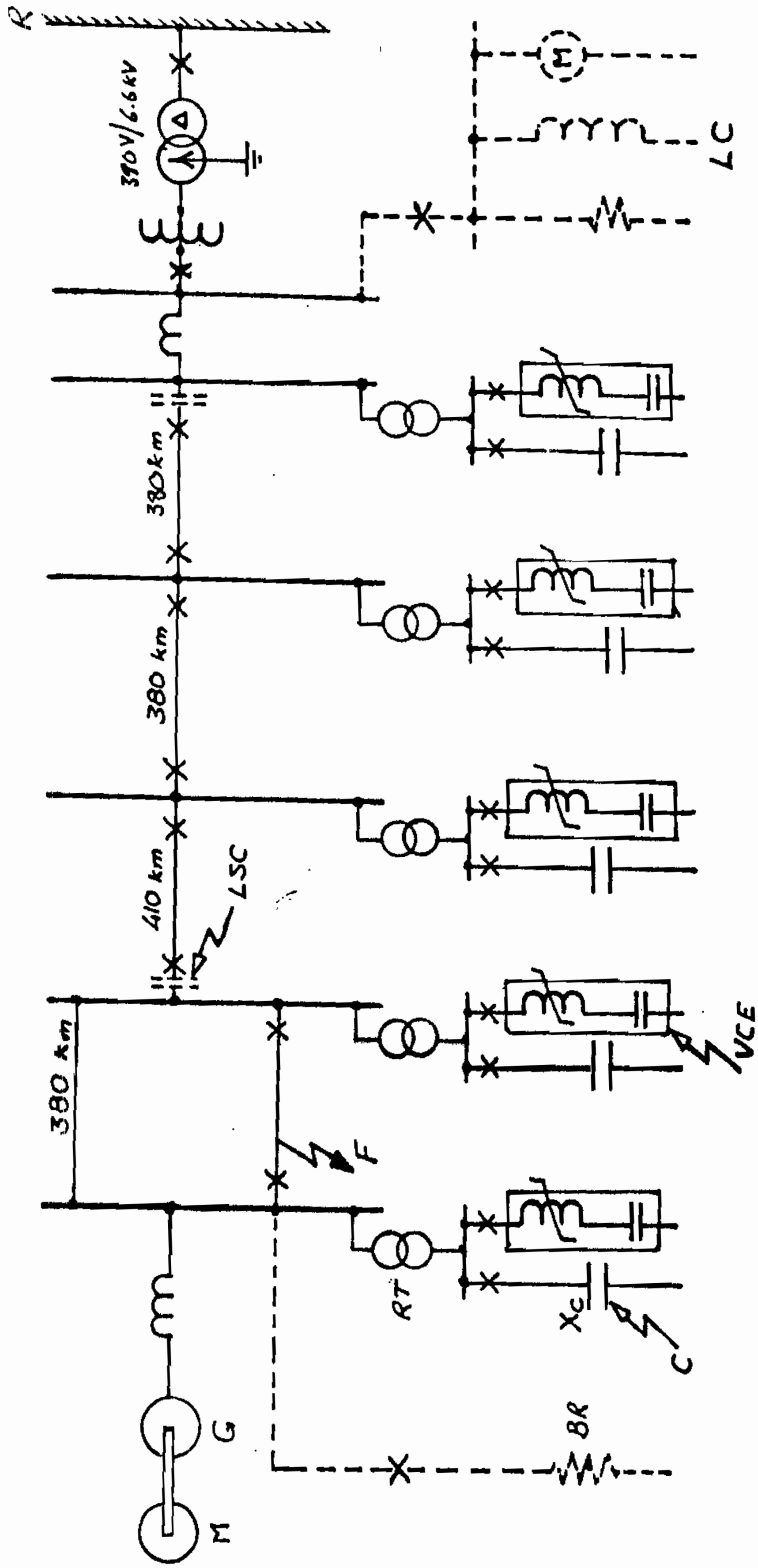
reactor has an extremely linear characteristic in the saturated region. The harmonic currents are cancelled out internally in this design by suitable choice of the flux phase-angle shifts between cores and by appropriate design of the magnitude of triple harmonic currents flowing in secondary mesh circuits. The reactor therefore virtually gives harmonic free operation under balanced conditions. (The basic principles of the Twin-Tripler and Treble-Tripler types of a.c. saturated reactor, are explained in Ref.(4)). This type of reactor is, for this reason, known as "harmonic-compensated saturated reactor".

However, due to manufacturing errors, etc., the impedance of each phase of the capacitor banks used with these network stabilizers, for the supply of reactive power[5], are not exactly the same and, therefore, unbalance occurs in the impedance of the shunt capacitor. Also, due to certain loading conditions, e.g. an industrial loading, unbalance in the system voltage occurs. Both of these unbalances result in harmonics to be generated in the current flowing through compensator elements and consequently, harmonic currents will be introduced in the system current through the regulating transformer[1].

The paper presents and discusses the results obtained by experimintal study aimed at evaluating the values of harmonic currents in both system and compensator currents, due to the unbalances mentioned above. The study is carried out using a model of an a.c. transmission system equipped by static compensators, with saturated reactors and switched shunt capacitors, distributed at approximately equal distances along the model line. As a result of this work it is concluded that, of all harmonics produced due to these unbalances, the third is the most observable in both compensator and system currents and therefore provision of harmonic filters is necessary for satisfactory operation of the system.

