S W I T C H I N G   S U R G E   P H E N O M E N A
A S S O C I A T E D   W I T H   T H E   V A C U U M
C O N T A C T O R

Michael North Jackson

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D E C L A R A T I O N

I, M. N. Jackson, make the following declarations; the practical work described in this dissertation was performed by me in my capacity as a Graduate Trainee and later as Design Engineer, in the Switchgear Engineering section of GEC Power Distribution (Pty) Ltd.; the subsequent theory and discussion is entirely my own work and is not based on any sources other than those listed as references in this dissertation.

TO MY WIFE

INA

ACKNOWLEDGEMENTS

The author is obliged to GEC Power Distribution for permission and time to undertake this dissertation.

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PREFACE

Vacuum switching devices are acknowledged to possess many positive features such as safety, quiet action, high reliability, low maintenance, small size and light weight. However, these merits are accompanied by a fear of switching surge which may cause a dielectric failure in the load insulation.

Having been convinced that vacuum switching devices are superior to any other kind of switches, continuous efforts have been extended in the study of switching surge mechanisms and to develop an effective surge protection method, by experimental data compiled in the laboratory and actual measuring data in field application. This dissertation describes the work done by the author, mainly at GEC Power Distribution, in determining the switching phenomena associated with the vacuum contactor.

The dissertation starts with an introduction describing briefly the development, advantages and construction of the vacuum contactor. It goes on to state the requirements of the contact materials, experience with vacuum contactors and reasons for the work done. It also lists and briefly describes the types of switching transients.

It was found that there are basically three known phenomena associated with vacuum switching.

a) Current chopping. This includes "three phase simultaneous interruption" (also known as virtual current chopping). A chapter on this subject examines the effect of contact materials, variation with current interrupted and surge impedance, effect of voltage level and arc stability and it's relationship to current chopping. The theory of overvoltages due to current chopping is given and this is compared with actual tests on a motor. Tests resulting in three phase simultaneous interruption when switching a transformer are also described.

b) Switch-on prestrikes. This chapter describes the mechanism of prestrikes, what they are functions of, and the effect of cable lengths. Tests on a simulated motor circuit are described as well as actual tests on a motor and a transformer.

c) Restrike transients. This chapter describes the mechanism of restrikes, their relationship to current chopping, actual tests on a motor and transformer, and comparison between theory and results.

The results of all the tests performed show that in some cases it is desirable to fit some form of surge protection. The last chapter describe the forms of suppressors available, and their effects on the switching surges. Tests are described in which the component values of RC suppressers are arrived at and their success in dealing with both prestrikes and restrikes.

The last section sums up the position as regards coping with the surges in pratice; when and what protection should be employed.

CHAPTER 1

GENERAL EXPOSE ON VACUUM CONTACTORS

1.1 DEVELOPMENT OF THE VACUUM CONTACTOR

The vacuum switch originated early in the history of electrical engineering. Rittenhouse (1) states that the earliest patent was filed in 1893, and may have been inspired by the announcement of Paschen's law in 1889 (2), relating breakdown voltage to gas pressure and length of the discharge path.

In 1897, the first study of the topic of high voltage breakdown between two electrodes in vacuum was done (3). The first commercial vacuum switch in attributed (4) to the Swedish Birka Company in 1921. These switches were used to interrupt very low power. The first demonstration of real interrupting ability, however, was by Sorensen and Mendenhall of the California Institute of Technology in 1923/26. They succeeded in interrupting 926 amps. at 41 500 volts (5). Shortly after this, the General Electric Company acquired the patent rights from the California Institute of Technology and began an extensive development program. In spite of the optimism indicated by Sorensen, this program was terminated in 1931 without reaching industrial success, because of the unavailability of supporting technologies (6). Although it was not till 1955 that vacuum interrupters were first used commercially,[7] a vacuum contactor rated at 250 volts and 15 amps. was reported in 1934[8].

The vacuum contactor is very similar to the vacuum interrupter. It is usually employed to control motors and its lower rating makes it possible to use a smaller volume. The practical requirement of vacuum contactors differ from those of the vacuum interrupter:

a) The interrupting ability in terms of kA of the contactor is usually much lower than that of the interrupter.

b) The contactor has to repeat it's function many more times than does the interrupter.

c) The arc of this device must be stable for a duration of half a cycle and exist down to low values of curr nt. If the arc is not stable, overvoltages will result and may damage the motor's insulation.

The second requirement calls for bellows with a long life-time and for contacts with low erosion characteristics. The third requirement was first tackled by Reece[9]. Further work by the Central Research Laboratory of the Associated Electrical Industries (A.E.I.) and the Electrical Research Association, which pioneered most of the work, resulted in the first 3 phase 3,3 kV, 400 amp. vacuum contactor in Great Britain being introduced in 1965[10]. This is the forerunner of the GEC vacuum contactors upon which most of the research in this dissertation was carried out.

Development proceeded rapidly in Great Britain, the United States, Germany and Japan. In Japan there are more than 100,000 pole mounted vacuum switches alone[11].

1.2 ADVANTAGES OF THE VACUUM CONTACTOR

It was because researchers were convinced that vacuum switching devices were superior to any other kind of switches that continuous effort was made to overcome technological difficulties such as "out-gassing", sealing, and producing contact materials with suitable properties. (See 1.4.). Today vacuum contactors are acknowledged to possess many positive features, some of which are listed below.

a) Safety - not flammable.

b) Silent in operation.

c) High reliability.

d) Low maintenance.

e) Small size.

f) Lightweight.

g) Low actuator power requirement.

h) Excellent electrical and mechanical life.

i) May be used in any orientation.

For example, some of the advantages made by GEC [12] for their 3,3 and 6,6 kV contactors are:-

a) Long contact life - over 2 million operations at full load (typically 300 A).

b) Minimum maintenance - just a simple check with wear gauge every half million operations.

c) No problems due to current chopping.

d) No contact welding or oxidising - no arc chutes and no ionised gas.

e) Small size and containment of arc makes very compact equipment design possible.

f) Contacts do not bounce on closing due to good mechanical design without the need for extra springs.

g) The contactors are satisfactory for operation on a.c. frequencies up to 1000 Hz. c.s. for induction furnace duty. But because high frequencies produce local heating, some derating is necessary.

h) The contactors are suitable for use on frequencies below 50 Hz., such as in the rotor circuit of a slipring motor during starting, although their interrupting capacity is effected.

1.3 CONSTRUCTION AND OPERATION OF THE VACUUM CONTACTOR

A vacuum contactor is shown in Fig. 1.2 and the construction of a typical vacuum contactor interrupter is shown in Fig. 1.1.

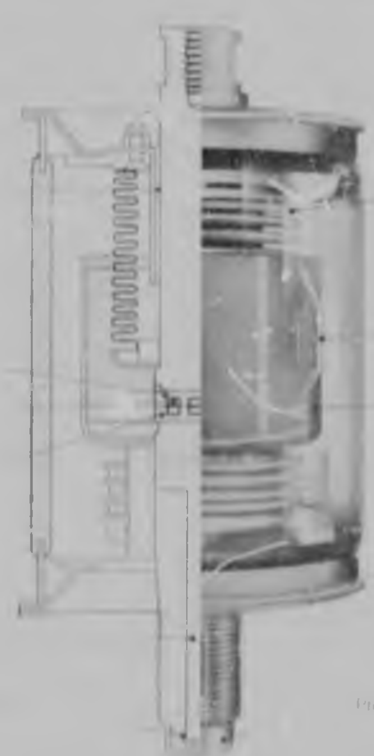


Fig. 1.1. Half section through a typical vacuum switch.

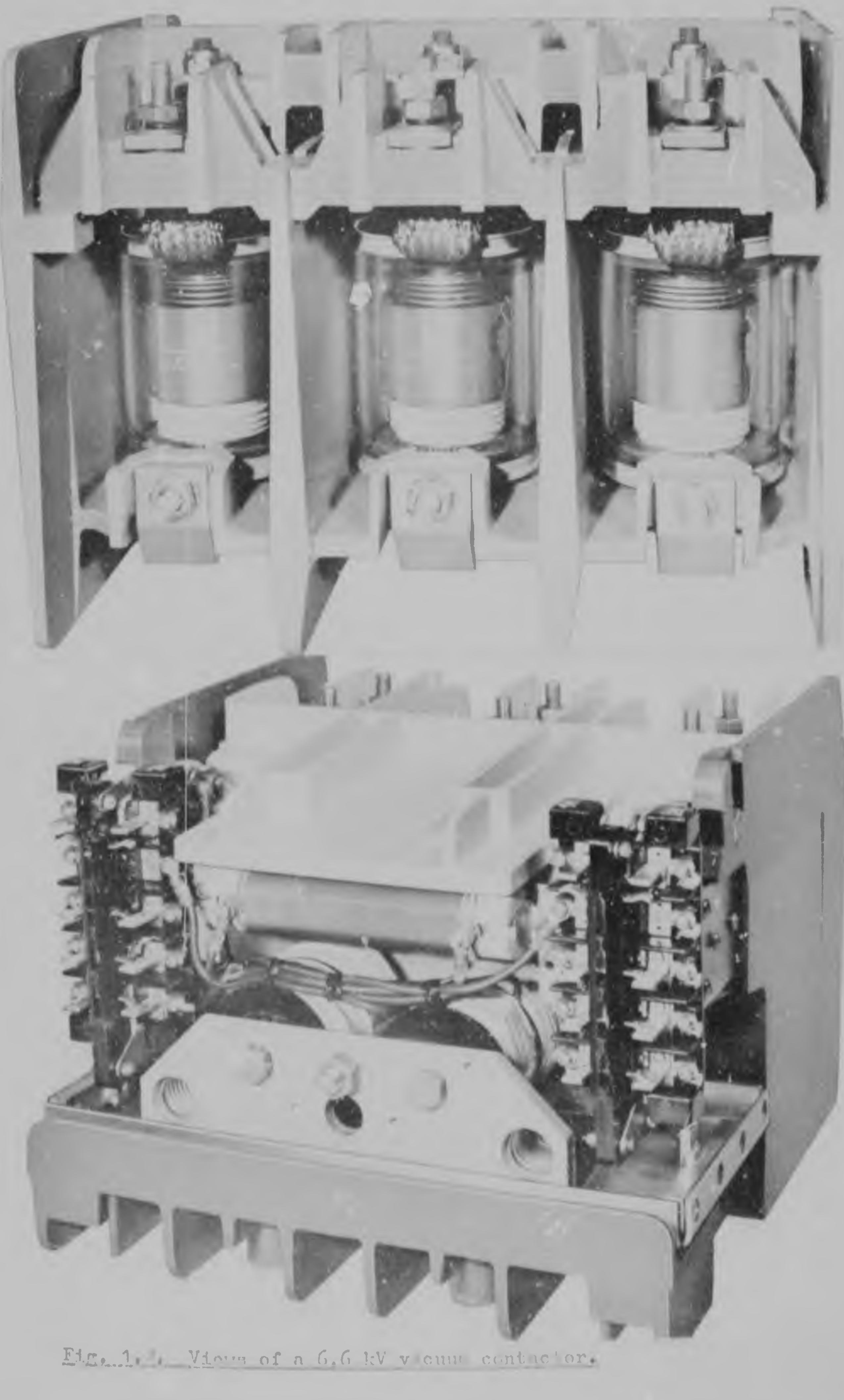


Fig. 1.2. Views of a 6.6 kV vacuum contactor.

An evacuated vessel contains a pair of contacts, one of which can be moved. These are surrounded by a shield which prevents metal vapour from condensing on the internal surface of the insulating envelope. The envelope may be made of any suitable material of which glass, glass ceramic, porcelain or alumina are examples. The contacts are faced with, have reservoirs of, or otherwise have sintered in them, one of a number of alloys to control the mechanical and electrical performance of the device. The stem of the moving contact is sealed with a metal bellows, usually stainless steel, so that a pressure of 10^{-6} to 10^{-7} Torr may be maintained for tens of years. This pressure is considerably lower than the 10^{-3} Torr strictly necessary for correct interrupter operation, but provides an adequate vacuum for the guaranteed life of the switch.

When contacts carrying a current are separated in a vacuum, initially as the contact pressure decreases, so does the contact area, and the temperature at the points of contact increases, until melting occurs and liquid metal bridges are formed. With the contacts continuing to part, these bridges grow longer until they become unstable and rupture. Arcs are then formed at these points. These arcs contain electrons, positive ions and neutral particles derived from the metal vapour. This vapour supplying the positive ions necessary for this arc is dependent on the flow of current; the larger the current, the greater the supply of vapour. When current ceases to flow, as at a natural system current zero, recondensation of the vapour re-establishes the vacuum. The interrupting capacity hangs wholly on the rapidity with which the metal vapour cloud disperses and restores the vacuum at and after the current zero.

On simple butt type contacts as used in vacuum contactors, the arc is in the diffuse state at peak currents of up to around

10 kA [13]. The diffuse arc spreads across the contact areas available to it and consists of many entirely separate arcs in parallel. Its heating effect is well distributed and it does little damage to the contacts with almost no gross melting . At higher currents the magnetic pinch effect causes the arc to contrict and boiling pools of metal perhaps 1cm. in diameter occur at both anode and cathode roots, with cooling times too long to ensure re-condensation of all metal vapour at the current zero. The arc will thus continue to re-ignite after every current zero. It is for this reason that contactors only have a rated interrupting ability of 5 - 7 kA. r.m.s. and are usually backed up by fuses to prevent the contactor from opening on fault currents any higher than this. The number of operations at 5 kA is also very limited.

1.4 REQUIREMENTS OF THE CONTACT MATERIALS

The mechanism of arc extinction in vacuum switches has been treated in detail by Reece[13], from whose papers the following factors are shown as having influence on the point at which an arc extinguishes in vacuum:-

(a) gas pressure,

(b) arcing voltage or work function of contact materials,

(c) vapour pressure of evaporated metal,

(d) electronic and thermionic emission from contacts.

Since gas pressure is extremely low by definition in a vacuum switch, the main variables on which the switch designer must adjudicate are those of the contact materials [14].

The properties required of the contact material are:

(a) good mechanical strength and electrical conductivity.

(b) good thermal conductivity to assist rapid cooling of the arc roots when breaking high currents.

(c) low weld and cold adhesion strengths at the contact surfaces to give easy and consistent separation.

(d) low and uniform erosion to give a long operating life.

(e) sufficient metal vapour for low-current arcing to minimise current chopping.

(f) limitation of metal vapour and thermionic emission after high current arcing at current zero to permit voltage recovery.

Materials having high vapour pressure at moderate temperatures usually provide a good supply of metal vapour with low arc energy, and are thus desirable for low chopping current performance. This characteristic is attended by high evaporation rate, with consequent loss of material from the contacts and reduced contact life. (d) & (e) are to some extent therefore conflicting. Materials having good mechanical strength (a) and low weld and cold adhesion strengths (c) such as tungsten and molybdenum, do not have high vapour pressure at moderate temperatures and thus chop relatively large currents. These requirements are therefore in conflict with (e). On the one hand it is required to have sufficient metal vapour for stable arcing down to low currents and on the other hand after high current arcing it is necessary to limit the metal vapour near current zero so as to allow the arc to cease, the metal vapour to recondense and the voltage to recover without a reignition occurring.

No single material complies with all the requirements so that the contact materials are mixtures or alloys. For example the materials chosen for GEC contactors are an antimony-based filler-alloy reservoir in annular grooves in molybdenum contacts. The filler-alloy provides the desired electrical characteristics, and the molybdenum gives the mechanical performance required of heavy-duty contactors.

The Toyo Denki contactor, on the other hand, has contacts consisting of a sintered tungsten matrix into which a copper alloy and antimony are infiltrated.

1.5 EXPERIENCE TO DATE WITH VACUUM CONTACTORS

Vacuum contactors were quickly accepted as an extremely reliable means of control. Soon they were operating successfully in many countries throughout the world[10].

They are used mostly for motor control in a very wide range of industries. Other applications include arc furnace transformer switching and capacitor switching. Duties vary from infrequent operation in process industries to very frequent arduous duty in steelworks.

It is the low maintenance of the vacuum contactor which appeals to the user, particularly where the switching is frequent and arduous. Applications of the vacuum contactor are dealt with in more detail by May[10] and Smith[15].

However, over the last several years, there have been cases of insulation failure, more particularly in this country[16]. This has led to extensive investigation into the whole subject of switching transients and how to cope with them. Most of the research has been conducted in Japan[17, 18, 19], and the United States[20, 21, 22, 23, 24] with some also in Great Britain[25, 26, 27] and lately in South Africa[28, 29, 30].

Statements have been made as to the suppression requirements when switching motors or transformers[17, 30]. Others advocate ensuring adequate load insulation[29] and only the use of surge suppression in special cases. The subject of surge suppression is dealt with in more detail in chapter 6.

1.6 REASONS FOR WORK DONE

In 1977 a decision on whether to supply surge suppression devices with a large order obtained by GEC Machines and GEC Power Distribution to supply induction motors switched by vacuum contactors had to be taken. The motors were 6,6 kV and varied in size down to 200 kW. In the light of the then prevailing controversy on the subject, it was decided to undertake a project to investigate the surge effects, taking into account all the system parameters and to determine whether the motor insulation was adequate. The work required close technical co-operation between the two GEC Companies mentioned, with considerable assistance from the University of the Witwatersrand and the C.S.I.R. Papers reporting some of the results have been published by Reynders and Landy[31] and Speedy[29].

The author was involved in determining the switching phenomena associated with the vacuum contactor switching an induction motor. After this he took part in a research program conducted jointly by GEC Distribution Switchgear (U.K.) and UMIST investigating switching transients associated with oil, SF_6 and vacuum circuit breakers. He also managed to do some experiments at UMIST into current chopping and arc stability of the vacuum contactor. On his return to South Africa, he continued with research into current chopping, vacuum contactors switching transformers and on site measurements of arc transformer switching.

This dissertation summaries the results obtained during this work over the past two and a half years.

CHAPTER 2

INTRODUCTION TO SWITCHING SURGES

Switching surges, or transients as they are sometimes called, can occur either on closure or opening of a switch. All switching devices produce surges and industry has had to cope with these since the beginning. These have been known to exist at least since the 1930s, but the study of them has increased since the advent of the vacuum switch.

Earlier vacuum contactors were prone to current chopping and overvoltages caused thereby were hazardous to the motors they switched. Contact materials having low chopping levels were introduced only for the attention to become focussed on another source of switching transient , the prestrike. Although all switches strike before actual contact on closure, the remarkable ability of the vacuum switch to interrupt high frequency currents and to suddenly recover it's dielectric strength, has resulted in multiple prestrike occurring. The vacuum contactors are particularly bad in this respect, as having relatively slow operating speeds and lower dielectric strength than circuit breakers, they can produce tens of prestrikes on closure.

Provided the contacts make relatively simultaneously, the order of magnitude of these prestrikes is low and this in itself presents little danger to load insulation. However, depending on circuit parameters the rates of rise can be high, resulting in uneven voltage distribution in the load insulation. Motors in particular sometimes do not have much impulse withstand capability, so that line end coils in particular, experience overstressing of turn to turn insulation.