2. A.C. TRANSMISSION SYSTEM MODEL:

The a.c. transmission system model[6] used in this study is a three phase representation of a generating station, a transmission line, including its compensator devices, and an infinite busbar load, as illustrated by Fig. (2). The transmitted power is supplied by a suitably controlled alternator driven by a d.c. motor. The model rating of 250 kW is substantially higher than that of conventional transient network analysers or micro-machine systems. It has been chosen to permit good modelling of the relatively low resistances of real lines and their compensation devices, in order to permit an adequate assessment of the damping of the transient and sub-harmonic oscillations. The laboratory mains supply at 50 Hz acts as an infinite busbar, and instrumentation and point-on-wave control features are included



VCE = Voltage controlling element

LCS = Line series capacitors

LC = Load circuits

R = 6.6 kV, 3-phase, 50 Hz laboratory supply.

RT = Regulating or step-down transformer

M = Driving motor

G = 3-phase alternator

BR = Brake resistors

C = Switched capacitors (switched reactors also available for connection), reactance X_c

Fig. 2 : Transmission System Model

for fault application, switching and recording. The effective transient reactance of the generator plus the generator transformer is adjustable by means of external series inductances, and so also is the total terminal impedance at the receiving end of the line.

The complete line representation is by 16 three-phase, lumped line sections, together with earth return impedances, and it can be used to represent transmission lines of varying lengths up to 1550 km at 50 Hz (equivalent to 1290 km at 60 Hz). Typically it is split into four line sections of approximately equal lengths with three intermediate sub-stations as shown in Fig. 2. The lumped impedances in each π or T section can be adjusted, but typically the values are chosen to give a surge impedance impedance (Z_c) of 0.864 ohm and a surge impedance power level (P_s) of 176 kW at line voltage (V_L) of 390 V(where $P_s = V_L^2/Z_c$). One or two line sections can comprise two circuits in parallel; one circuit is proportioned to represent a single circuit and the other to represent one or more circuits in parallel on a real system. This arrangement can be used to represent the case of a fault on one line section (for example at F in Fig. 2), which is cleared by tripping out a single circuit which may be later reclosed if required.

Five harmonic-compensated model saturated reactors, of the Treple-Tripler type are available for use as static compensators in conjuction with slope-correction capacitors (which are connected in series with the saturated reactors, Fig. 2), and if required switched shunt capacitors. Each reactor has a nominal rating of 100 kVAr and a saturated reference voltage level[1] of about 390 V which determines the base voltage used for the line. The effective rating of each compensator can be adjusted in particular tests (e.g. down to 20 kVAr) by inclusion of an adjustable series linear reactor which increases the basic slope reactance including the step-up transformer reactance. The slope-correction capacitors are provided with adjustable bypass damping circuits, for which the frequency response is given in Fig. 3. Linear shunt reactors and series capacitor banks are available for line compensation, whilst resistor banks are available to simulate loads and brake resistors.

The flexible model, with its high power level, enables studies to be made of phenomena which are difficult or impractically expensive to investigate by digital computer analysis. The model is primarily intended to study line performance with different compensation methods, and for this purpose the generator model used is adequate.

For the present investigation, only one compensator is used, namely the second from the left (Fig. 2), with its rating adjusted to full nominal. The whole transmission line length, however, is operated throughout the investigation.

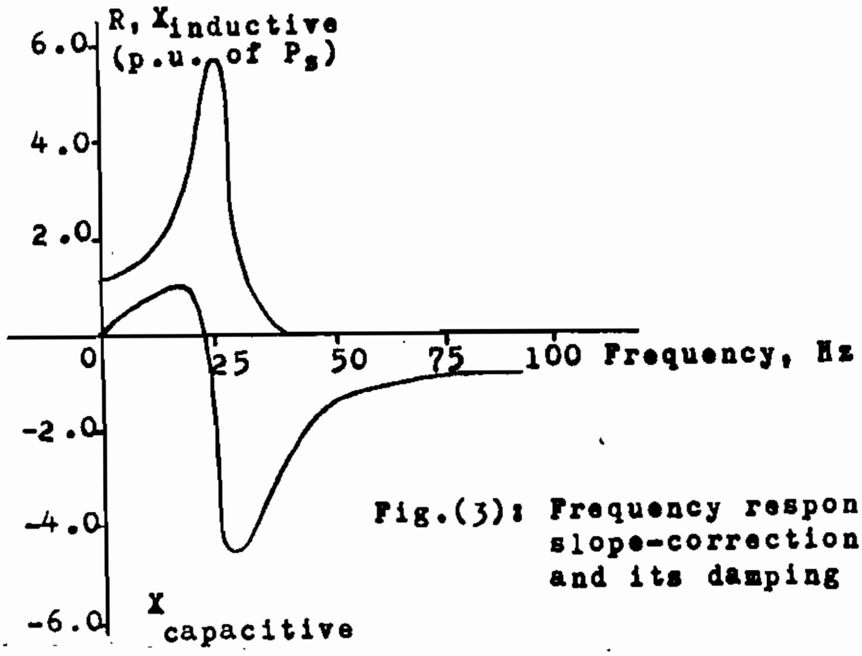


Fig.(3): Frequency response of the slope-correction capacitor and its damping circuit.

3. Results and Discussion:

Due to the unbalance in the shunt capacitor impedance, one should expect harmonics to be generated in both the secondary and the primary voltages and currents of the step-down transformer. It is found that, the most dominant harmonic generated in all is the third harmonic. Figures 4 and 5 show the maximum percentage values of harmonics generated in the primary and the secondary currents, respectively, when plotted against the percentage unbalance in the shunt capacitor reactance $(= 100\frac{\Delta X_c}{X_c})$. These percentage harmonic values are calculated with respect to the reactor current. It should also be noted that, these results were obtained under normal load conditions in the voltage controlling element(7), i.e. the current withdrawn from the supply is very small.

It can be seen from these figures that the percentage value of the 3rd harmonic increases almost linearily with the percentage unbalance in the shunt capacitor reactance. Whereas higher order harmonics values remain roughly constant throughout. It can also be seen that, due to the presence of a regulating transformer the values of harmonic currents are smaller on the primary (system) side than on the secondary (reactor) side of the transformer. For example, an unbalance in the shunt capacitor reactance of about 10% results in a maximum 3rd harmonic value of about 6% in the primary caurrent and of about 8% in the secondary current; both values are taken as percentage of the reactor current.

As far as the current of the saturated reactor is concerned, the laboratory investigations showed that for 16% and 9.7% unbalance in the shunt capacitor impedance the maximum unbalance in the reactor current (and consequently in the V.C.E. current) is found to be 10% and 4% respectively. The unbalance in the VCE current is reduced to a maximum of 2% when the unbalance in the shunt capacitor impedance is reduced to 6.26%. It can therefore be suggested that the unbalance in the rating of the components of the VCE, due to unbalance in the shunt capacitor impedance, may be in the range of 30% to 60% of the unbalance in the shunt capacitor impedance.

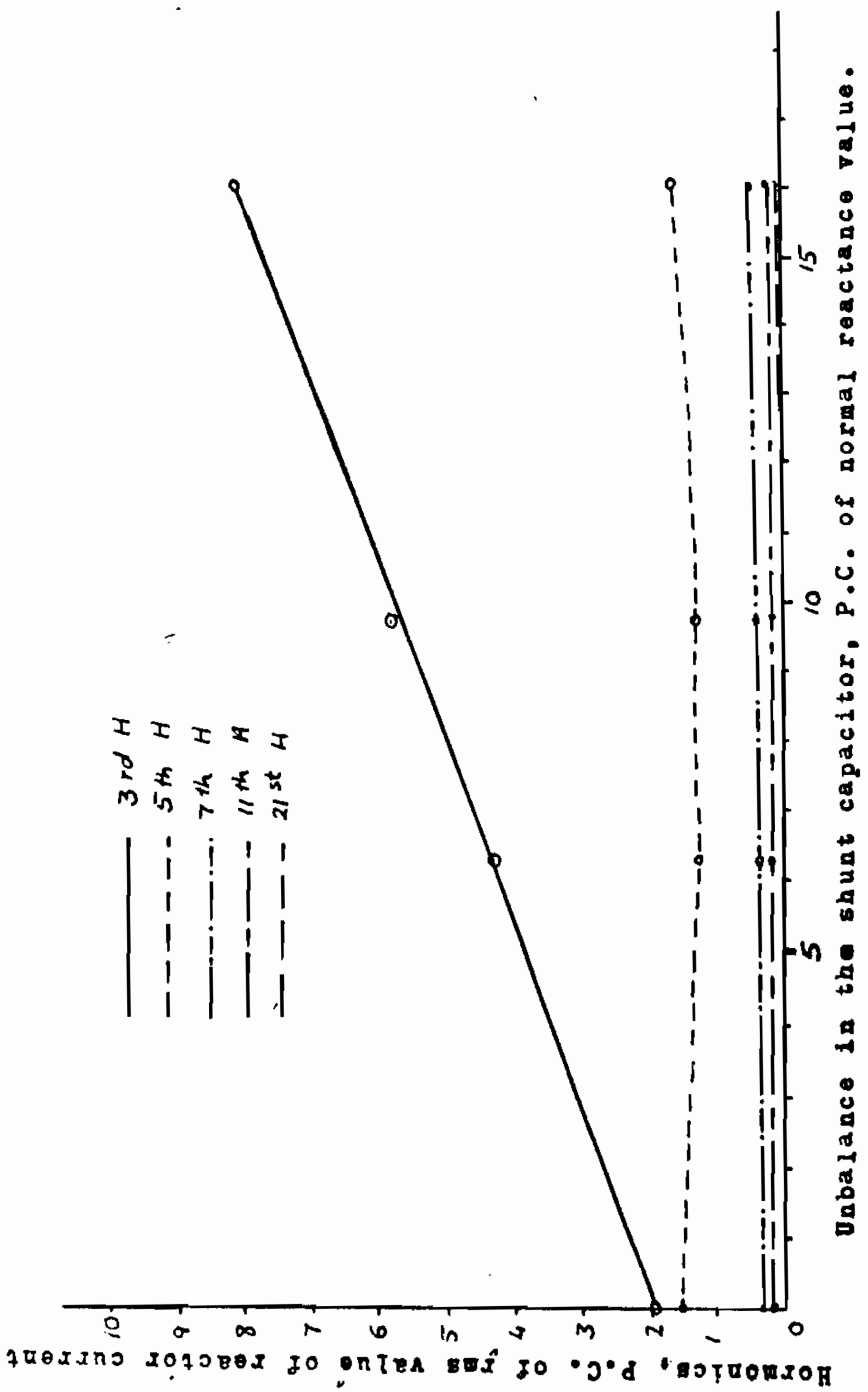


Fig. 4 : Maximum harmonic values in primary current due to unbalance in the shunt capacitor.