This aspect of vacuum contactors, has resulted in the policy of many users in this country, to be to fit RC suppressors to protect machines from these high rates of rise. Motor manufacturers have also now begun to produce machines with better impulse withstand capability than perhaps so in the past. These two steps have resulted in the number of reported failures of machines switched by vacuum contactors to decrease. When motors are switched off during starting, it is also possible for a restrike to occur. This is common to all switches if a current zero occurs at or soon after contacts part and the dielectric strength is unable to withstand the recovery voltage of the circuit. However, in practice restriking is rare with motor switching, only occurring on inching or stalled switch-off. Here the magnitudes can be large due to voltage escalation, but generally the rates of rise are not as steep as with prestriking. Oil and air-break switches are both prone to produce restrike transients and in the past if these have been a problem, they have been overcome by fitting voltage limiting devices, such as lightning surge arresters.

CHAPTER 3

CURRENT CHOPPING

3.1. INTRODUCTION

The problems associated with "chopping current" originally held up development of the vacuum contactor as in the earliest stages chopping currents were very high, sometimes 50 amps. and therefore the surge voltages generated when current chopping took place were also excessively high.

Chopping current is defined as the current at which the arc can no longer sustain itself and at which value it suddenly reduces to zero. This causes a sudden change in the magnetic flux in the inductance of the circuit and this together with the circuits capacitance produces a chopping overvoltage transient. The theory is dealt with in more detail in 3.7.

3.2 EFFECT OF CONTACT MATERIALS

All types of switchgear interrupt current before reaching a current zero(32). This is due to the instability of the arc at low currents. Vacuum arc stability and the mechanism of arc extinction has been discussed in detail by Reece (13), Kesaev (33), Paul(34) and Farrall(35). It has been shown that vacuum arc stability is related to the thermal properties of the contact material and is affected to a small extent by the surge impedance of the circuit in which the contactor operates.

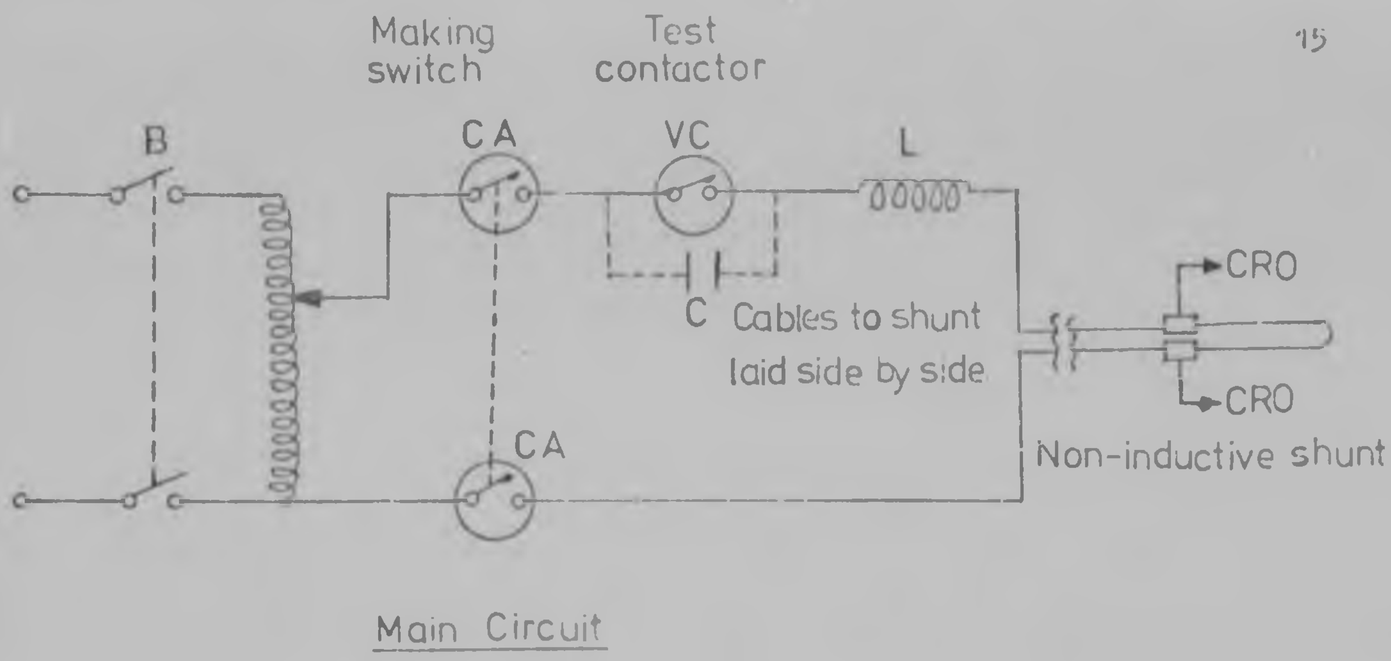
Tests were performed to compare the current chopping level of a GEC contactor with it's equivalent Toyo Denki vacuum contactor. Both contactors were suitable for operation at 6,6 kV. The test circuit used is shown in figure 3.1 and is described in 3.3. The results for chopping 20 amps. r.m.s. are shown graphically in figure 3.2. Also shown are the results for the V.I.L. (Vacuum Interrupters Ltd.) vacuum circuit breaker and GE's (General Electric's) vacuum circuit breaker. These are taken from Ismail(25). The contact material for V.I.L. bottles is CLR, which is a chromium-copper alloy, and for GE's bottles is a copper-bismuth alloy. It can be seen that the GEC contactor has the lowest current chopping level of the four vacuum switches.

3.3 VARIATION WITH CONTACTOR CURRENT AND SHUNT CAPACITANCE

3.3.1 TEST CIRCUIT AND DESCRIPTION OF TESTS

Six different levels of supply current viz. 5, 10, 20, 45, 100 and 200 amps. were interrupted. These were regulated by means of the auto-transformer shown in figure 3.1 whose full load was 400 amps. at 230 volts. The current in the circuit was limited by an inductive reactance L. At each value of supply current the current chopping level was also found for different values of parallel capacitance, viz. 0,00353, 0,0125, 0,0429, 0,1 and 0,15μF.

The operation of the test circuit was as follows. The vacuum contactor VC was closed and in turn closed the auxiliary contactor CA via VC3 onto the test supply. CA in turn initiated the timer relay T via CA3 which after about one second operated relay K via T2 to open the vacuum contactor



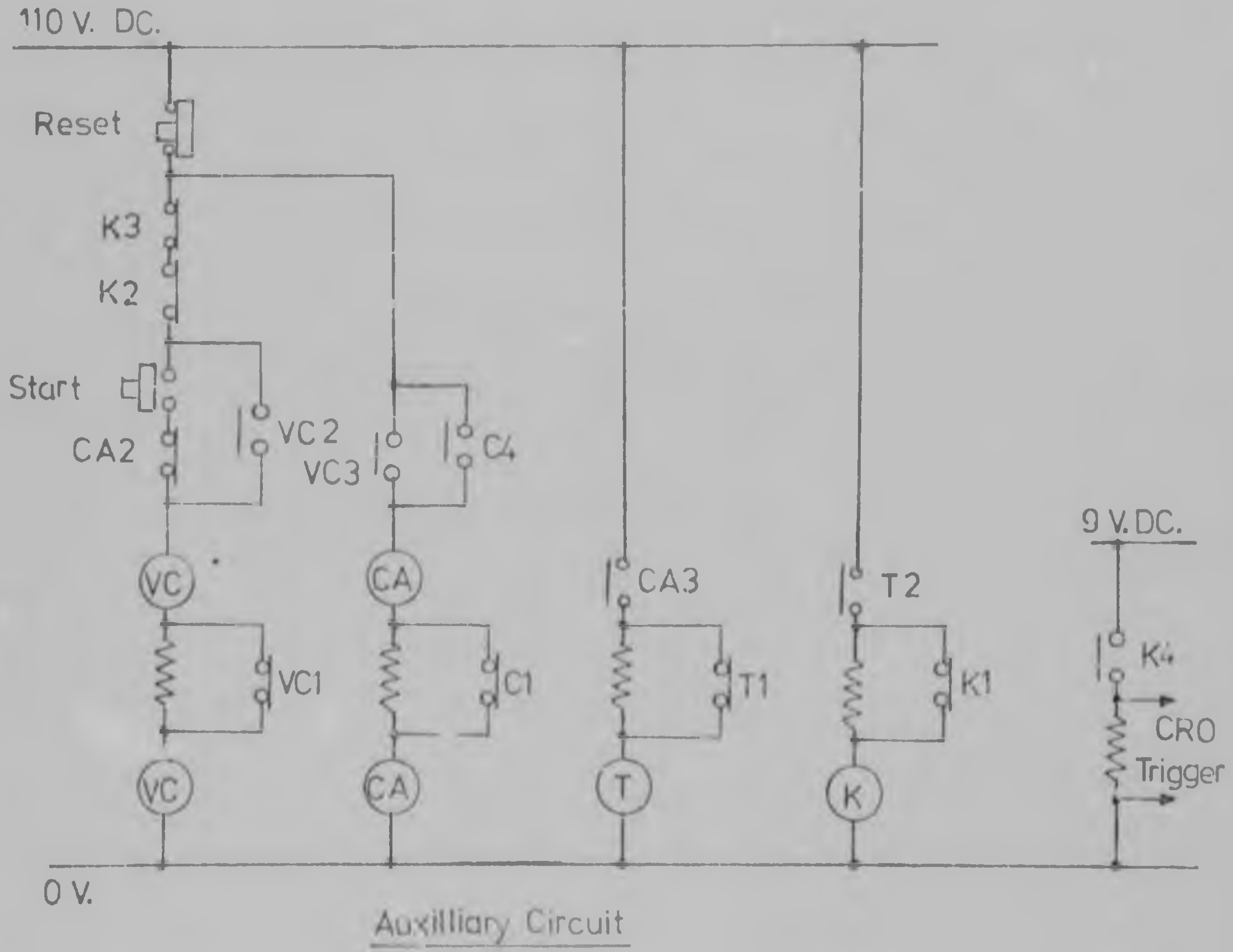


Fig. 3.1. Test circuits to determine chopping currents

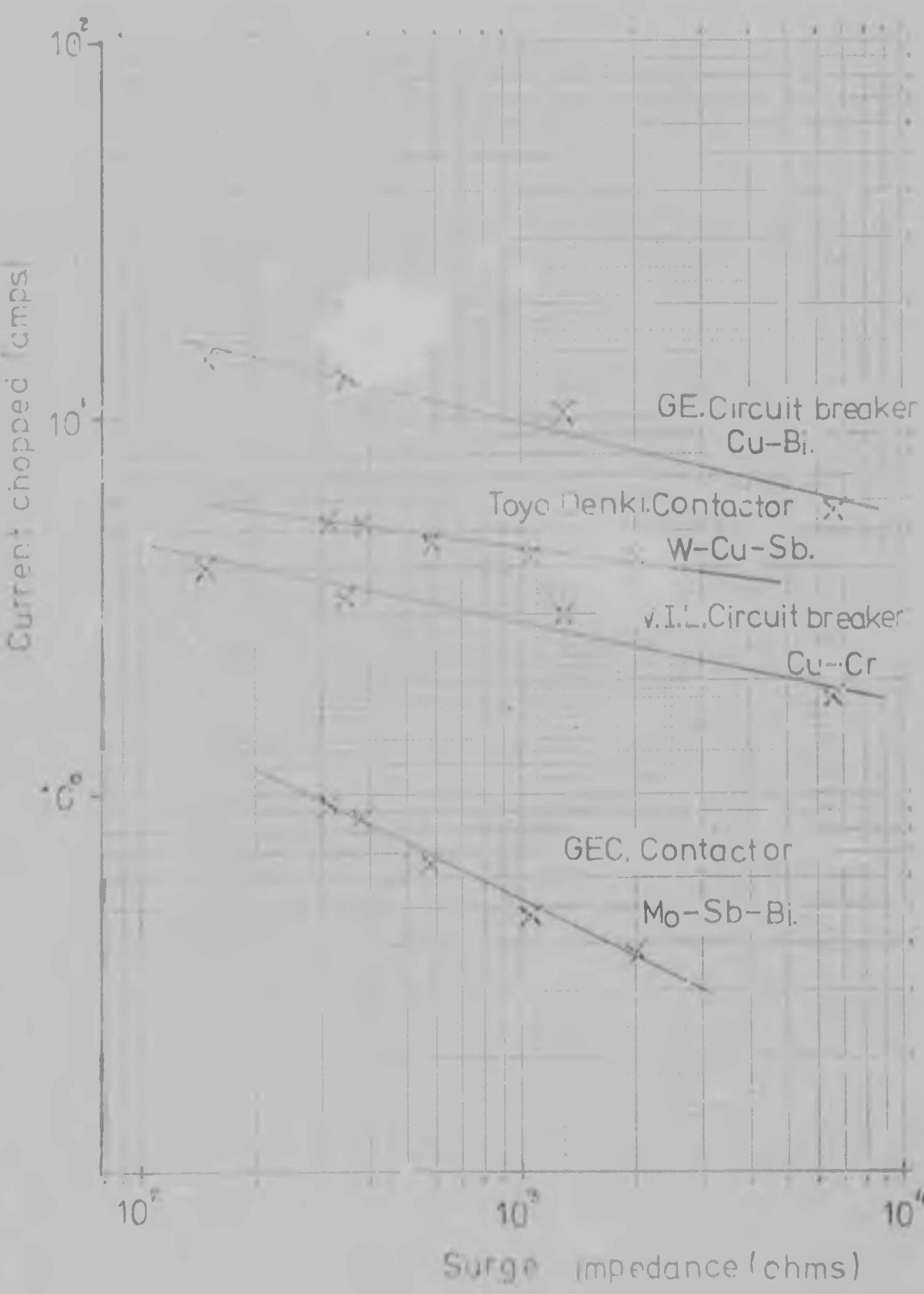


Fig 3.2 Comparison of current chopping level for different contact materials. Supply current = 20 A r.m.s.

VC via K2 and K3. The ensuing current chop and transient were recorded by means of a shunt and storage oscilloscope (Tektronix 466).

Because the test circuit is inductive the current chop leaves some energy trapped in the inductance. The current continues to flow by circulating via the capacitance and the current then oscillates at a frequency determined by L and C. A current transient occurs as shown in figure 3.3

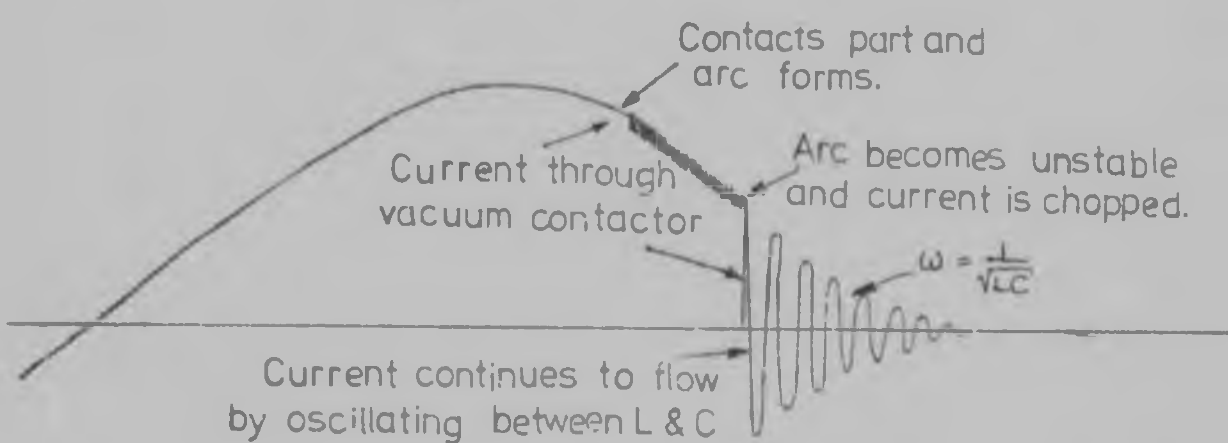


Fig. 3.3. Current transient when chopping occurs.

The oscillation is damped by the losses of the circuit and eventually decays to zero. The chopping level of the vacuum contactor was determined by measuring the initial magnitude of this oscillation or "ringing". Thirty shots were taken of each test (i.e. at each value of supply current and parallel capacitance) to determine the distribution of the current chopping level and its mean value. The switching operation was completely random and not controlled by point-on-wave switching.

When performing current chopping tests the supply voltage cannot be reduced indefinitely to give corresponding low currents. This is because the arc has a minimum stable arc voltage (see 3.5). If the voltage applied is less than this, the vacuum contactor will be able to chop even the peak value of very large currents.

For this reason the voltage was not allowed to drop to less than about 40 to 50 volts. The choke used for the 200 amp. tests (i.e. when supply voltage was at maximum) had a total impedance of about 1 ohm. Thus at 45V. the minimum current possible was at 45A. Another coil of higher impedance was used for the 5, 10 and 20 amp. tests. Readings ere taken of current chopping levels at a supply current of 45 amps. using both the low impedance and high impedance chokes.

The former is referred to in the results as the "45 B" tests while the latter as "45".

Three contactors were tested:-

a) GEC type VB3AD400B5 rated 3,3 k OA.

b) GEC type VC3AD400C7 rated 6,6 kV/400A.

c) Toyo Denki type 3VE-6E5 rated 3,3 kV/6,6 kV/400A.

3.3.2 RESULTS

The full results of the current chopping levels of the three vacuum contactors tested at different currents and for different values of parallel capacitance are shown in table 3.1. The results are also given in graphical form in figure 3.4 to 3.9. The broken lines on the graphs indicate that the points to the right of the broken line were obtained with the low

Table 3.1. Current chopping levels for varying supply current and parallel capacitance.

Supply Current (amps. r.m.s.)		GEC 6,6 KV					GEC 3,3 K					TOYO DENKI				
		Parallel Capacitance µF					Parallel Capacitance µF					Parallel Capacitance µF				
		.00353	.0125	.0459	0.1	0.15	.00353	.0125	.0459	0.1	0.15	.00353	.0125	.0459	0.1	0.15
5	mean $\bar{x}$	0,43	0,55	0,75	0,89	0,93	0,40	0,40	0,55	0,65	0,67	4,54	4,99	4,87	5,31	5,20
	std. dev. s	0,09	0,10	0,15	0,15	0,19	0,18	0,17	0,13	0,24	0,24	0,44	0,50	0,62	0,51	0,60
	max.	0,60	0,80	1,00	1,30	1,40	0,60	0,70	0,70	0,90	1,30	5,00	5,80	5,80	6,00	6,60
	min.	0,20	0,40	0,50	0,70	0,60	0,10	0,10	0,20	0,30	0,20	3,60	4,20	3,80	4,40	4,00
10	mean $\bar{x}$	0,42	0,50	0,66	0,86	0,89	0,48	0,51	0,63	0,73	0,81	5,15	5,39	5,39	5,60	5,60
	std. dev. s	0,07	0,11	0,08	0,15	0,20	0,13	0,16	0,18	0,16	0,22	0,84	0,55	0,88	0,74	0,80
	max.	0,60	0,80	0,80	1,40	1,60	0,90	0,80	1,20	1,20	1,40	6,40	6,00	7,20	7,00	7,40
	min.	0,30	0,40	0,50	0,70	0,70	0,20	0,20	0,30	0,50	0,60	3,20	4,20	4,00	4,00	4,40
20	mean $\bar{x}$	0,38	0,49	0,66	0,88	0,94	0,55	0,53	0,65	0,81	0,97	4,30	4,37	4,68	5,22	5,27
	std. dev. s	0,06	0,07	0,09	0,10	0,12	0,12	0,09	0,12	0,11	0,28	0,47	0,94	0,75	0,75	0,65
	max.	0,50	0,80	0,90	1,10	1,30	0,80	0,70	0,90	1,00	1,50	5,00	6,00	6,40	7,00	6,60
	min.	0,30	0,40	0,50	0,70	0,80	0,30	0,30	0,50	0,60	0,60	3,40	3,00	3,00	4,00	4,00

Table 3.1 continued.