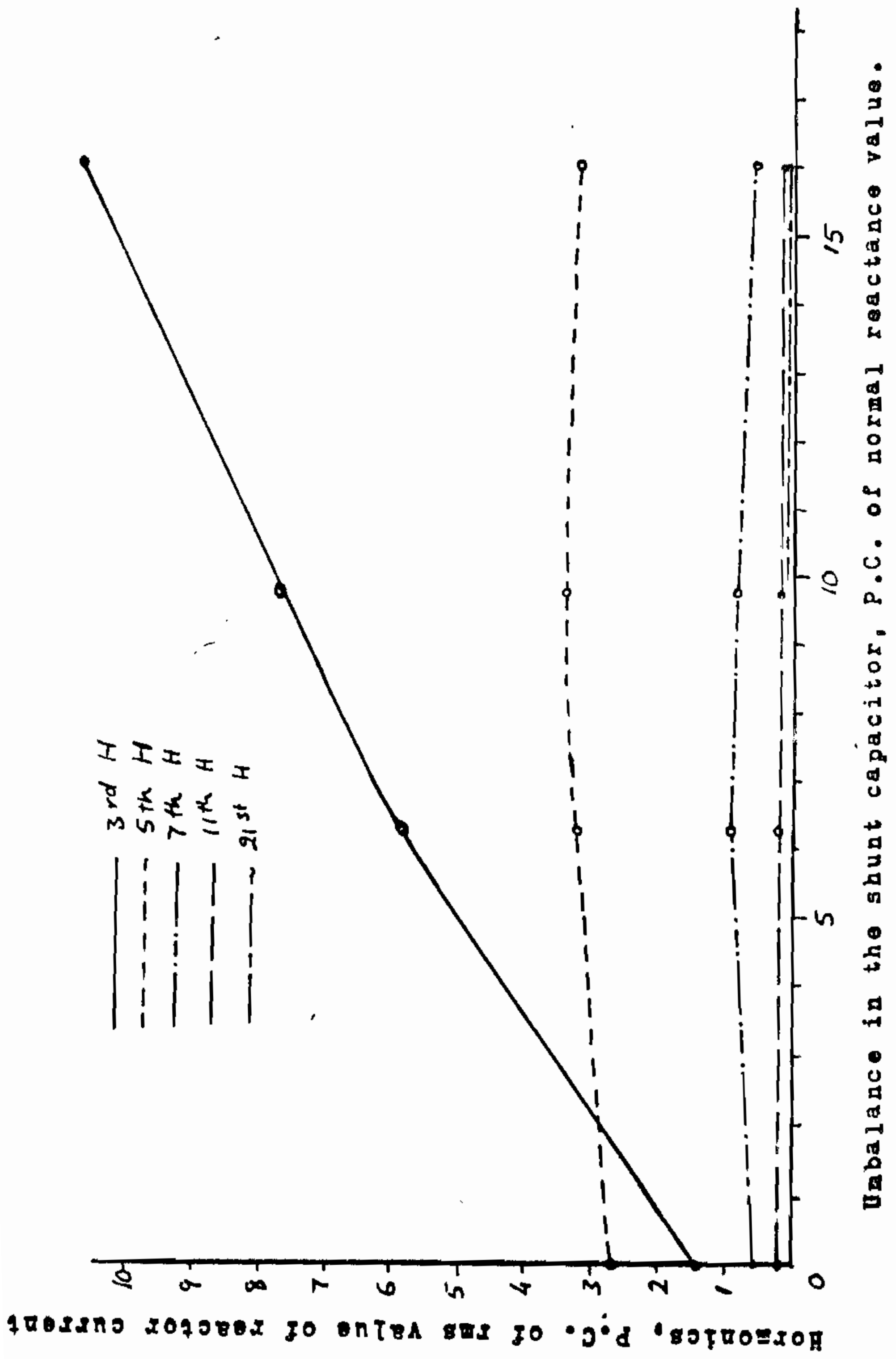


Fig. 5 : Maximum harmonic values in secondary current due to unbalance in the shunt capacitor.

Accordingly, a maximum unbalance of about 4.5% would occur in the rating of the VCE components if the unbalance in the shunt capacitor impedance reaches 10%.

Figures 6 to 9 show the variation of the maximum percentage values of harmonic currents with the percentage unbalance in the primary voltage. Figs. 6 and 8 are obtained with the shunt capacitor out of service while Figs. 7 and 9 are obtained with the shunt capacitor in service. All these curves are obtained when the current in the VCE is equal to its full-load value. Also, the percentage harmonic values are calculated with respect to the VCE (or reactor) current.

Again it can be seen that, while the values of higher order harmonics remain more or less constant over the whole range of voltage unbalance values, the value of the 3rd harmonio increases almost linearily as the voltage unbalance increases. The percentage harmonic values are generally higher when the shunt capacitor is in service. Under this condition, however, the current through the step-down transformer is almost negligible since the VCE current is supplied by the shunt capacitor.

The curves show that, for a voltage unbalance value of 0.05% the maximum third harmonic current value when the shunt capacitor is out of service is 3.5% for the primary current, and 2.5% for the secondary current. The 3rd harmonic values are seen to increase to 4.5% and 3.7%, respectively, when the shunt capacitor is in service. When the voltage unbalance increases to 2% the 3rd harmonic current values increase to 7% for the primary current, and to 5.3% for the secondary current when the shunt capacitor is out of service. These values become 13% and 11.6% respectively, when the capacitor is connected. Here, again, the regulating transformer causes a reduction in the harmonic values.