45 mean $\bar{x}$	0,35	0,51	0,80	1,13	1,34	0,38	0,55	0,83	1,10	1,31	3,30	3,67	4,14	4,57	4,93
std. dev. s	0,05	0,06	0,06	0,12	0,08	0,11	0,09	0,12	0,10	0,09	0,37	0,67	0,62	0,63	0,47
max.	0,40	0,60	0,90	1,40	1,50	0,50	0,90	1,10	1,40	1,50	4,00	5,00	5,60	6,00	6,00
min.	0,30	0,40	0,70	1,00	1,20	0,10	0,40	0,70	1,00	1,20	2,40	2,20	3,00	3,60	3,80
45B mean $\bar{x}$	0,35	0,50	0,69	0,87	0,94	0,35	0,65	0,71	0,84	0,90	3,43	4,65	4,69	4,85	4,75
std. dev. s	0,06	0,09	0,12	0,10	0,13	0,13	0,18	0,10	0,11	0,18	0,45	0,91	0,83	0,71	0,64
max.	0,40	0,70	1,00	1,20	1,20	0,60	0,90	0,90	1,20	1,30	4,00	6,40	6,80	6,40	6,00
min.	0,20	0,40	0,50	0,70	0,70	0,10	0,20	0,50	0,70	0,60	2,00	3,00	3,40	3,80	3,20
100 mean $\bar{x}$	0,36	0,42	0,67	0,90	1,06	0,37	0,63	0,78	0,89	1,05	2,26	3,81	3,78	3,52	3,74
std. dev. s	0,07	0,06	0,10	0,11	0,11	0,10	0,09	0,14	0,07	0,07	0,36	0,55	0,79	0,62	0,50
max.	0,50	0,50	0,90	1,20	1,30	0,60	0,80	1,20	1,10	1,20	2,80	5,20	5,00	4,80	4,80
min.	0,30	0,30	0,50	0,80	0,90	0,20	0,50	0,60	0,80	1,00	1,60	2,80	2,40	2,80	2,80
200 mean $\bar{x}$		0,47	0,87	1,35	1,69		0,45	1,06	1,45	1,84		1,39	2,50	3,19	3,40
std. dev. s		0,13	0,08	0,06	0,04		0,05	0,06	0,07	0,06		0,40	0,43	0,50	0,45
max.		0,70	1,10	1,60	1,80		0,50	1,20	1,60	2,00		2,30	3,30	4,40	4,00
min.		0,30	0,80	1,20	1,60		0,40	1,00	1,30	1,70		0,70	1,70	2,40	2,30

Fig.3.4. GEC 6,6kV Contactor Type VC3AD400C7

Current chopped vs.parallel capacitance for various values of supply current.

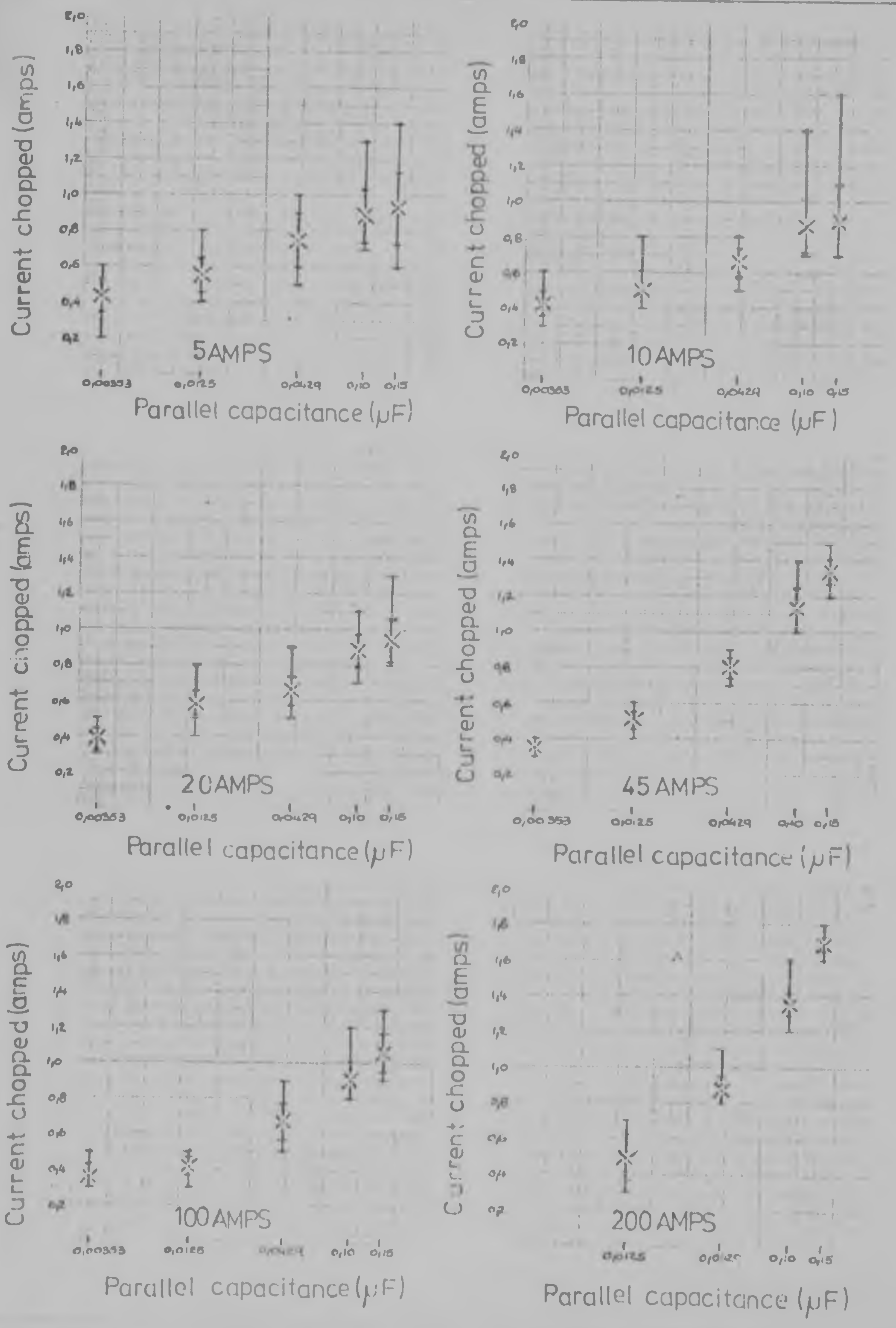


Fig.3.5. GEC 6,6 kV Contactor Type VC3AD400C7

Current chopped vs. supply current for different values of parallel capacitance.

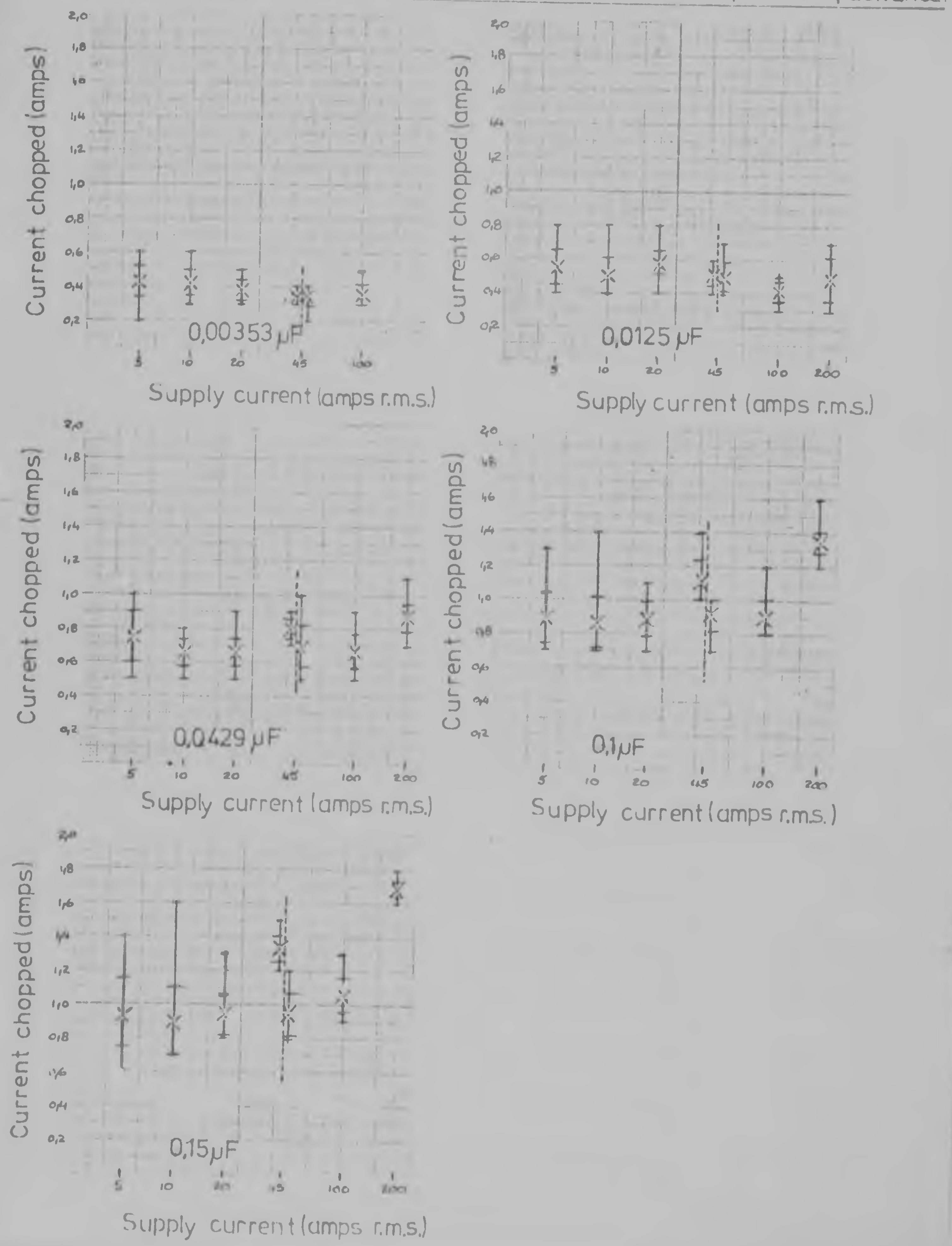


Fig. 3.6. GEC 3,3kV Contactor Type VB3AD400B5

Current chopped vs. parallel capacitance for various values of supply current

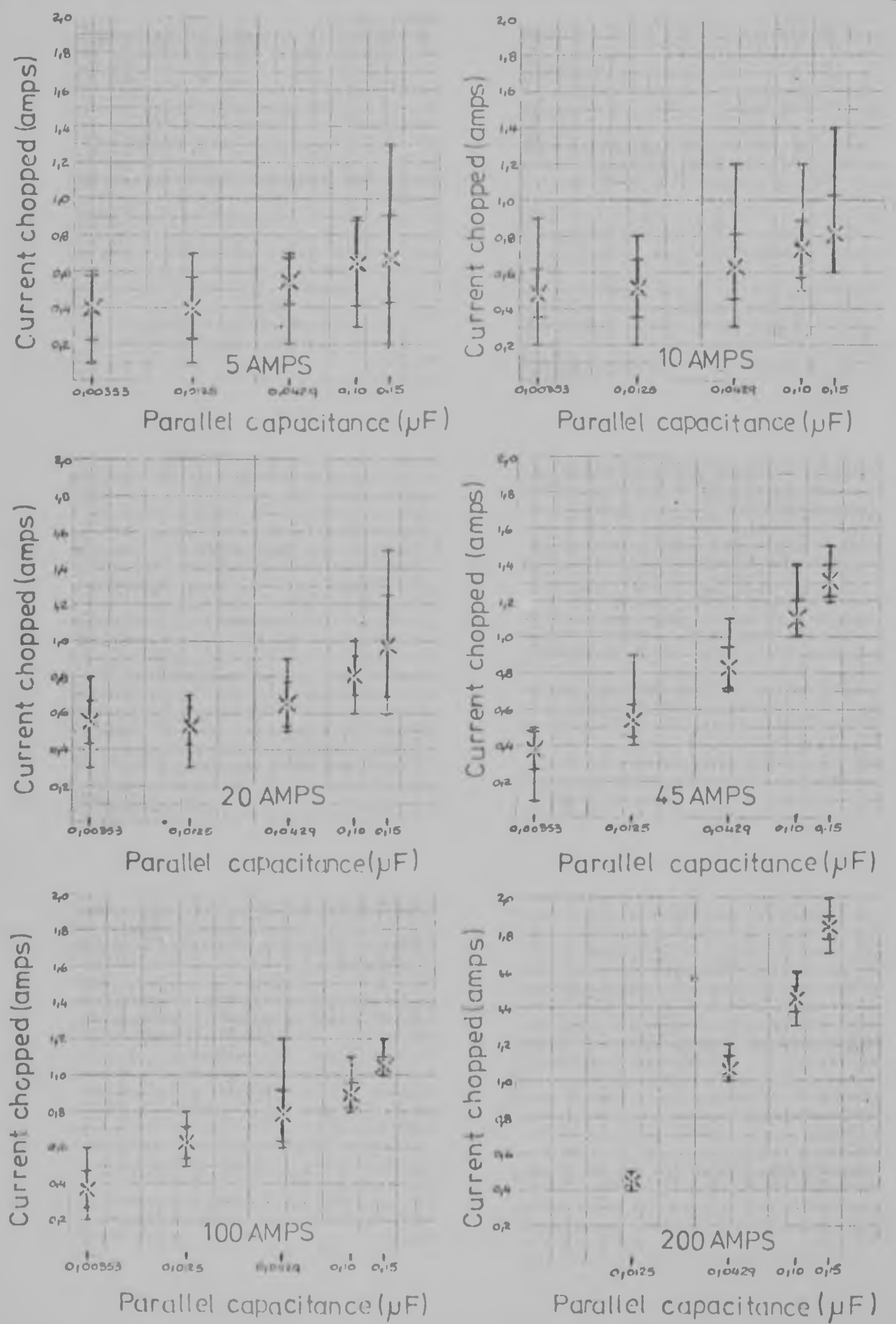


Fig.3.7. GEC 3,3 Contactor Type VB3AD400B5.