The conneotion of filter arms in parallel with the shunt capacitor, as seen in Fig. 10, nearly completely eliminated harmonic currents, due to either unbalances, for both primary and secondary currents of the regulating transformer. The oscillograms of Fig. 11 are given as an illustration of the harmonic currents flowing in both the 5th and the high-pass filters. These harmonic currents are present because the filters act as a sink for harmonics from the system.

4. Conclusions:

A laboratory a.c. transmission system is used to investigate the harmonic contents in compensator and system currents, due to unbalances in both system voltage and compensator shunt capacitor impedance. The investigation showed that, of all

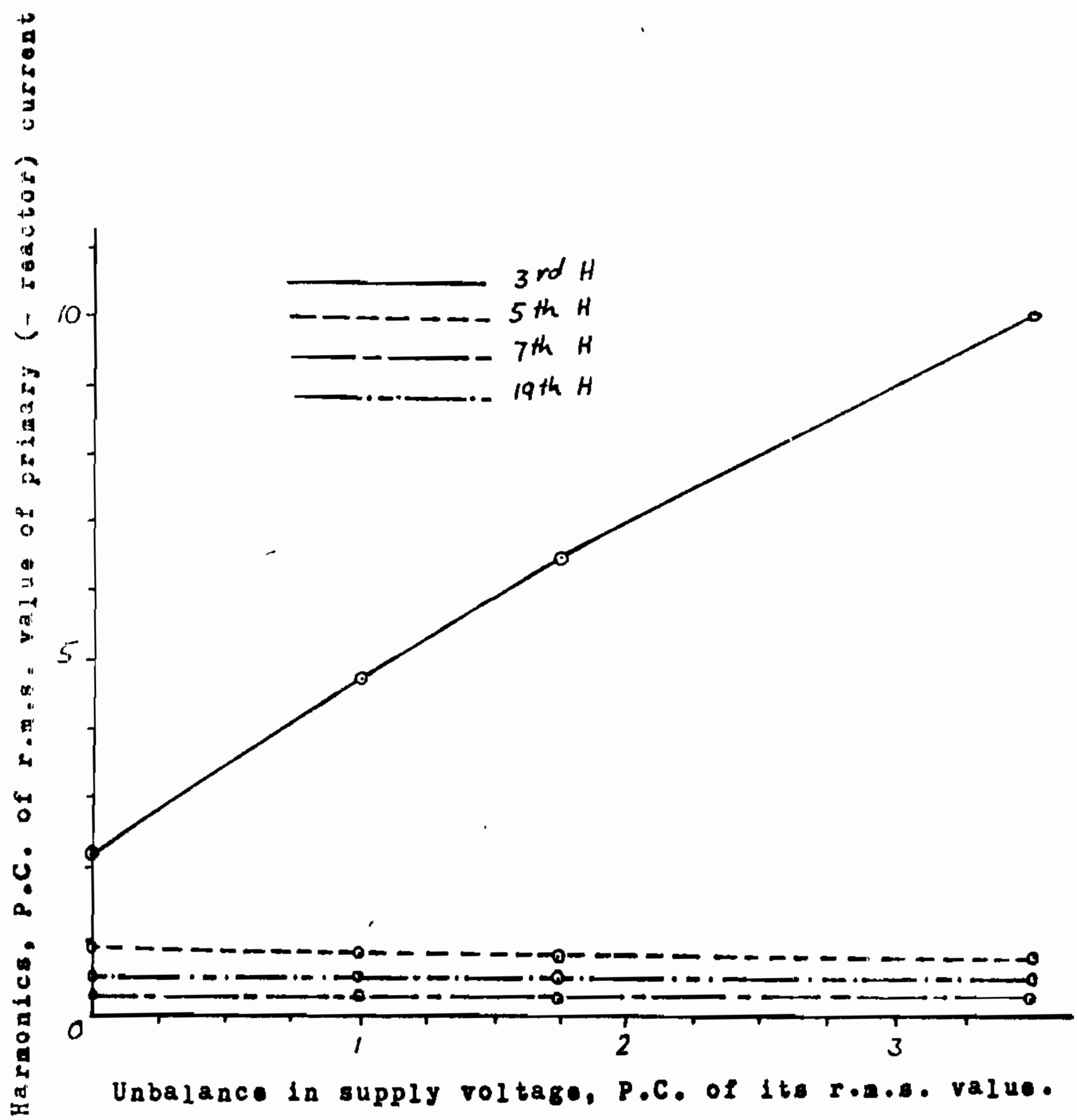


Fig. 6 : Maximum harmonic values in primary current due to unbalance in supply voltage . (i) Without shunt capacitor.