Current chopped vs. supply current for different values of parallel capacitance

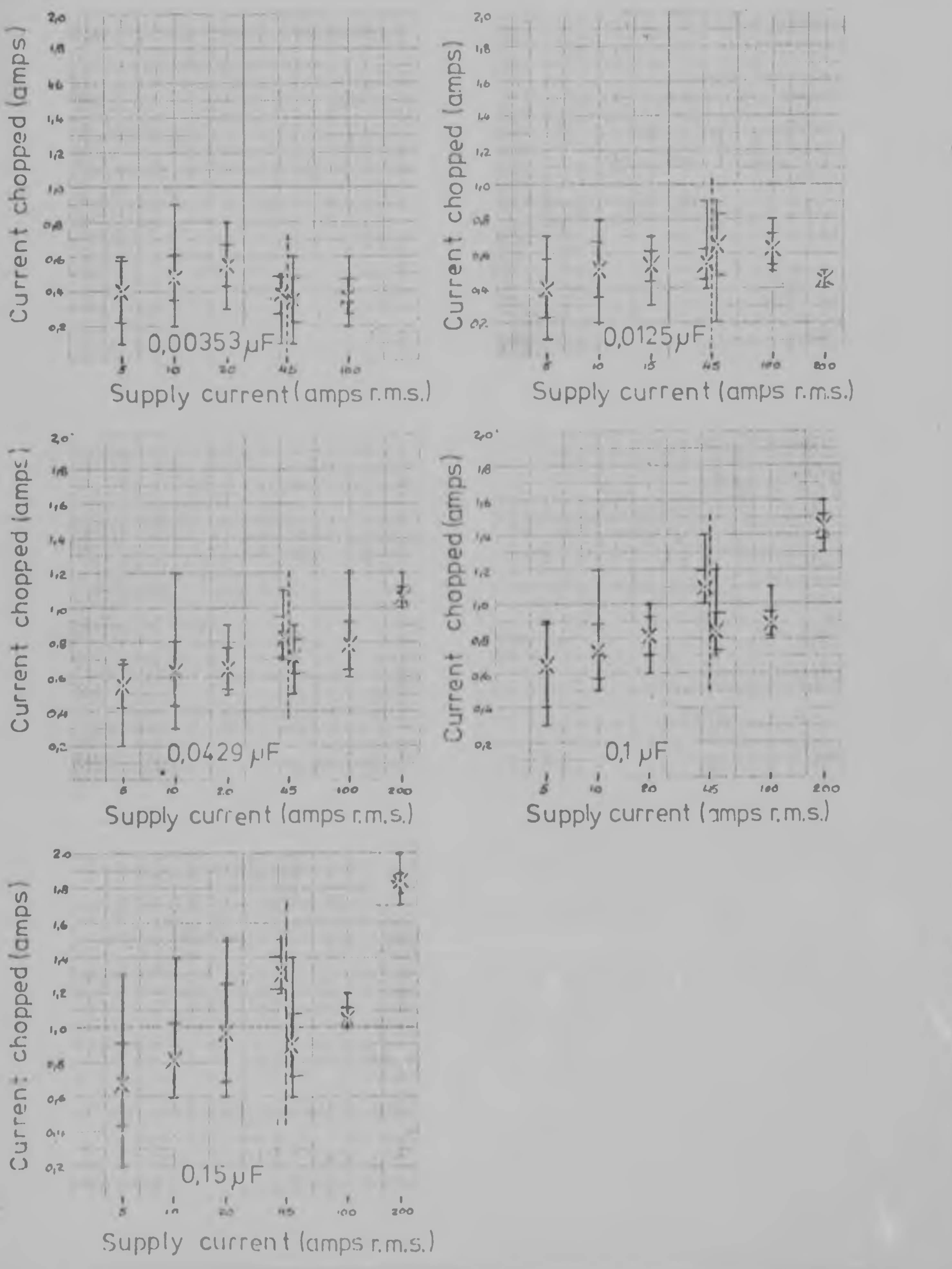


Fig.3.8. Toyo Denki 3,3/6,6 kV Contactor Type 3VE-6E5

Current chopped vs. parallel capacitance for various values of supply current

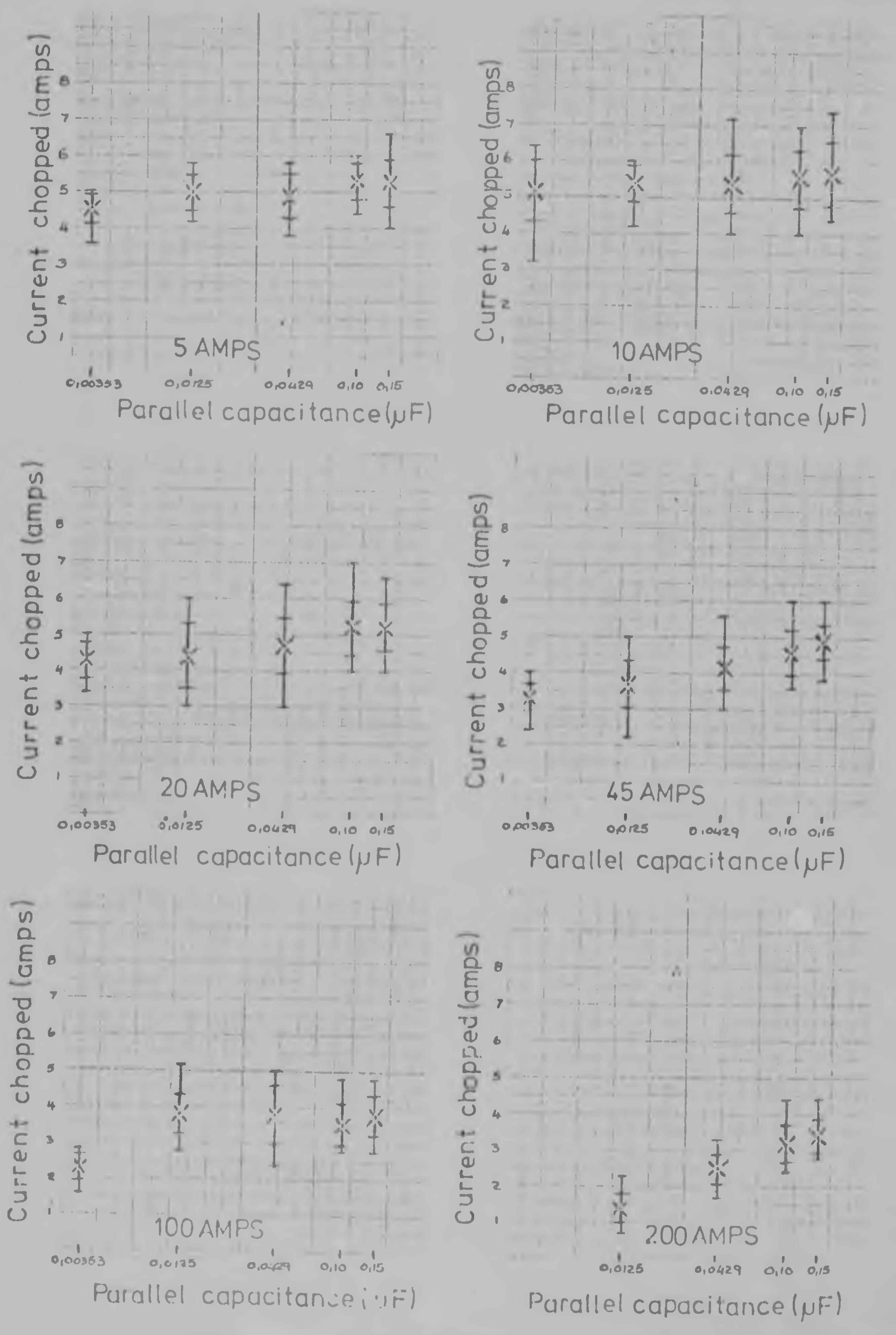
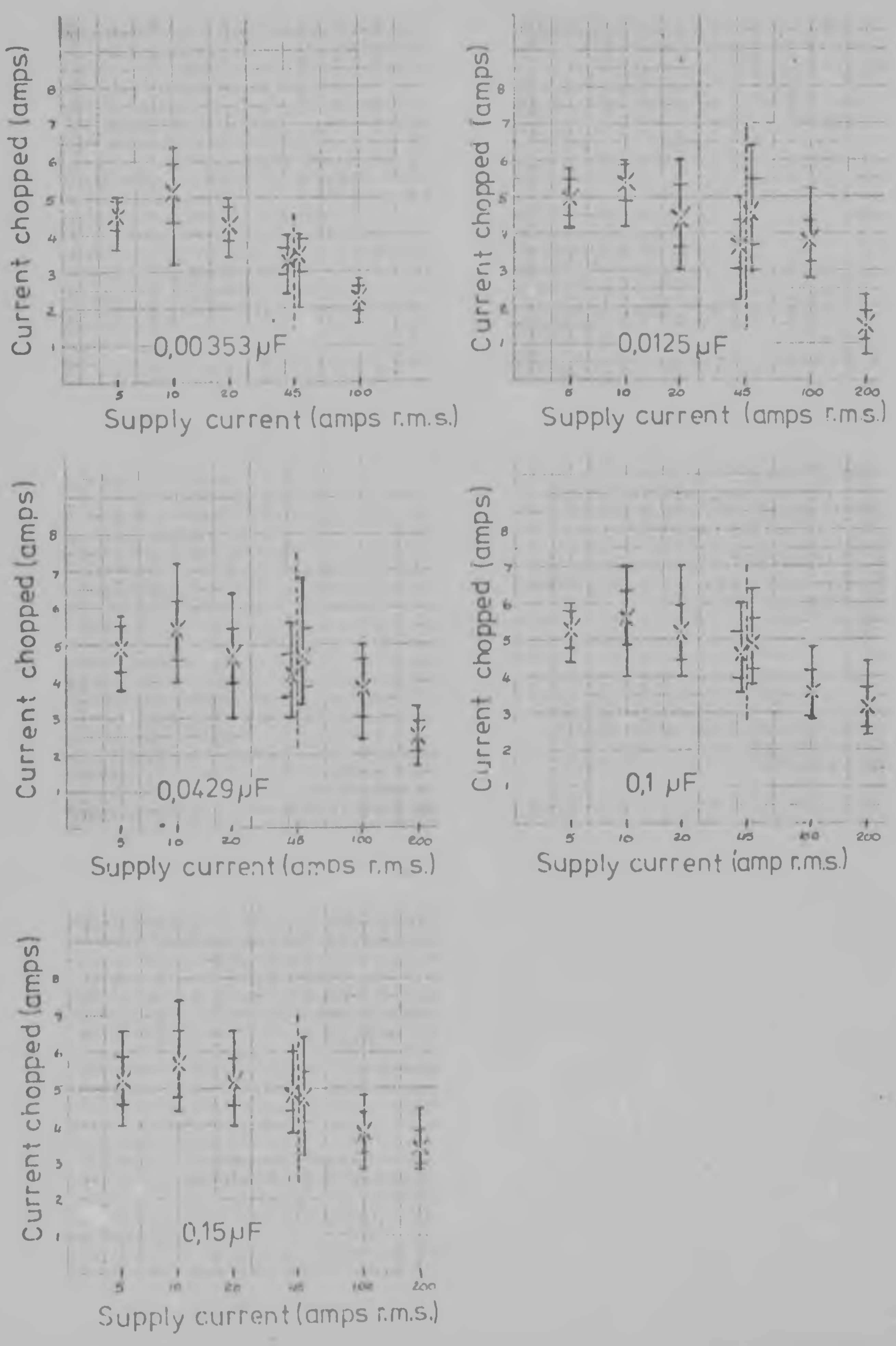


Fig.3.9. Toyo Denki 3,3/6,6kV Contactor Type 3VE-6E5

Current chopped vs. supply current for different values of parallel capacitance



impedance choke while those to the left were obtained with the high impedance choke.

The mean current chopping level of the GEC 6,6 kV vacuum contactor varies from 0,35A (45A supply, 0,00353uF) to 1,69A (200A supply, 0,15uF). The largest and smallest currents chopped through the whole range of tests on this contactor were 1,8A and 0,2A respectively.

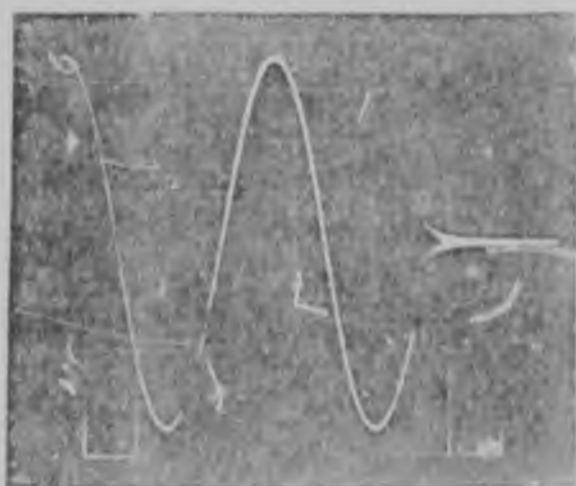
Current chopping characteristics of the GEC 3,3 kV contactor are similar to those of the 6,6 kV unit. This is expected as the contact material is the same for both contactors. The mean current chopping level for this contactor varies from 0,35A (45A supply, 0,00353μF) to 1,84A (200A supply, 0,15μF). The largest and smallest value recorded were 2,0A and 0,1A respectively.

Depending on the magnitude of the contactor current and parallel capacitance, the Toyo Denki contactor has a current chopping level generally some 3 to 10 times higher than that of the GEC contactors. Results show that the mean current chopped by this contactor varied from 1,39A (200A supply, 0,00353uF) to 5,67A (10A supply, 0,15uF). Highest and lowest values recorded were 7,4A and 0,7A respectively.

The results show that, for all three contactors, current chopping level increases with parallel capacitance and that the increase is greater for larger supply currents.

With greater values of parallel capacitance the current chopping level of the GEC contactors is shown to slightly increase with supply current whereas the chopping level of the Toyo Denki always decreases with supply current no matter what the value of parallel capacitance.

[illegible] ot [illegible] of the ringing or oscillation [illegible] current chopping level are shown in [illegible] 3.10 and 3.11.



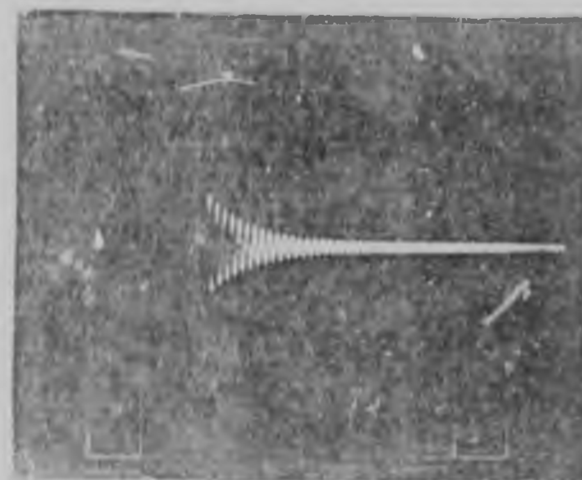
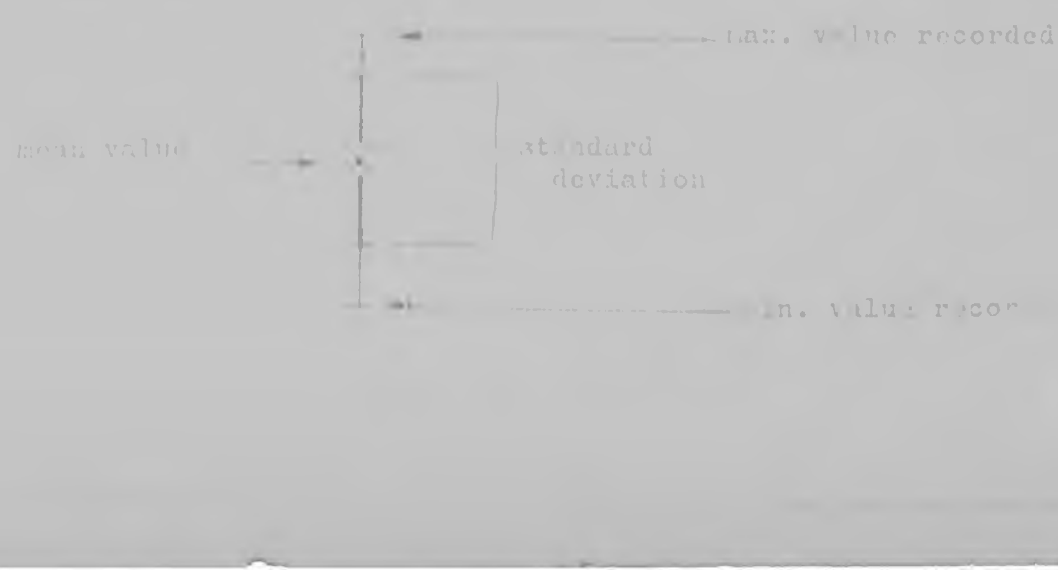


Fig 3.10 [illegible] current chopping [illegible]

Fig 3.11 An expanded view of the oscillation

[illegible] of current chopping in the [illegible] r.m.s. [illegible] parallel [illegible] A. [illegible]

[illegible] .9 the mean, standard deviation [illegible] and minimum values recorded are given as [illegible].



3.4 EFFECT OF VOLTAGE LEVEL

As can be seen from the results in 3.3.2 there is practically no difference in the current chopping level between a 3,3 kV and 6,6 kV vacuum contactor. This can be ascribed to the very low arc voltage of vacuum switches. Paul [34] extensively investigated arc voltages of various elements in vacuum and a graph from his results is reproduced in figure 3.12.

From this it can be seen that the max. arcing voltage he measured was about 23 volts viz. for Mo and W. Thus above 50 volts one would not expect the voltage level of the supply to have any effect on the stability of the currents.

3.5 ARC STABILITY AND IT'S RELATIONSHIP TO CURRENT CHOPPING

3.5.1 TEST CIRCUIT AND DESCRIPTION OF TESTS

This series of tests was conducted at UMIST in Manchester on a GEC type VC3AD400C 6,6 kV/400A vacuum contactor. The circuit diagram is shown in figure 3.13. The vacuum contactor was closed by pushing the close push button. This operated contactor B which closed and caused current to flow in the vacuum contactor closing coils. The vacuum contactor (V.C.) closed and the V.C. N/O auxiliary contact caused voltage to be supplied to contactor C. The vacuum contactor was now ready to be tripped. Initiation of the trip push button caused contactor A to close. This initiated current to flow through the vacuum contactor limited by resistor R and also the timer T to operate. After approx 0,3 sec. the timer operated and caused B to trip out. This tripped the vacuum contactor. The sequence was reset by pushing the

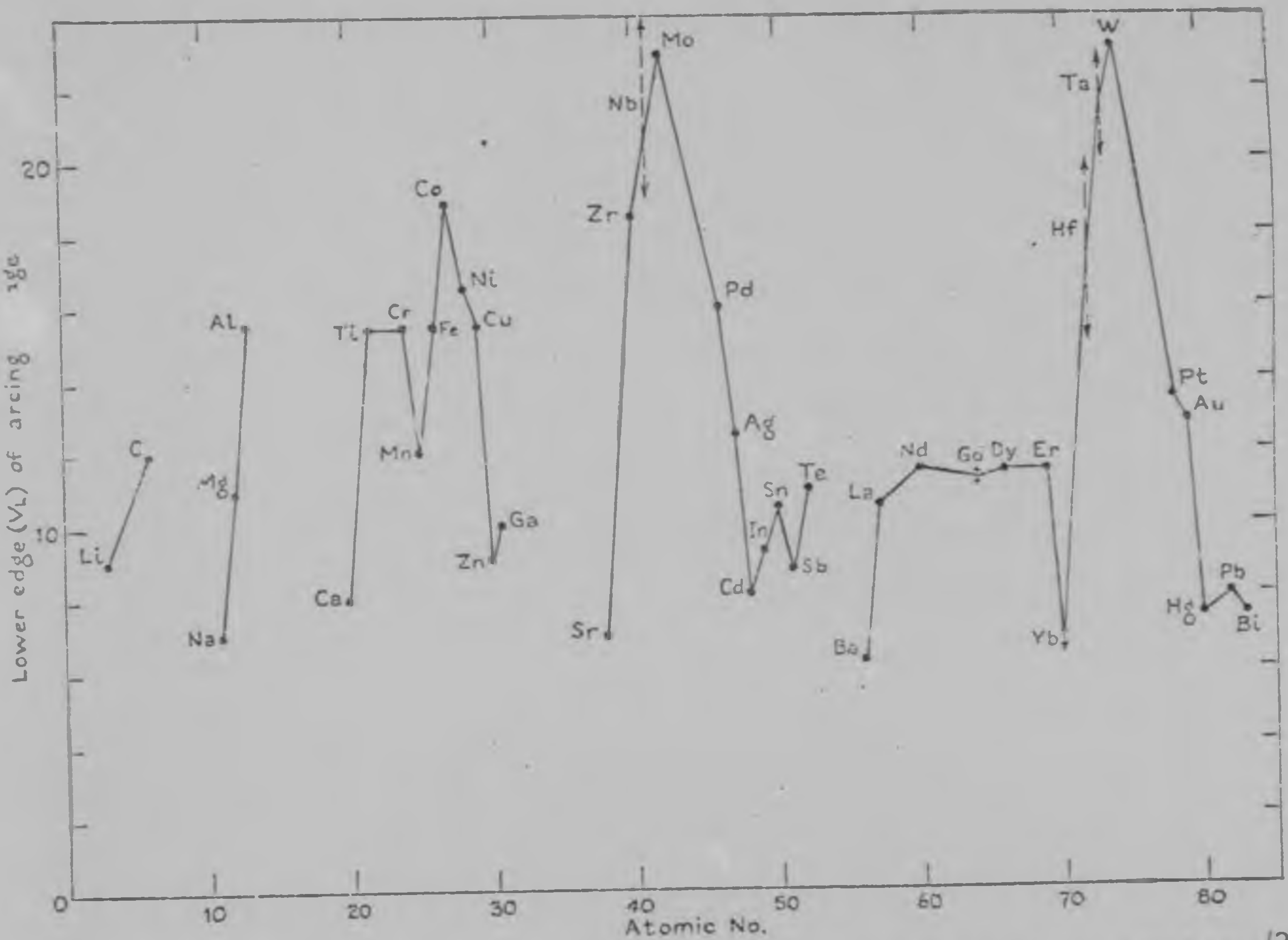


Fig.3.12. Graph of lower edge of arcing voltage against atomic number (ref. Paul[34])