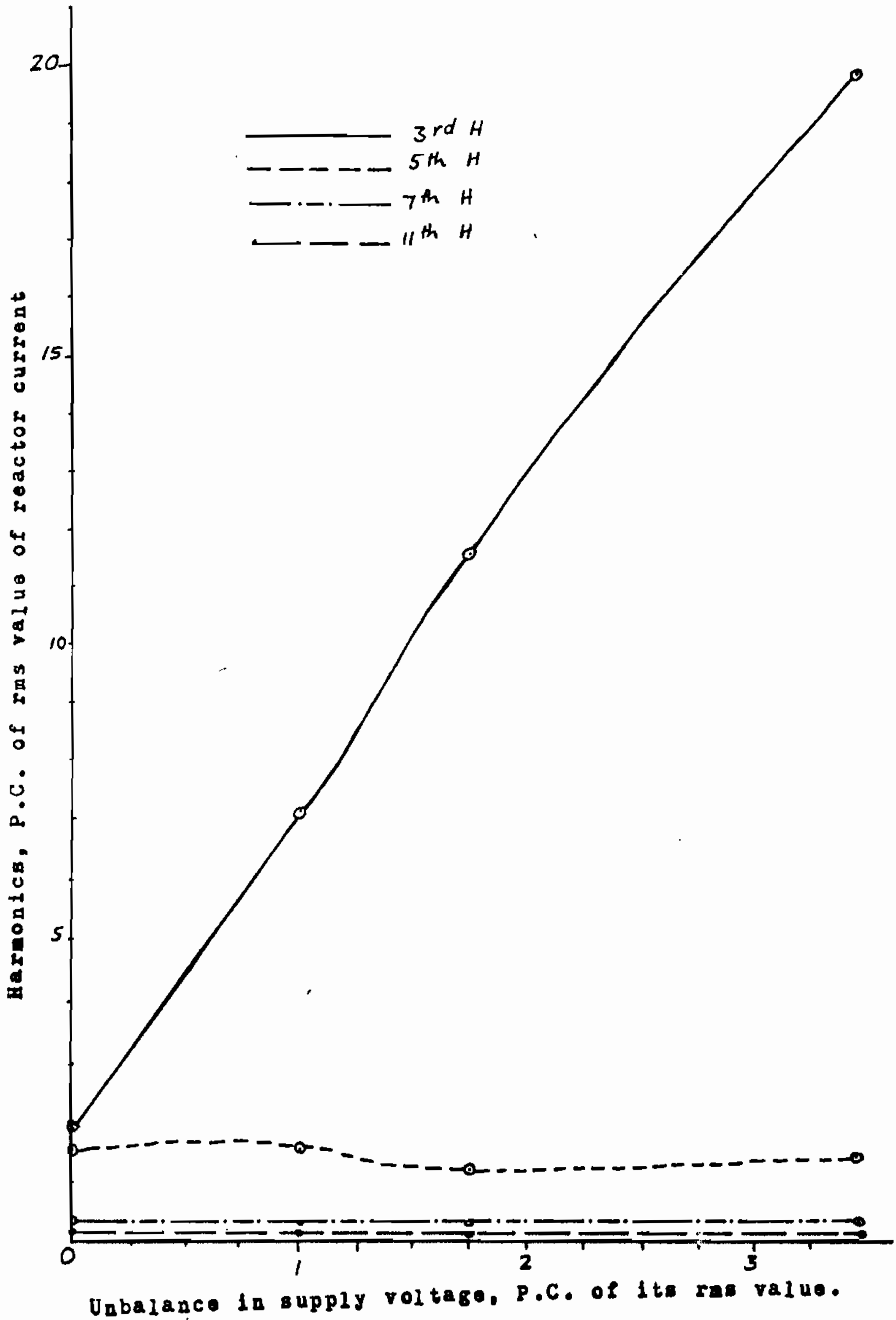


Fig. 7 : Maximum harmonic value in primary current due to unbalance in supply voltage. (ii) With shunt capacitor.