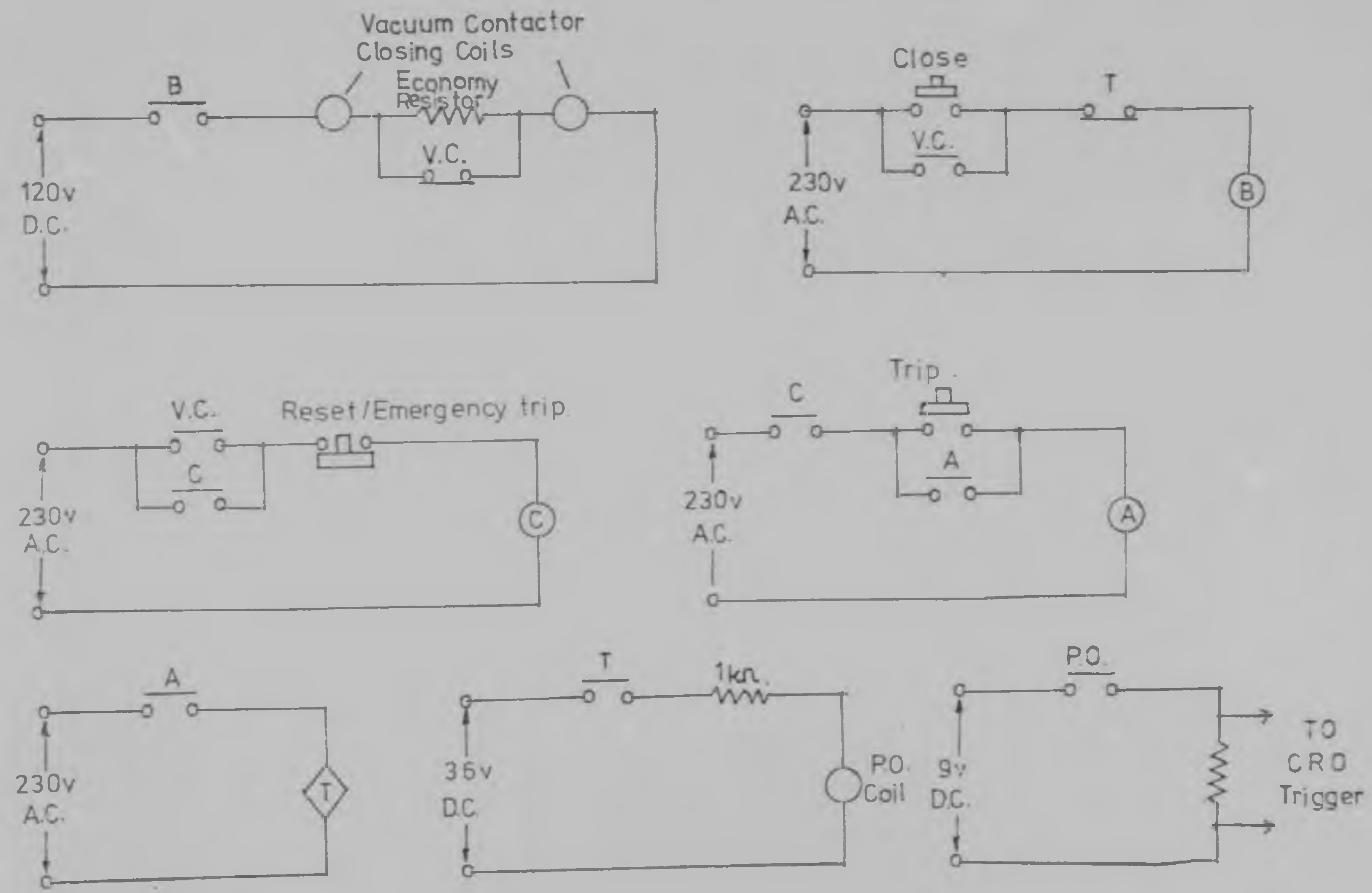


Fig 3.13 Circuit diagram for determing arc stability of 6,6 kV vacuum contactor

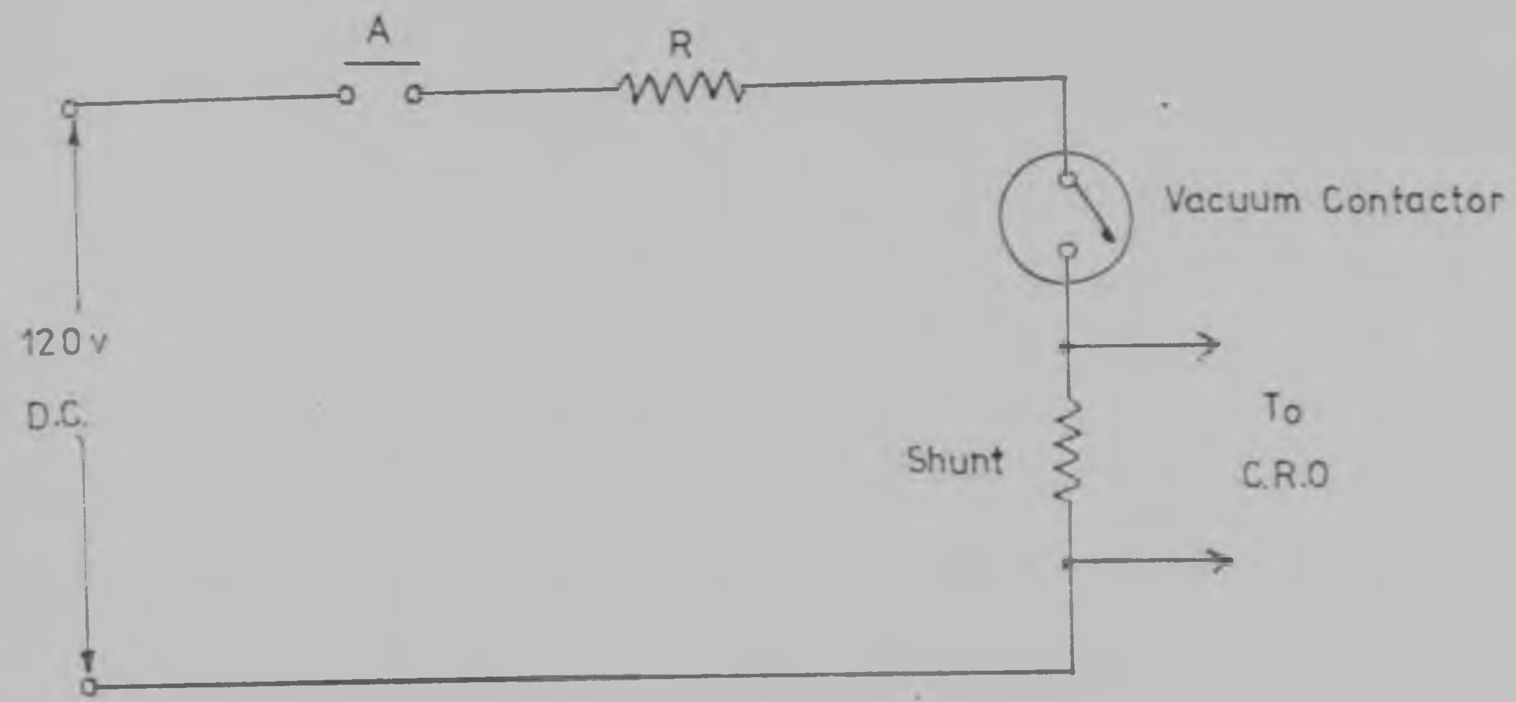


Fig.3.13. Continued. Main circuit.

reset push button which tripped contactor C. This push button could also be used to emergency interrupt the d.c. current in the vacuum contactor by opening contactor A.

3.5.2 RESULTS

Photographs of the arcing times are shown in figure 3.14 and 3.15. Figure 3.16 shows the full results over the range of current 0,2 to 1,0 amp.

In a three phase circuit operating at 50 Hz, a natural current zero will occur every 3,3 msec. on each of the phases in turn. Thus when a switch opens on a three phase circuit, the longest duration of arcing that will occur before the first current zero appears on a phase, is 3,3 msec. Usually with a vacuum switch, the first current zero is the first phase to clear. The remaining two phases then pull into step and are interrupted simultaneously 5 msec. later. If the a.c. current can be considered as a series of instantaneous d.c. currents, each value of current having a certain arc duration, it can be seen that for the first phase to clear, a d.c. current with an arc duration of longer than 3,3 msec., should arc longer than the time till a natural current zero. It should not therefore chop at that value of current. Thus the arc duration interval of 3,3 msec. might be used as a guide to determine current chopping levels. Using this guide, from figure 3.16 it can be seen that the minimum and maximum levels of chopping current are approx. 0,28A and 0,68A respectively when no parallel capacitance is present. The average value is 0,32A approx.

Figure 3.17 shows the probability of the arc duration being less than 3,3 msec. Taking the 50% probability value a magnitude of 0,37A is arrived at as the "average current chopping level".

The results show that current chopping is directly related

100 msec.

Fig. 3.14. Photos of arcing duration of 0,5 amps. d.c.

10 msec.

Fig. 3.15. Photos of arcing duration of 0,3 amps. d.c.

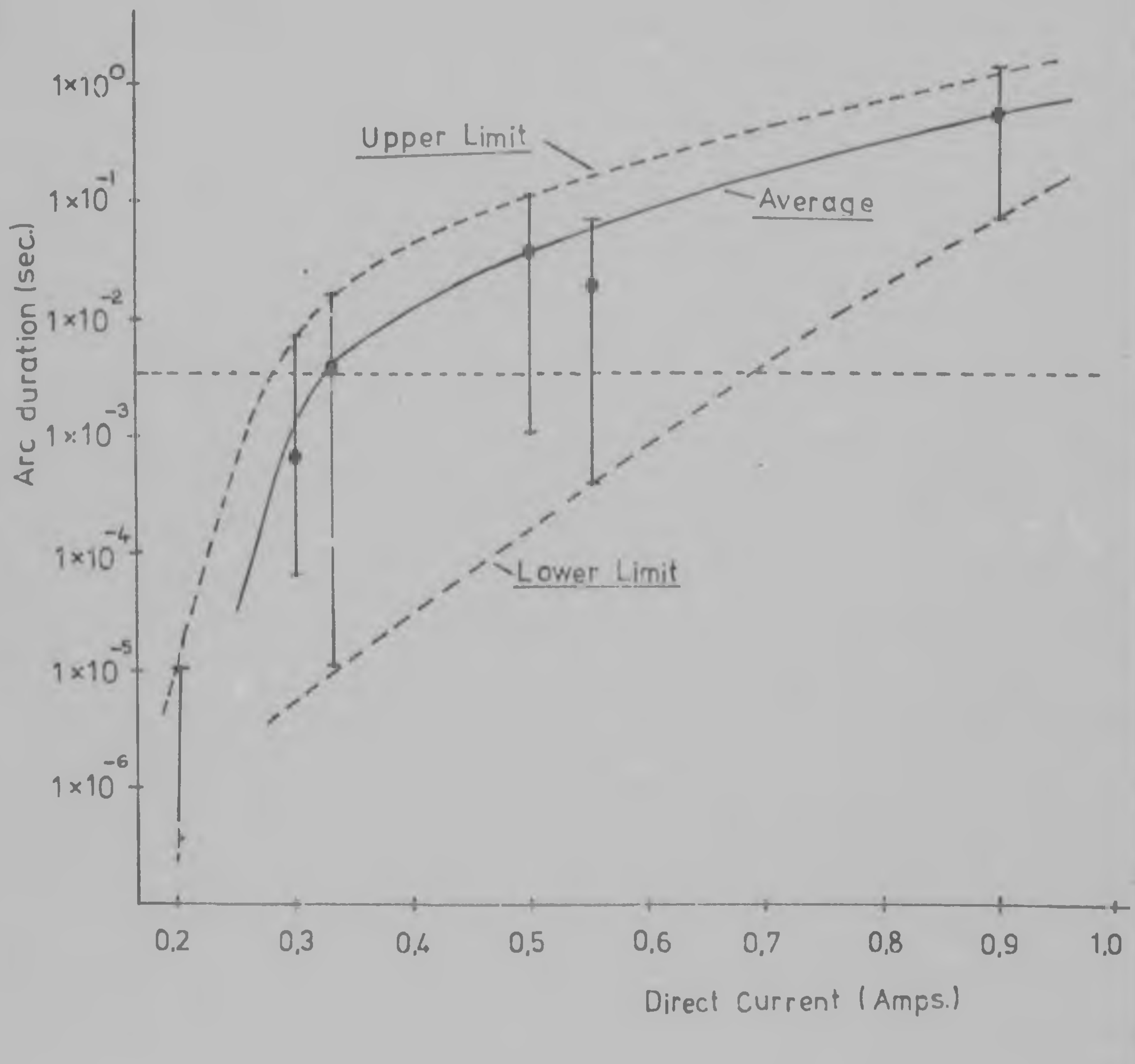


Fig.3.16 Arc duration of GEC 6.6kV vacuum contactor

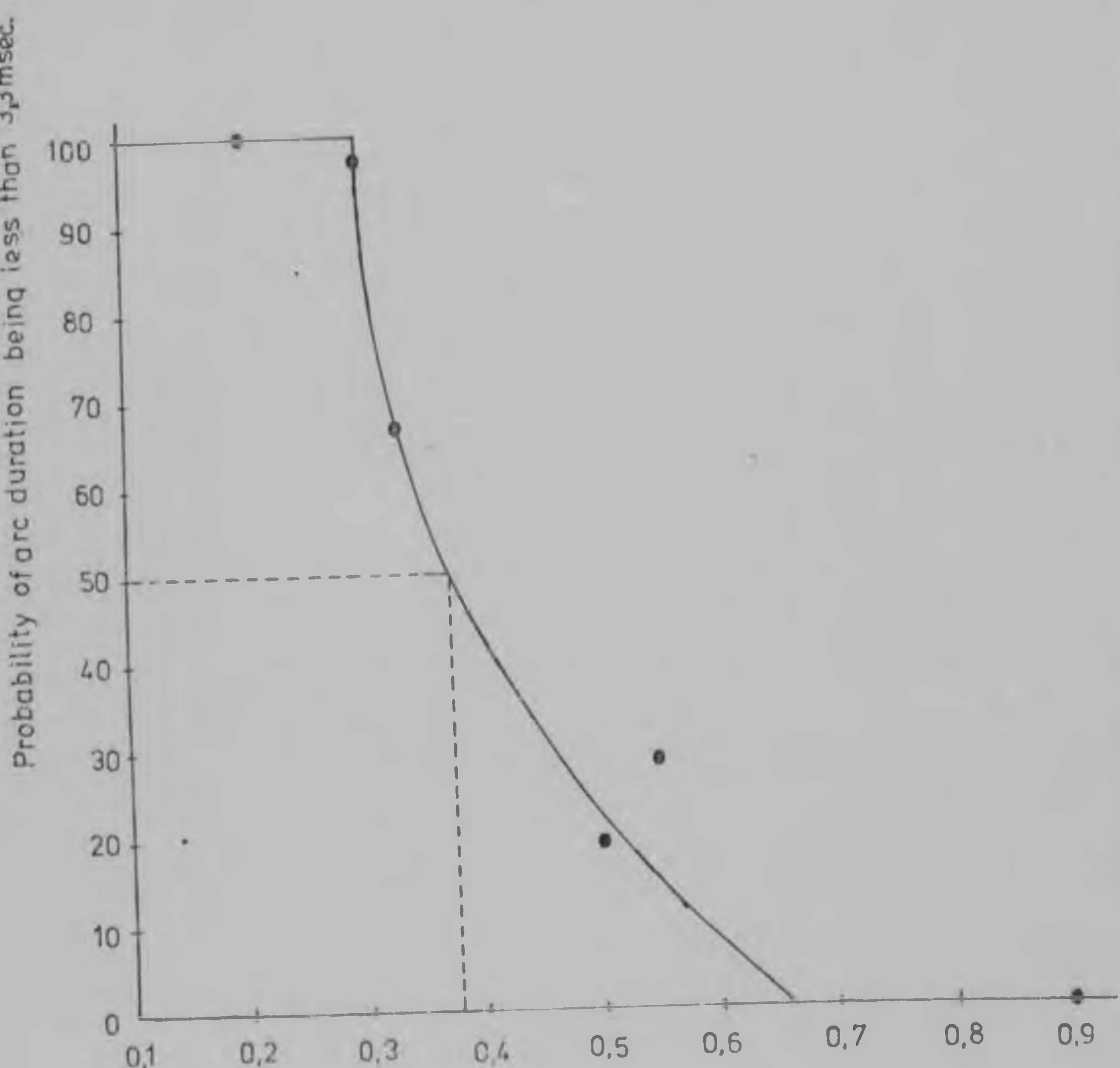


Fig.3.17. Probability of arc duration being less than 3,3 msec.

to d.c. arc stability i.e. the shorter the d.c. arcing time for a given contact material, the higher the current chopping level is likely to be. Comparison with other vacuum interrupters[25] shows that for 5A d.c., the arcing time for antimony-bismuth (GEC contactor) is an average of 2 secs., for CLR (the proprietary material of V.I.L.) it is 1 msec. and for copper-bismuth (GE's interrupter) it is 0,1 msec. This agrees with the known chopping levels of these interrupters.

Using the 3,3 msec. technique, the average value of current chopping is determined to be 0,32A by one method and 0,37A by the second method. Tests results from 3.3.2 show that for the lowest value of parallel capacitance the current chopping level varied from 0,36 to 0,43A for values of supply current from 100A down to 5A. There is therefore a very close relationship between the two methods used i.e. arc stability and actual current chopping measurements.

The arcing duration and also the current chopping, are random. However, the limits derived in this set of tests yield a band between 0,28A and 0,68A as the values of current that will be chopped using the GEC contactor without any external parallel capacitance.

3.6 THEORY OF OVERVOLTAGES DUE TO CURRENT CHOPPING

The subject of chopping overvoltages has been covered by Lee[36] and Greenwood[37] and more recently by Damstra[38] and Tuohy[23].

Consider figure 3.18, a generalised single phase representation of a circuit containing load-side capacitance C, inductance L and resistance R. When the current I through the switch is chopped, the current I_L through the inductance continues to flow by circulating in the capacitance. The voltage across the load oscillates at a frequency determined by the magnitudes of L and C. This oscillation will be damped due to the losses or resistance present in the circuit. However, for simplicity first consider

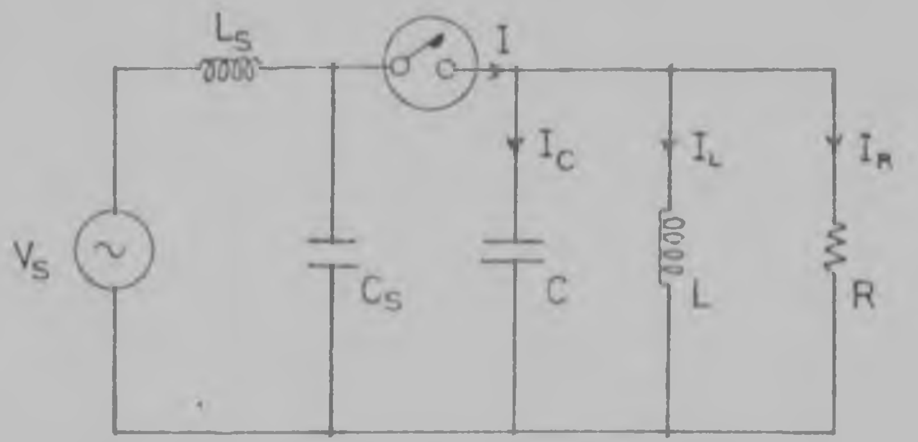


Fig.3.18. Simplified equivalent circuit for current chopping.

the case of a circuit with no losses. If the load current I is inductive i.e. lagging power factor, the voltage induced in the inductance by the current chop opposes this change in current. The first half-cycle of the oscillation is therefore added to the supply voltage as shown in figure 3.19.

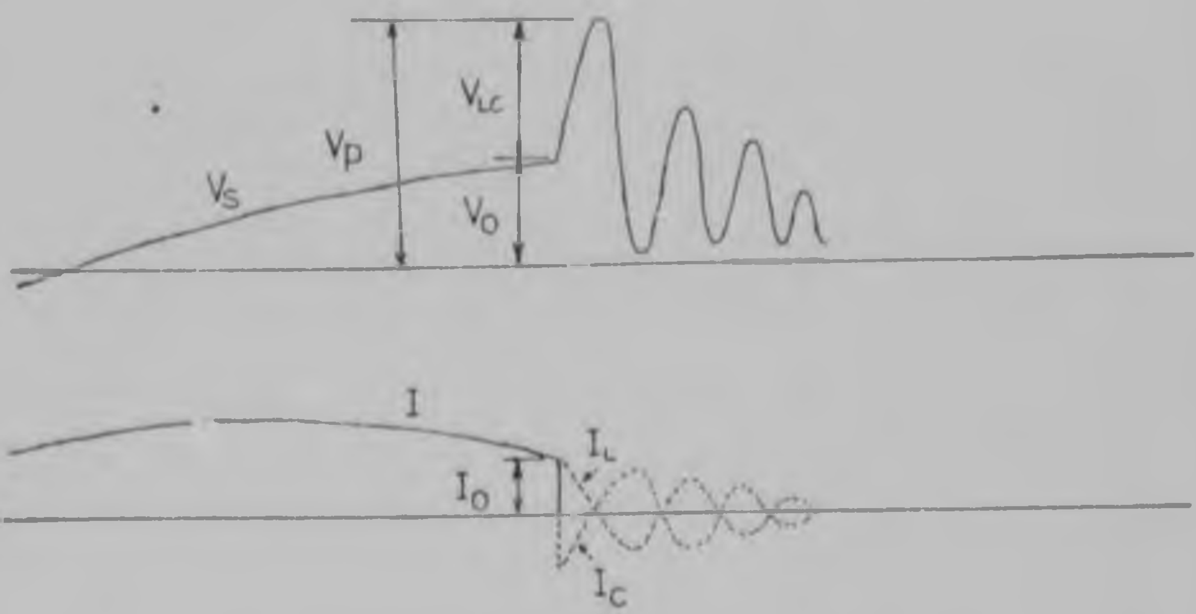


Fig 3.19. Current and voltage associated with current chopping

Energy stored in capacitor just before interruption = $\frac{1}{2}CV_o^2$

Energy released from the inductance by the current chop = $\frac{1}{2}LI_o^2$

Energy in capacitor after current chop = $\frac{1}{2}CV_p^2$

Equating energy before and after current chop and neglecting losses,

$$\frac{1}{2}CV_p^2 = \frac{1}{2}CV_o^2 + \frac{1}{2}LI_o^2 \qquad \text{... (1)}$$

This gives the maximum transient voltage peak V_p across the load as,

$$V_p = \sqrt{V_o^2 + I_o^2\,(L/C)} \qquad \text{... (2)}$$

Thus the added overvoltage generated by the energy trapped in the circuit when current chopping occurs is,

$$V_{LC} = I_o\sqrt{L/C} \qquad \text{... (3)}$$

where I_o is the current chopped and $\sqrt{L/C}$ is known as the surge impedance of the load. The voltage across the load, from the time of current chopping is described by,

$$V = I_o\sqrt{L/C}\ \sin\omega_o t + V_o\cos\omega t \qquad \text{... (4)}$$

where V_o is the voltage across the load at the instant of current chopping and $\omega_o = \sqrt{1/LC}$, and $\omega = 2\pi \times$ power frequency.

If losses are considered eqn. (4) is modified by a damping term and becomes,

$$V = e^{-\frac{t}{2RC}}\,(I_o\sqrt{L/C}\ \sin\omega_o t + V_o\cos\omega t) \qquad \text{... (5)}$$

where ω_o now becomes, $\sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}}$.

The overvoltage generated by current chopping is thus shown to be a function of the current chopped and the surge impedance and damping of the circuit.

3.7 ACTUAL [illegible] ON A MOTOR

The test circuit of figure 3.20 was used. These were 3 phase tests at 6,6 kV using a 6,6 kV GEC vacuum contactor, 18 and 90 meters of 6,6 kV P.I.L.C. (paper insulated, lead-covered) cable, and a [illegible] kV, 200 kW motor supplied by GEC Machines. Thirty μF capacitors were connected on the supply side on each phase between line and neutral (neutral earthed) to simulate connected cables and power factor correction capacitors. The monitoring equipment used consisted of two digital storage oscilloscopes (Gould Advance OS4000), two Tektronix 556 oscilloscopes, and a 7 channel tape recorder (Philips Analog 7).

Nineteen switch-offs at full speed on no-load with 18m. of [illegible] were recorded. As all three phases were monitored this yielded 52 transients. The average maximum voltage swing was 0,5 p.u. (1 p.u. = [illegible],4 kV) with a maximum of 1,0 p.u. A typical switch-off showing current chopping is shown in figure 3.21 and the histogram in figure 3.22. The frequency of oscillation was constant and approximately 10 kHz.

The values of surge impedance for induction machines varies widely and cannot be generalised in terms of machine rating although there is a tendency for values of surge impedance to be higher for smaller machines. From collated manufactures' specifications and other published information (14) it appears that values of surge impedance of between 1 and 3 kohms are common. The value of the surge impedance of the motor used was not available but the surge impedance for a similar 6.6 kV 2[illegible]5 kW motor was measured to be 2 193 ohms. Therefore, assuming the surge impedance of the 200 kW motor to be of the order of 2 200 ohms, the ave[illegible] chopping current of the GEC contactor is calculated to be 0,61 amps. (approx.) with a max. of 1,22 amps., using the results from figure 3.22 and equation (3) on page 39.

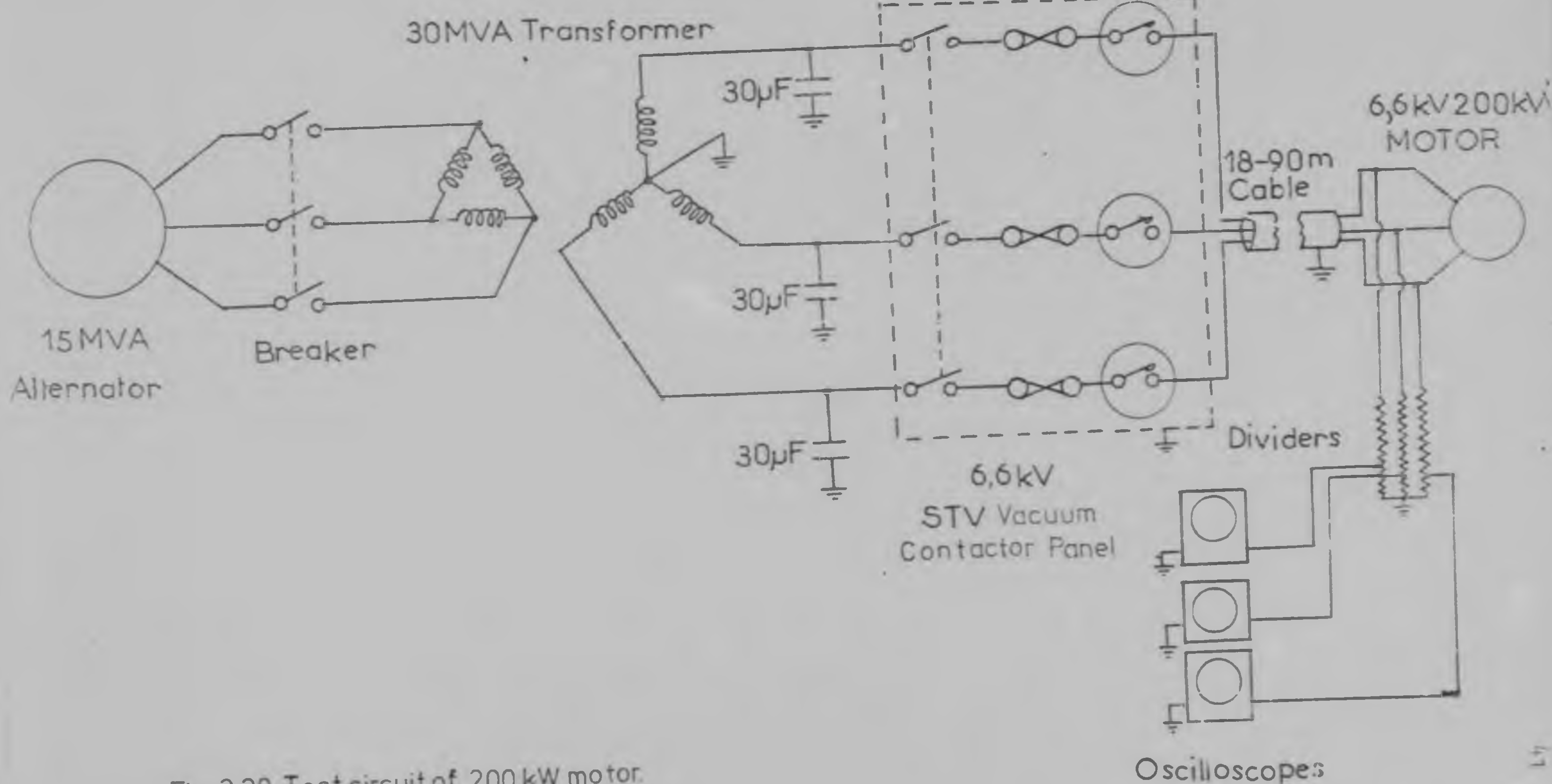


Fig. 3.20. Test circuit of 200 kW motor.

Trace polarity reversed

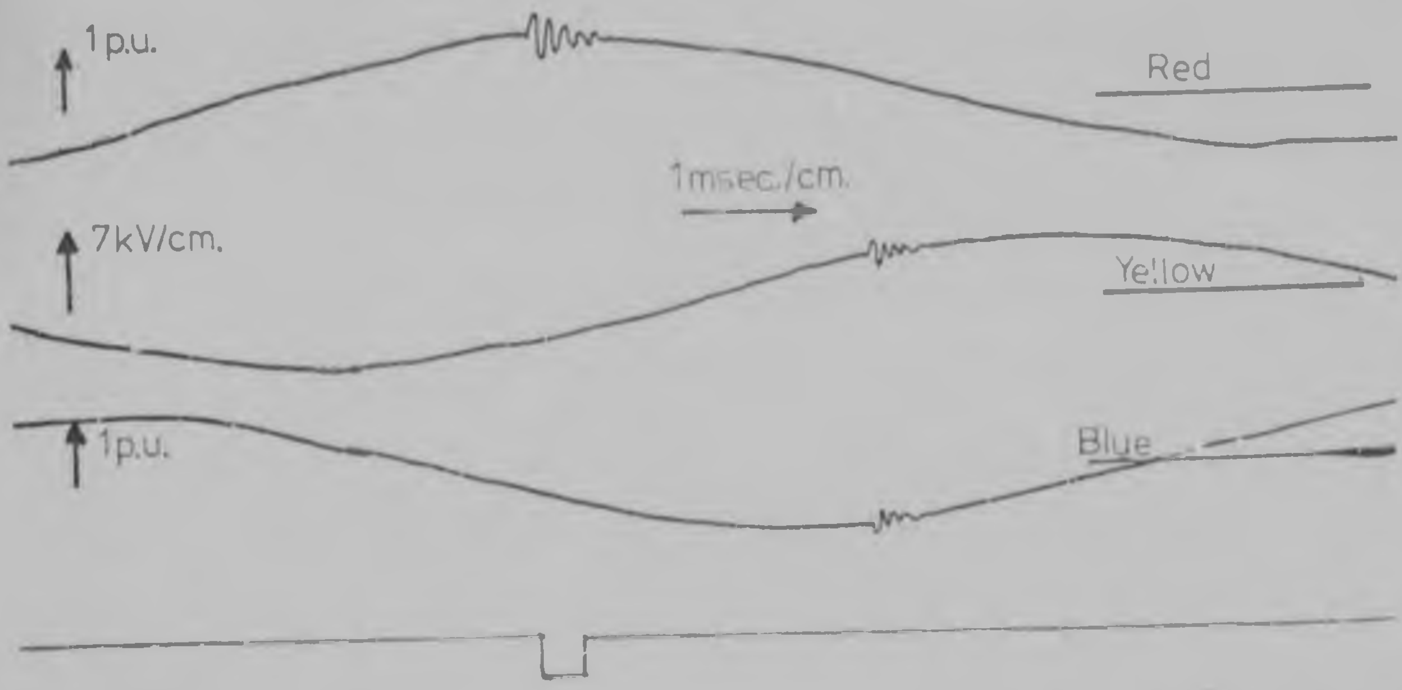
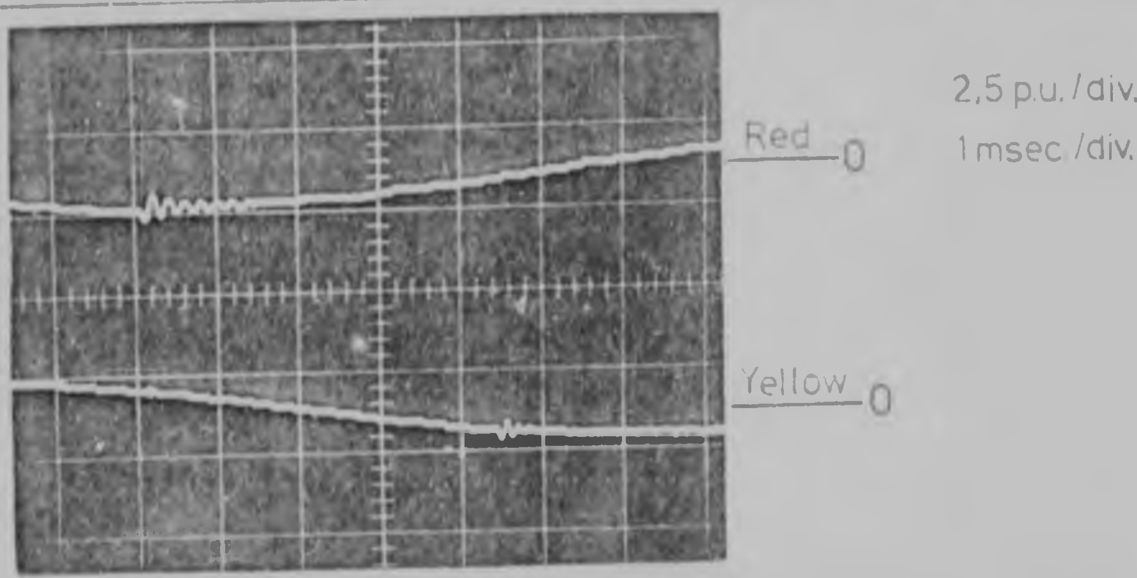
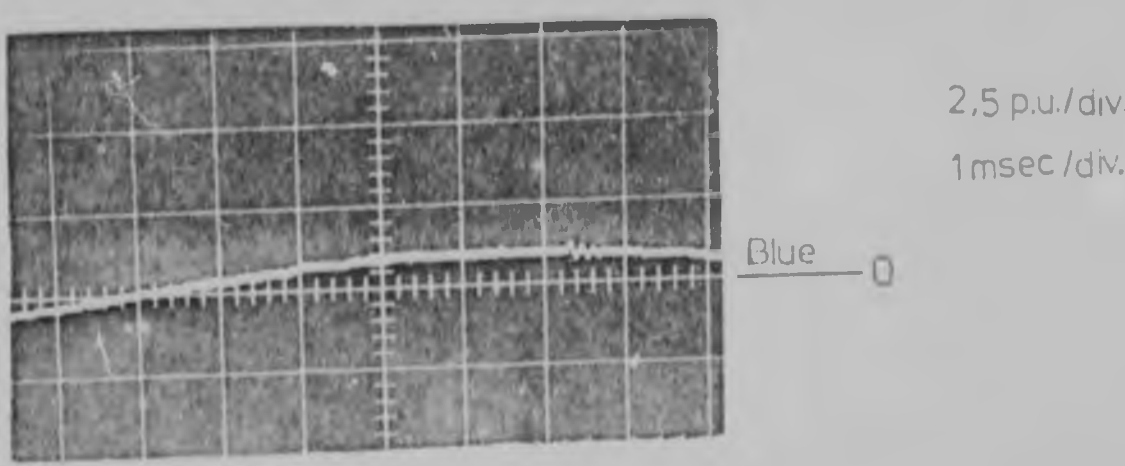


Fig.3.21. Current chopping transients when switching off an induction motor





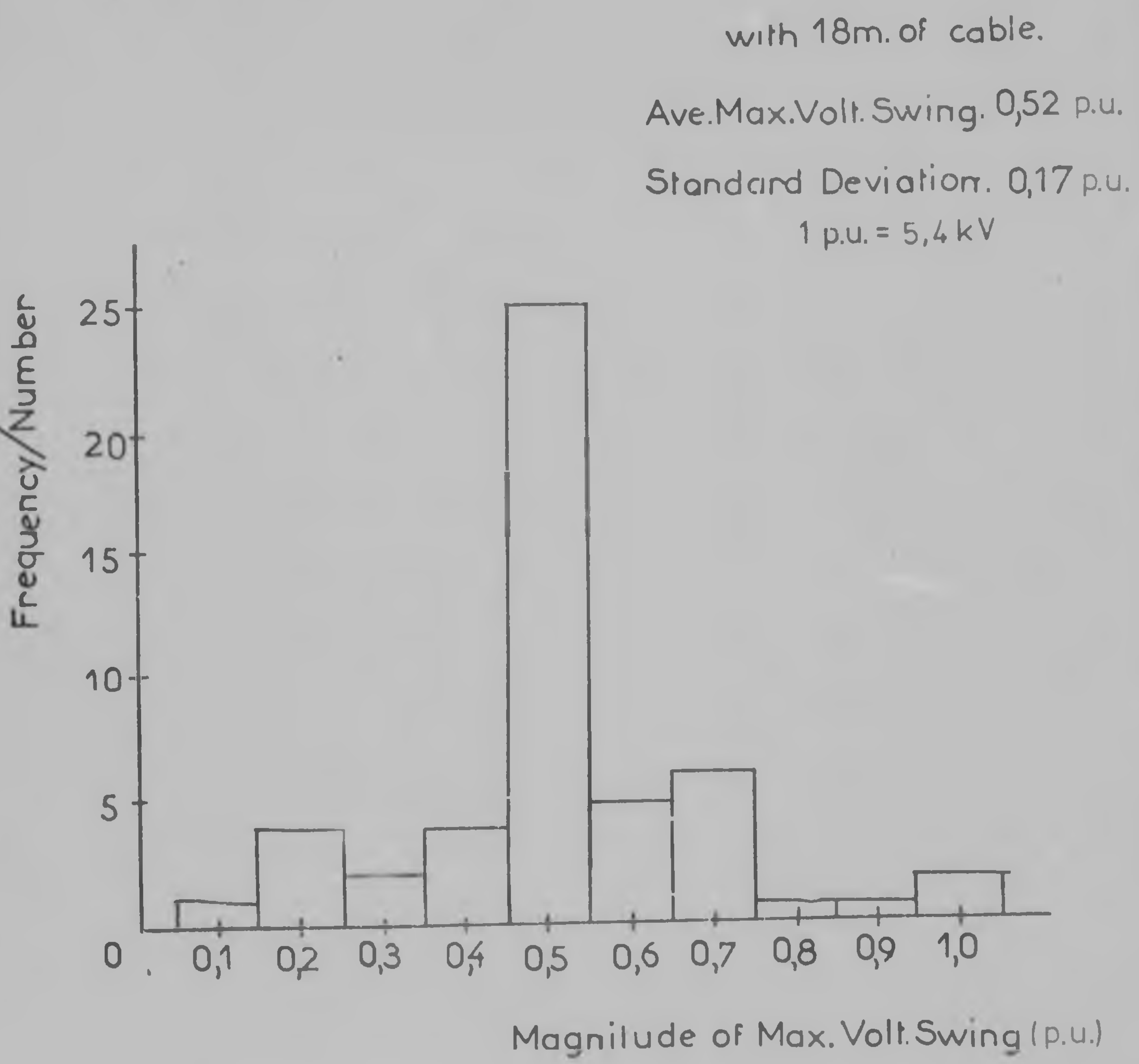


Fig.3.22. Probability of switch-off (full speed) max. voltage swings.