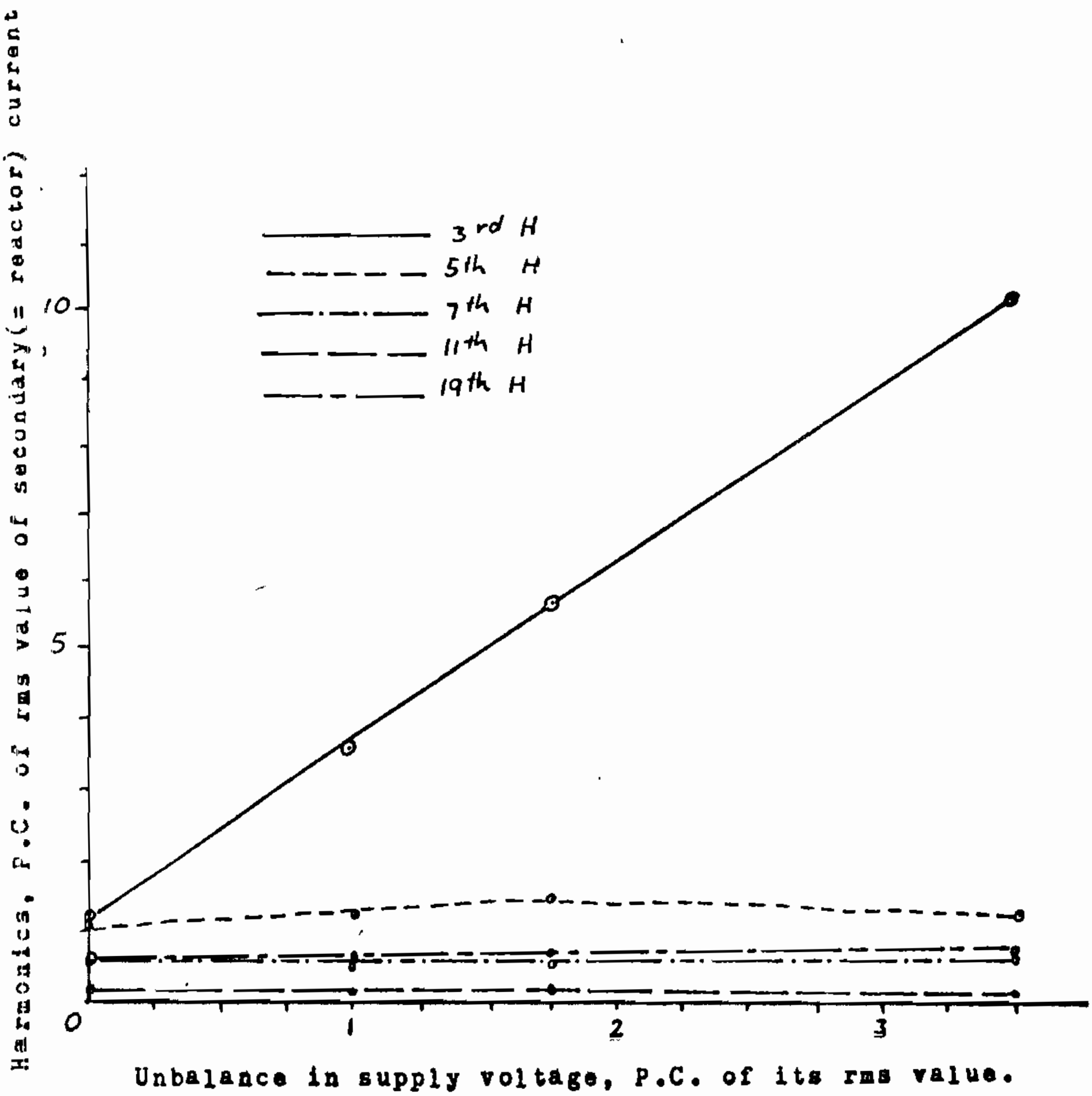


Fig. 8 : Maximum harmonic values in secondary current due to unbalance in supply voltage. (i) Without shunt capacitor.

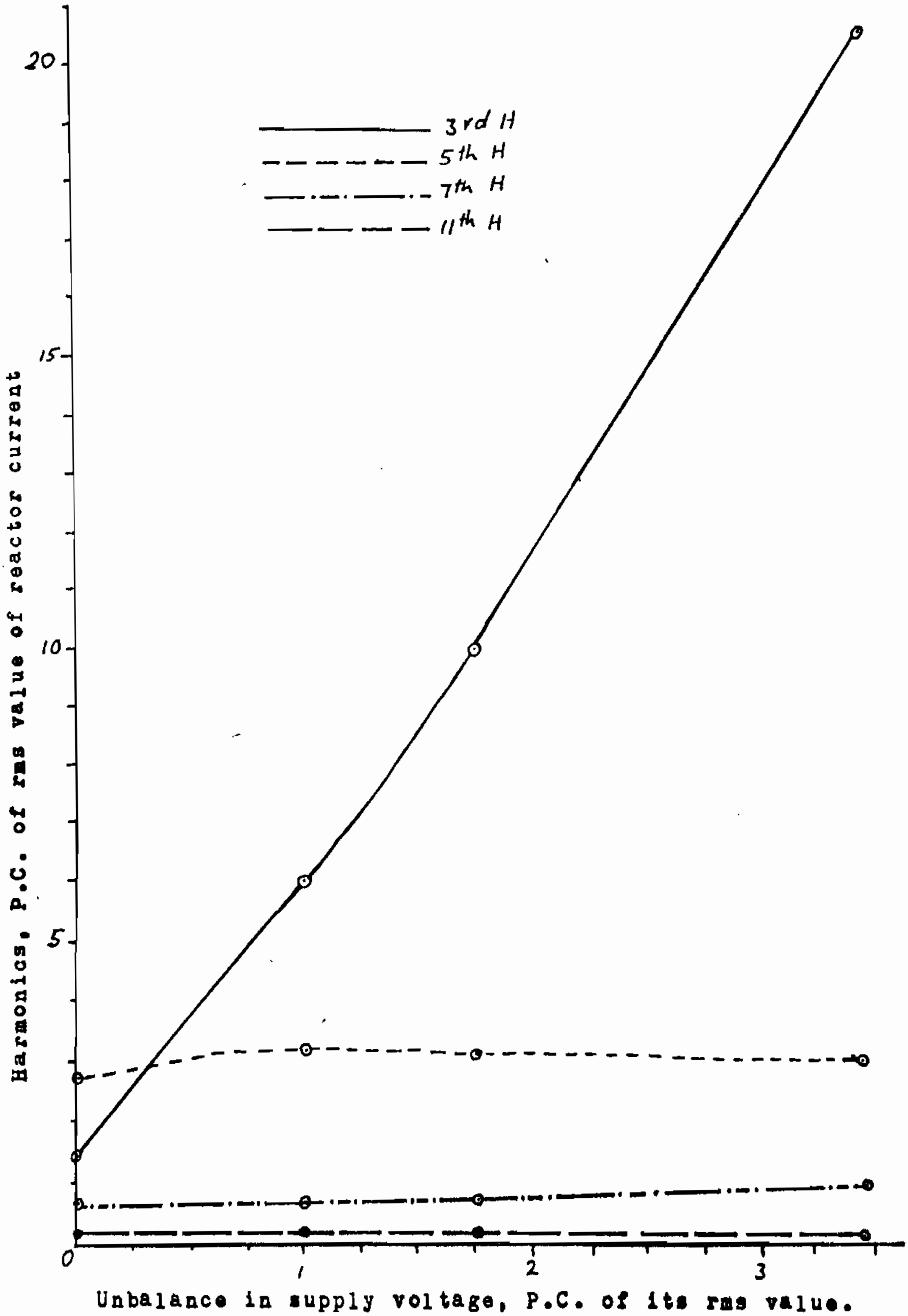


Fig. 9 : Maximum harmonic values in secondary current due to unbalance in supply voltage. (ii) With shunt capacitor.