The magnitudes of the current chopping transient with 90m. of cable were very similar to that of the 18m. of cable except that the frequency of oscillation was observed to drop to 3,5 kHz (approx.).

3.8 COMPARISON BETWEEN THEORY AND RESULTS

Graphs of capacitance and inductance of various cable sizes are shown in figure 3.23. These were translated from Konorski[39]. From this it can be seen that the capacitance of 6,6 kV cable, (35 mm^2) is approx. 0,25 μF/km. Therefore the capacitance of 18m. of cable is approx. 0,0045 μF. The cable capacitance as well as that of the 30 μF capacitors are both between line and earth. They are thus effectively in series across the vacuum contactors. Therefore the total parallel capacitance in the motor tests with 18m. of cable was approx. 0,0045 uF. From 3.3.2 the average current chopping level should therefore be approx. 0,45 amps. (considering the 5A curves) with a max. of 0,68 amps.

With 90m. of cable, the parallel capacitance should be approx. 0,0225 μF giving an average current chopping level of approx. 0,70 amps. and a max. of 0,90 amps.

The calculations from the actual overvoltages of 0,61 amps. average and max. 1,22 amps. are thus in quite good agreement, and shows that calculation can give approx. the correct values.

The frequency of the current chopping transient is given by,

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

With 18m. of cable C= 0,0045 μF and the motor's inductance was calculated to be L = 86 mH. This yields a frequency of 8 kHz. approx. compared with the measured 10 kHz. For the 90 m. of cable the calculated figure is 3,6 kHz and the measured frequency 3,5 kHz. Again the correlation is very good.

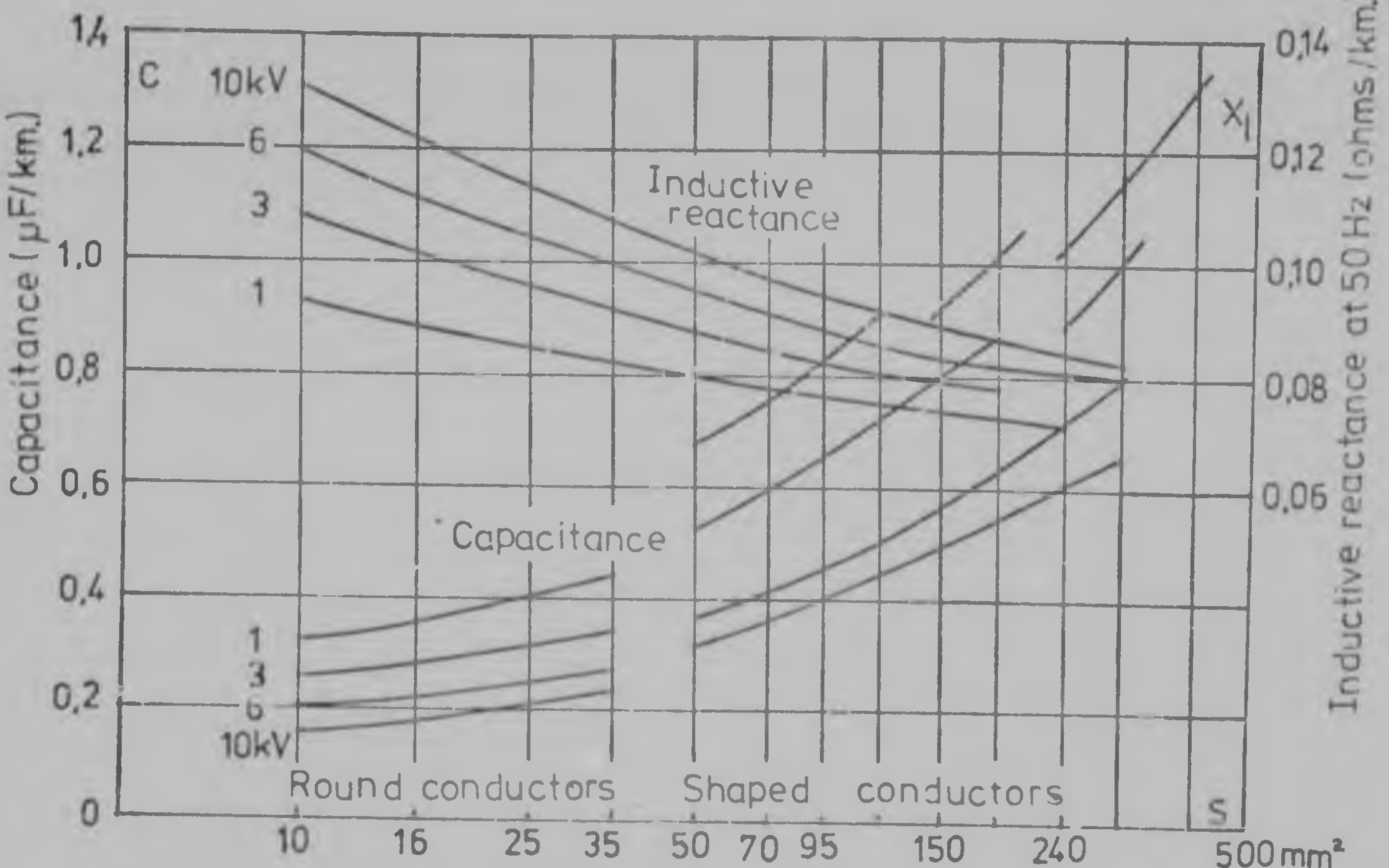
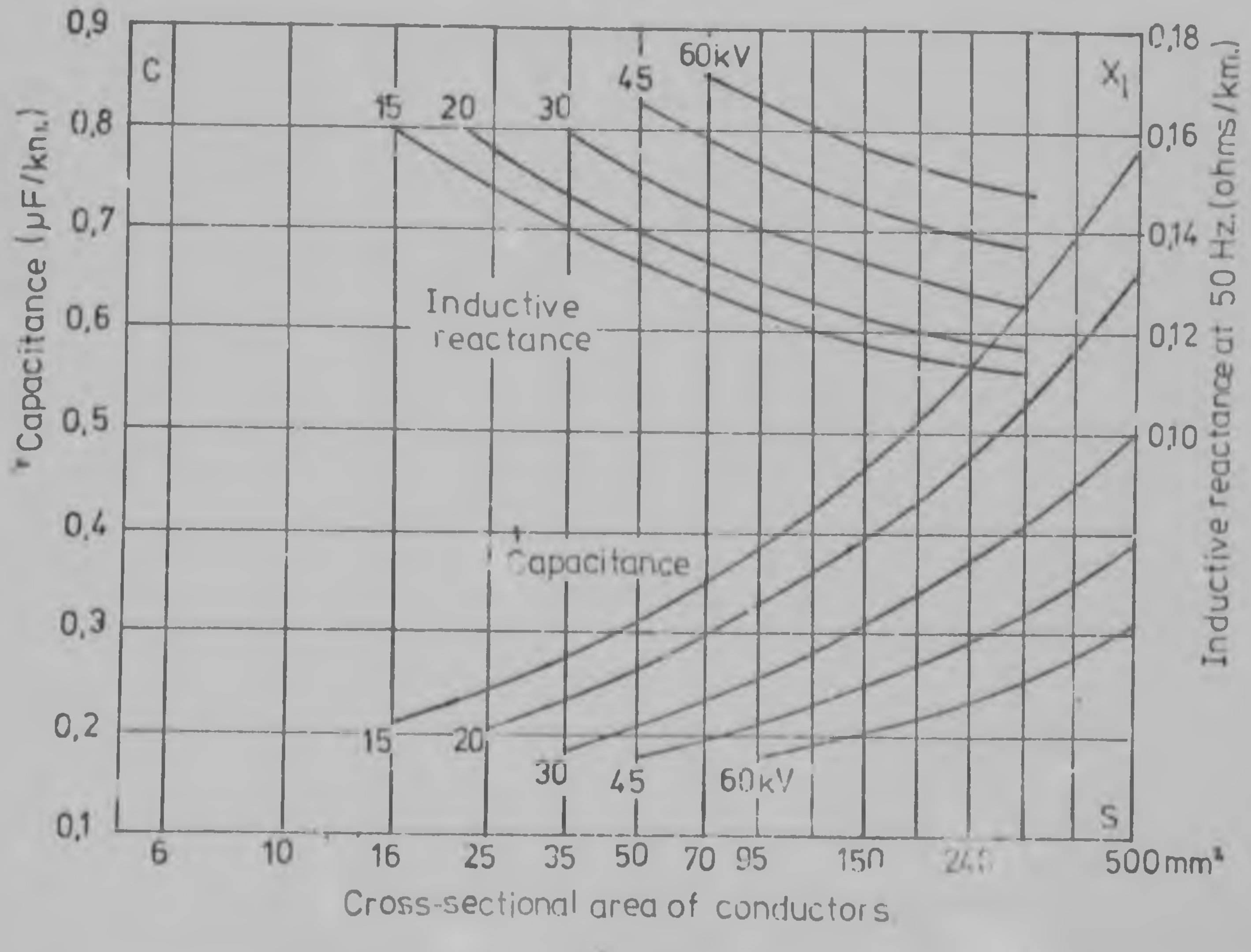


Fig.3.23. Capacitance and inductive reactance of three phase paper insulated cables.



3.9 VIRTUAL CURRENT CHOPPING

This has been reported and discussed in various papers (19, 21). This phenomena can be explained as follows: The first interrupting phase produces multiple reignition which causes transient current to flow and high frequency current is induced in the other phases by mutual coupling of the three phase circuit. As a result, this high-frequency current is superimposed on it's interruption current to produce a current zero.In the paper by Murano et al (19), they say "The smaller the current chopping value of the contact material of the vacuum switch, the smaller the high frequency arc extinguishing capability, and the more difficult the occurance of the three-phase simultaneous interruption becomes".

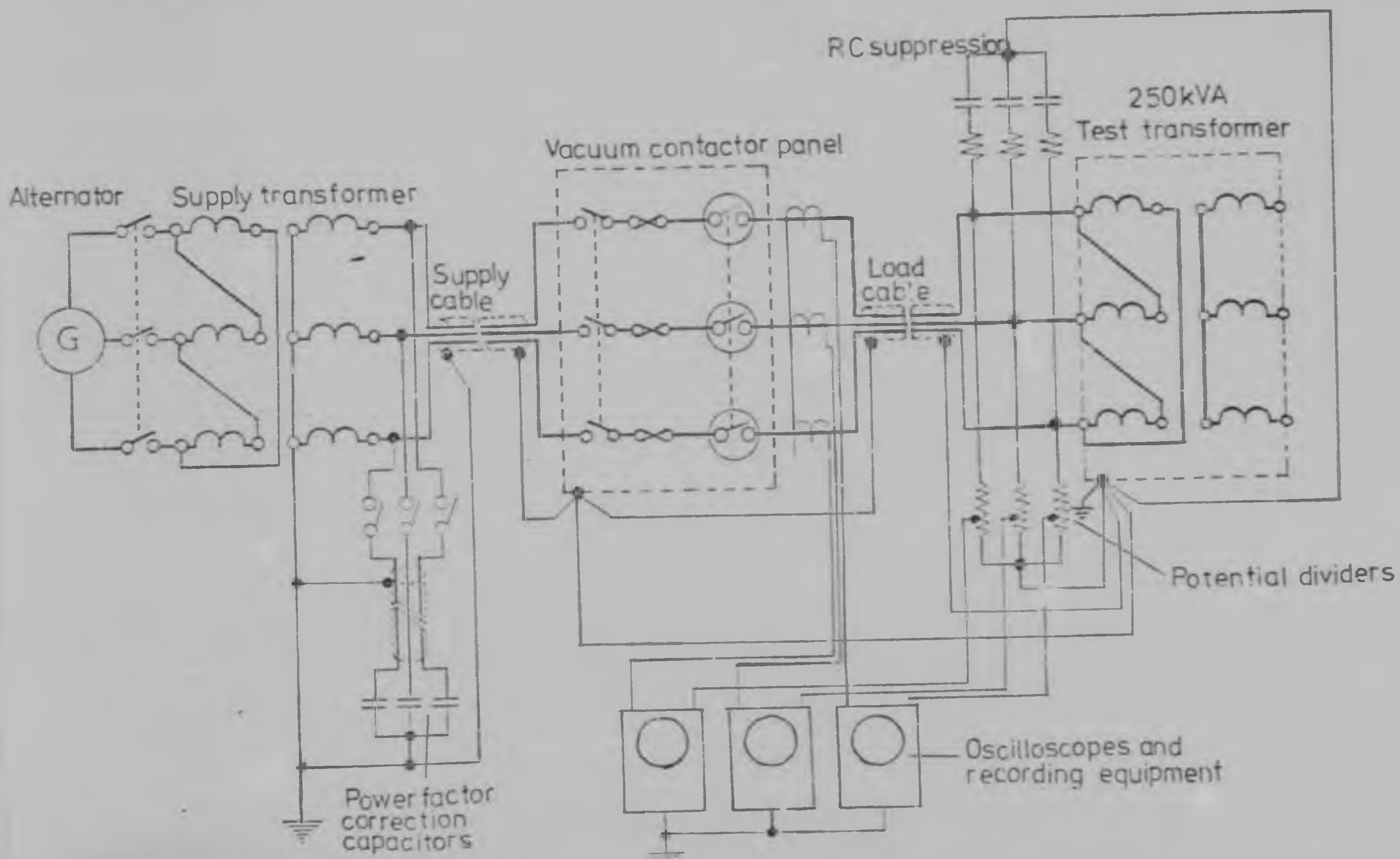
The experiments done on the motor tend to bear this out since no virtual current chopping was observed during all the tests done, when using the low current chopping GEC contactor.

Tests are described in 3.10 switching a small distribution transformer. Here the no load magnetising current of the transformer was comparable with the current chopping level of the contactor and switch-off three-phase simaltaneous interruption was very much in evidence.

3.10 TESTS ON A TRANSFORMER

The test circuit is shown in figure 3.24 and it's equivalent single phase diagram is given in figure 3.25 showing actual circuit values. The cable parameters are strictly distributed values but have been shown as lumped values for simplicity. The transformer used in the tests had a magnetising current of only 0,27 amps., which was below the normal current chopping level of the contactor.

Fig.3.24. Circuit for switching tests on 250 kVA transformer.



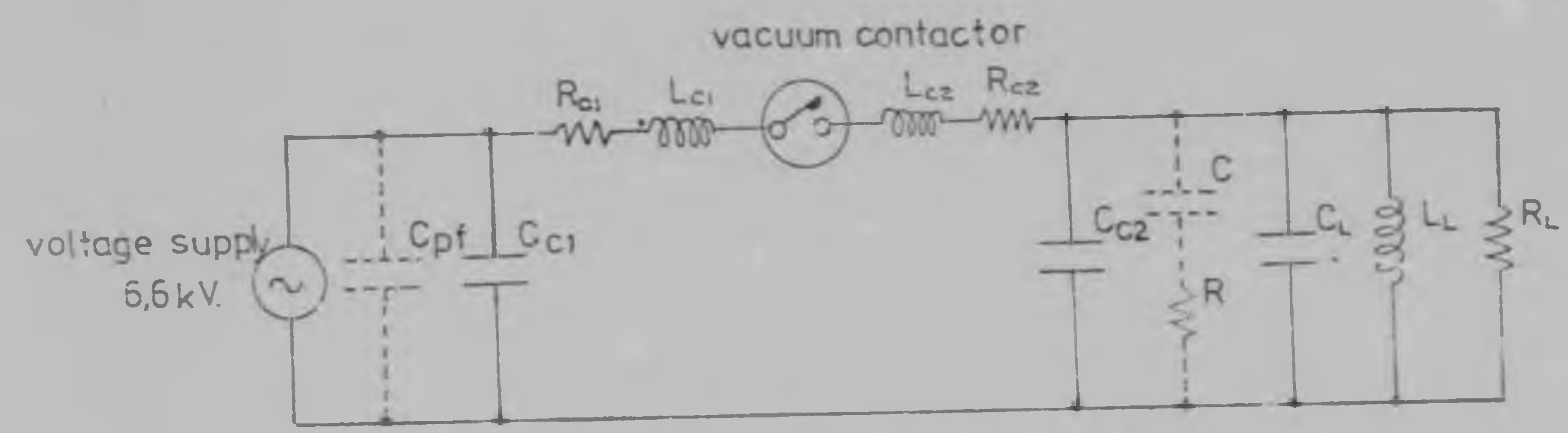


Fig. 3.25 Equivalent single phase diagram of test circuit.

C_{pf}	= Power factor correction capacitance	= 17µF
R_{C1}	= Resistance of Cable 1	= 0,009 ohms
L_{C1}	= Inductance of Cable 1	= 6.30 µH
C_{C1}	= Capacitance of Cable 1	= 4680pF
R_{C2}	= Resistance of Cable 2	= 0,046 ohms
L_{C2}	= Inductance of Cable 2	= 31,5 µF
C_{C2}	= Capacitance of Cable 2	= 23400pF
C_L	= HV to earth capacitance of Transformer	= 1728pF
L_L	= Magnetising inductance of Transformer	= 168H
R_L	= Equivalent iron loss resistance of Transformer	= 220 ohms

C = 0,3uF } CR Suppressor
R = 75 ohms }

Two lengths of cable were used in the tests, 18 and 90m. The vacuum contactor was a 6,6 kV GEC type VC3AD400C7 rated at 400 amps. The power factor correction capacitors and CR suppressor were connected to the circuit to examine their effect on the transients.

The results are further discussed in 4.6.2, 5.5.2 and 6.1.4 Of interest here is only the fact that three-phase simultaneous interruption occured. A typical switch-off restrike transient is shown in figure 3.26. Also monitored were the high frequency currents. The largest transients obtained were with the power factor correction capacitors connected to the supply, RC surge suppressor disconnected, short cable between transformer and contactor panel and no supply cable i.e. the supply was connected to the contactor by short, direct, single core cables.

Twelve switch-off operations were performed and for each operation measurements were made of maximum overvoltage, maximum voltage swing, number of strikes and duration of transient. Graphs of the results are shown in figure 3.27. The maximum overvoltage was 2,00 p.u. which shows that three-phase simultaneous interruption does not necessarily mean that very high overvoltage should occur. It should however be pointed out that the case where the current being interrupted is of the order of magnitude of the current chopping level is not the same as when the current is higher and is forced to zero by three-phase coupling of the circuit.