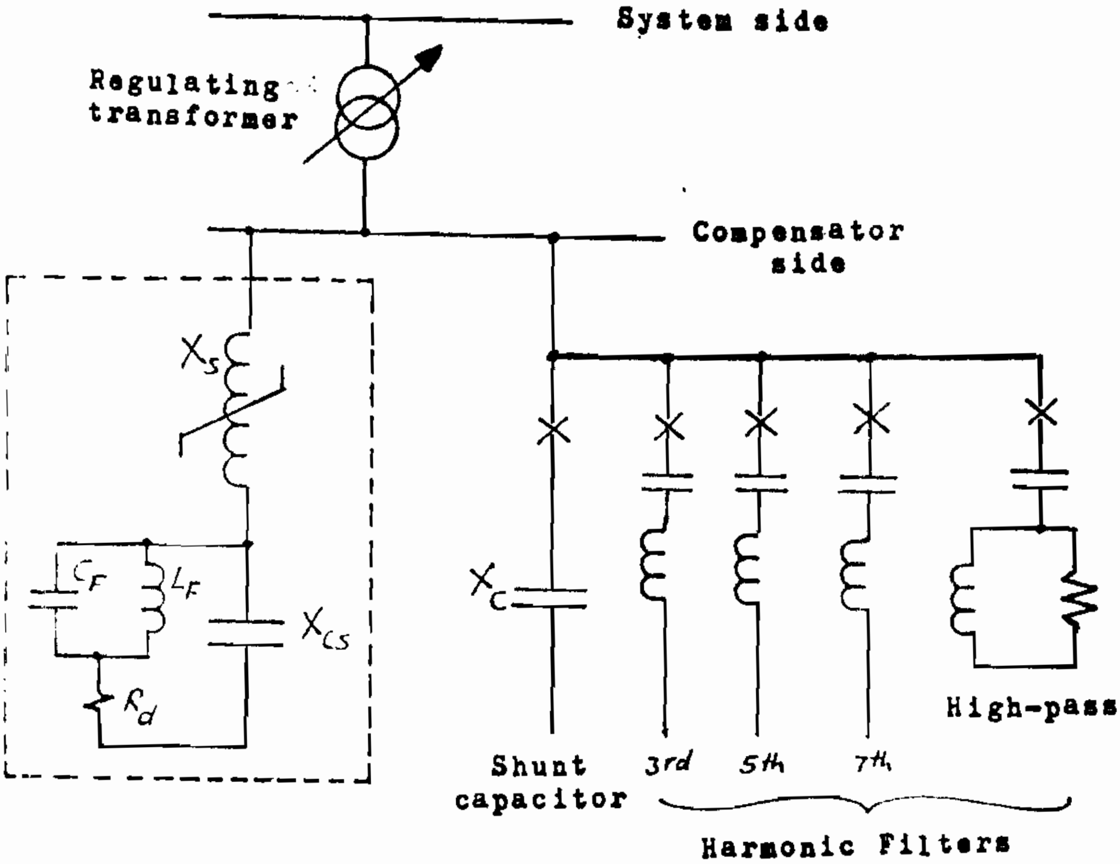
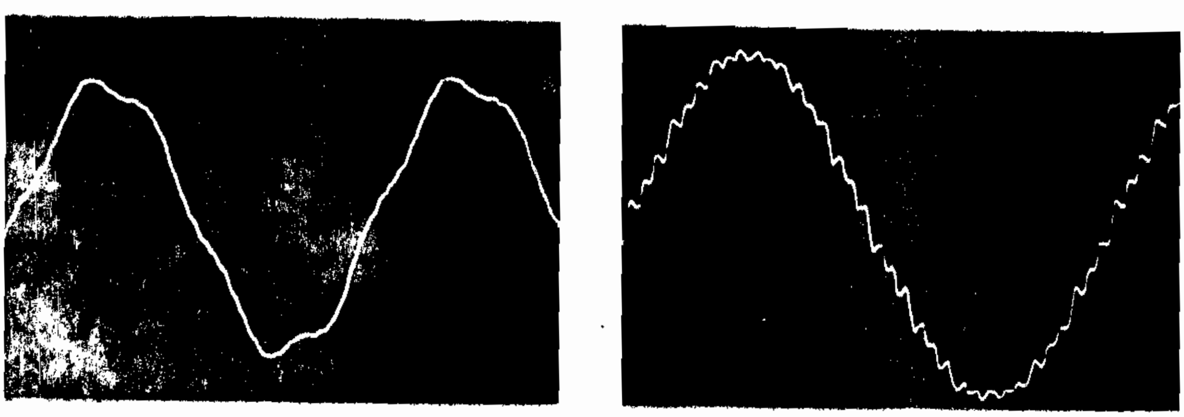


Fig. 10 : The connection of filter arms



(a) Fifth harmonic filter (b) High-pass filter

Fig. 11 : Harmonic currents in the filters

harmonics generated the 3rd is most dominant and increases in value as the percentage values of unbalances are increased. Higher harmonics, however, remain nearly constant in value with the increase in the unbalance values. This is true for both types of unbalances.

Although the regulating transformer is seen to cause a decreasing effect upon the harmonic contents in both cases of unbalances, this effect is far from enough. The reduction is caused only on the side opposite to that on which the unbalance exists. Harmonic filter arms are therefore necessary for satisfactory operation of the system.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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