3.11 CONCLUSIONS AND DISCUSSION

It has been shown that the current chopping level of a vacuum contactor depends strongly on the contact material. Similar tests

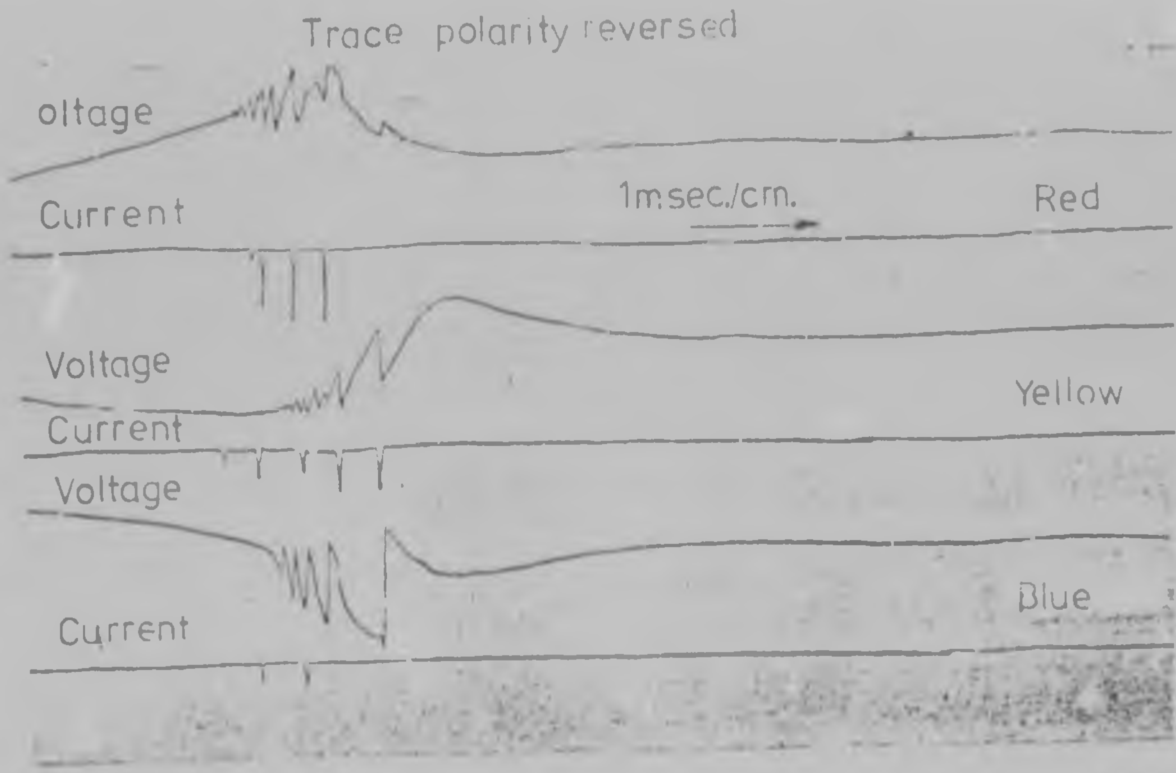
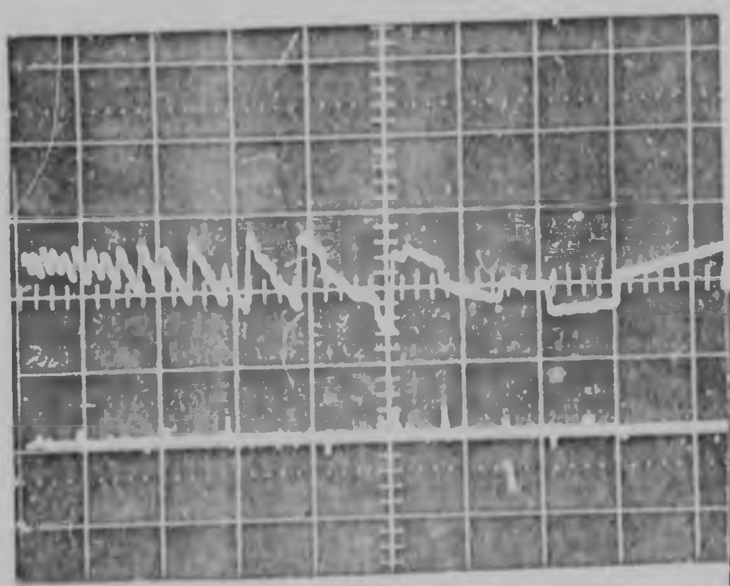
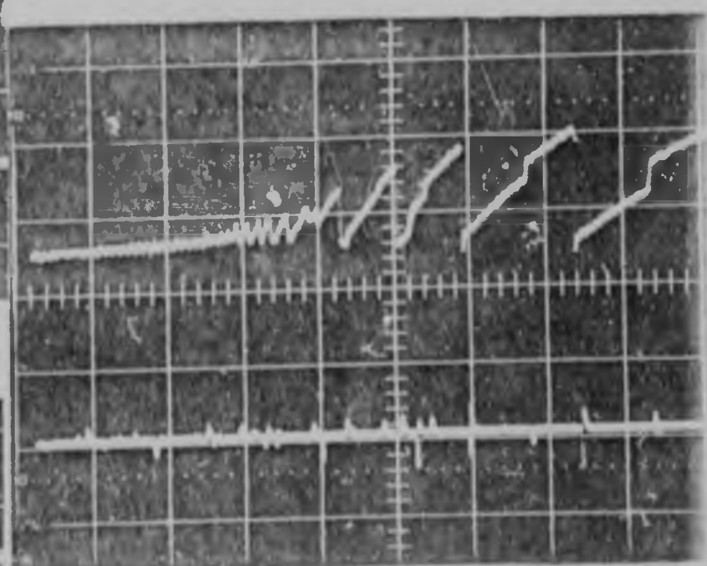


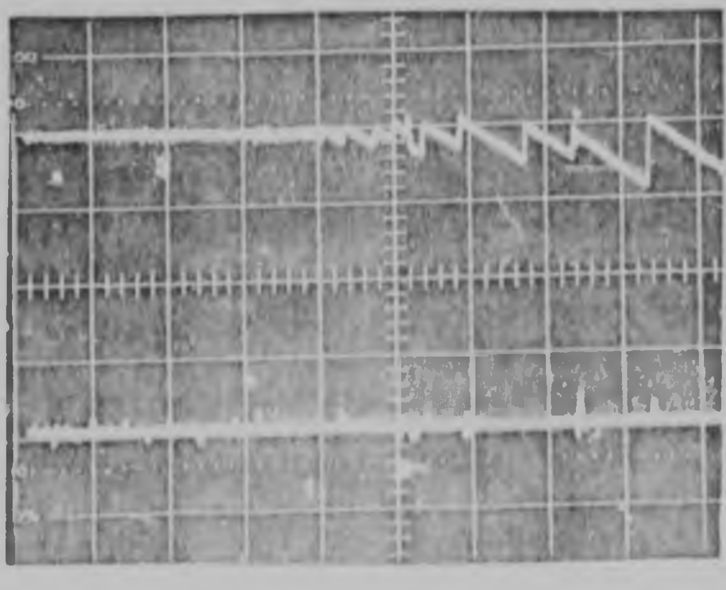
Fig.3.26. Switch-off three phase simultaneous interruption



Red phase



Blue phase



Yellow phase

Voltage: 1 p.u./div. (Top trace)

Current: 50 A./div. (Bottom trace)

Time: 200 μsec./div.

	Switch OFF
Max. overvoltage recorded (p.u. peak)	2,00
Average max. overvoltage (p.u. peak)	1,38
Standard deviation (p.u. peak)	0,28
Max. voltage swing recorded (p.u.peak-peak)	2,20
Average max. voltage swing(p.u. peak-peak)	1,35
Standard deviation (p.u. peak-peak)	0,49
Max. number of strikes recorded	8,00
Average number of strikes	3,89
Standard deviation	2,26
Max. duration of transient (ms)	4,69
Average duration of transient (ms)	3,12
Standard deviation (ms)	0,69

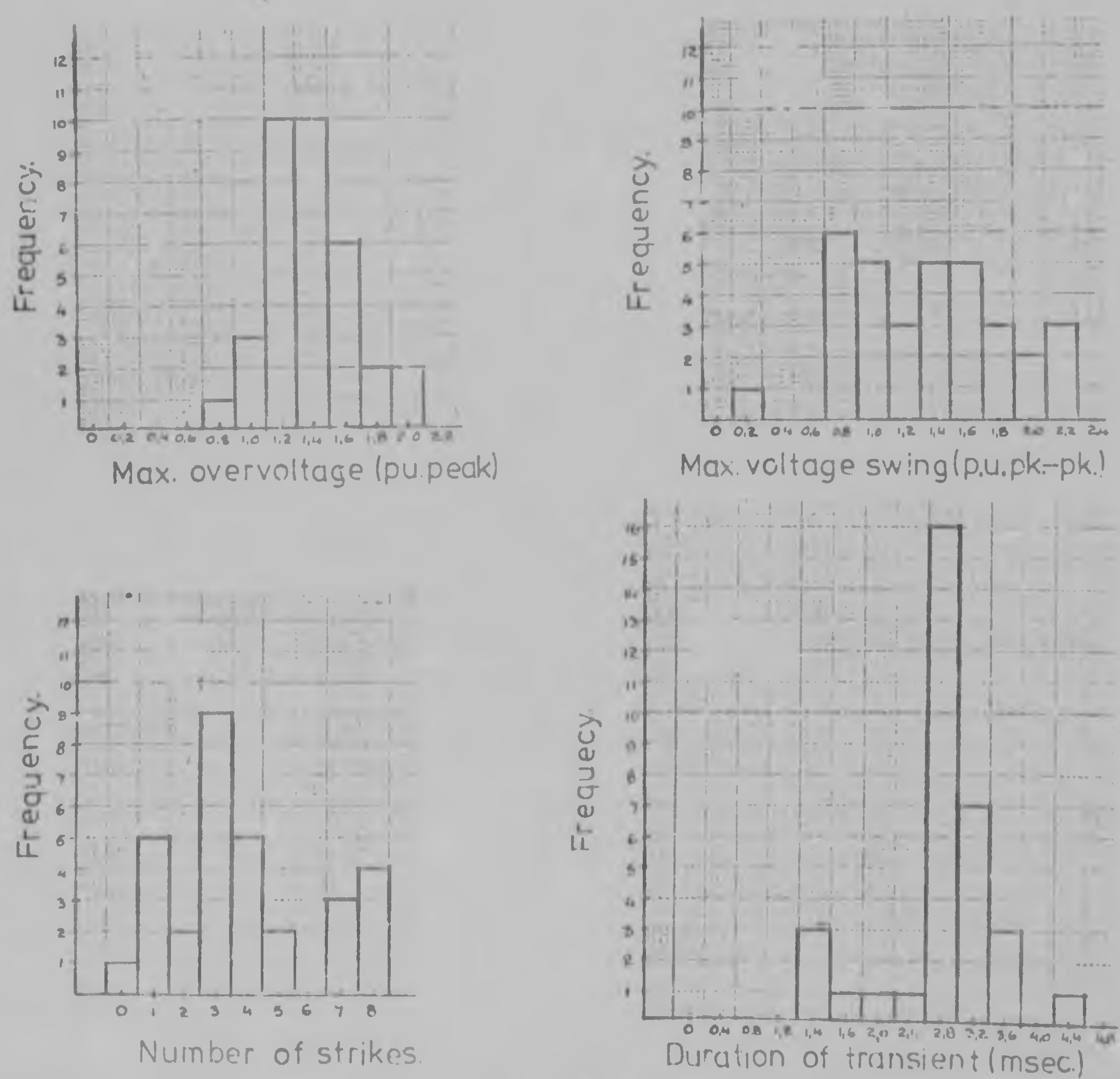


Fig 3.27. Results of transformer switch-off tests.

were conducted under the same external circuit conditions on two different contact materials namely the GEC with it's antimony-based filler-alloy reservoir in annular grooves in molybdenum contacts, and the Toyo Denki with contacts consisting of a sintered tungsten matrix into which a copper alloy and antimony are infiltrated. It can thus safely be said that the five to one ratio of chopping level (Toyo Denki/GEC) is solely due to the thermo-physical properties of the contact materials concerned. In other words, the more stable the arc is (as with the GEC contacts), the lower is it's chopping level and vice versa (as in the case of the Toyo Denki contacts). This is in agreement with the works of Ismail [illegible] and Burrage and Guertin [40]. The latter made current chopping measurements on various contact materials, whilst the former compared two vacuum interrupters viz. VILs and [illegible].

It was also found that the average chopping level increases with shunt capacitance. This agrees with the results of other workers [25, 41, 42, 43].

The effect is due to a drop of arc stability by the added shunt capacitance which reduces the arc voltage fluctuations that are necessary to keep the unstable arc burning. According to Kesaev [42], single or small groups of voltage pulses exist at cathode spots. Their amplitude and rate of rise dv/dt will be lowered by shunt capacitance and there will be a drop of arc restoring ability. Consequently the arc stability is reduced and the chopping level is raised.

It has been found by others [41, 44] that higher values of [illegible] results in smaller current chopping levels. This was found to be the case with the Toyo Denki contactor but not so with the GEC contactor.

The wide distributions of current chopping levels obtained in the tests were probably due to the fact that point-on-wave switching was not employed. Without this the arcing time varies widely and the contacts will be heated to different temperatures depending on the arcing time.

The results of actual motor tests confirm that the GEC contactor has a very low current chopping level. In no case of full speed, or near full speed, switch-off was any voltage transient of significant magnitude recorded. In any practical circuit, the frequency of the current chopping transient is relatively low, and unless of excessive magnitude, will not give rise to excessive machine turn to turn voltages.

No virtual current chopping occurred when the GEC vacuum contactor switched a high impedance (2,2 kohm) motor under worst case practical conditions, i.e. capacitance on the supply and short cables.

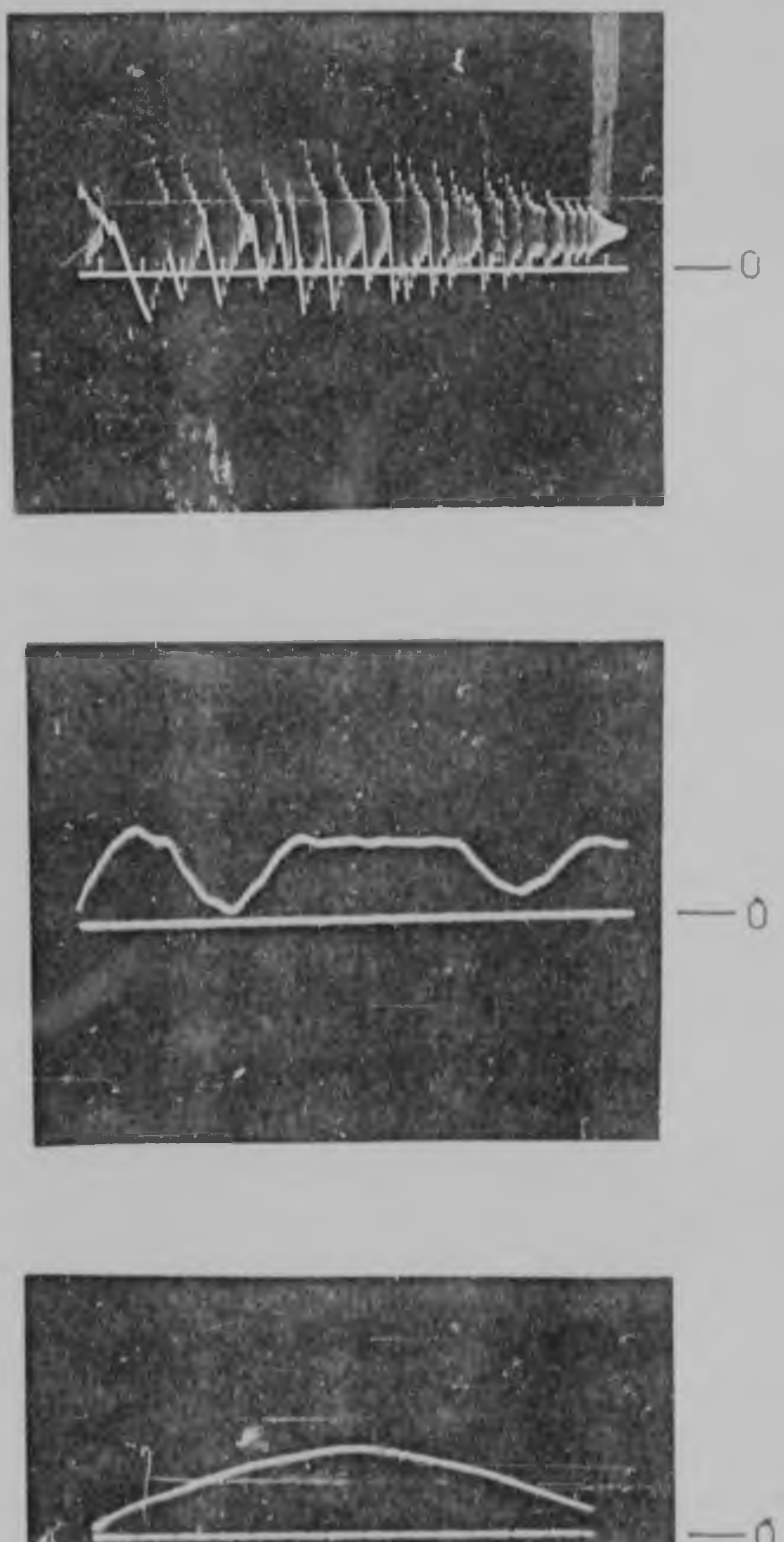
A form of three-phase simultaneous interruption was found to occur however when a 250 kVA transformer was switched, which had a magnetizing current lower than the current chopping level of the GEC contactor used. However, the largest voltage magnitude to earth recorded was only 2,0 p.u.

C H A P T E R 4

SWITCH-ON PRESTRIKES

4.1 MECHANISM OF A PRESTRIKE

Vacuum contactors, because of their inherent high rate of dielectric recovery, can produce during a late stage of the closing operation, a train of pulses. During the closing operation a stage is reached when an arc is struck between the approaching contacts. Depending on circuit constants, a high frequency oscillatory current may be super-imposed on the inrush current, and may create brief current zeros. By interrupting during one of these zeros, the vacuum contactor may isolate the load circuit whilst a substantial power frequency current is flowing. The resultant oscillation of the load circuit restores the voltage across the contact gap which again breaks down and the whole process, depending on the speed with which the contacts are closing and circuit constants, can be repeated many times before it is terminated as contacts touch. Each restrike increases the circuit energy and hence the prospective magnitude of the circuit recovery voltage and rate of rise of voltage across the contacts. Against this, the gap is reducing and so too the dielectric strength which determines the voltage at which the gap breaks down. The result is clearly discernable in figure 4.1 which shows a prestrike transient recorded on the single phase motor simulating circuit shown in figure 4.2. Figure 4.3 shows early prestrikes almost certainly caused by whiskers of with 100m. of cable



1 p.u./cm.
18.0 μsec/cm.

1 p.u./cm.
4.5 μsec/cm.

1 p.u./cm.
0.9 μsec/cm.

Fig. 4.1. Prestrike transient recorded on a single phase motor simulating circuit.

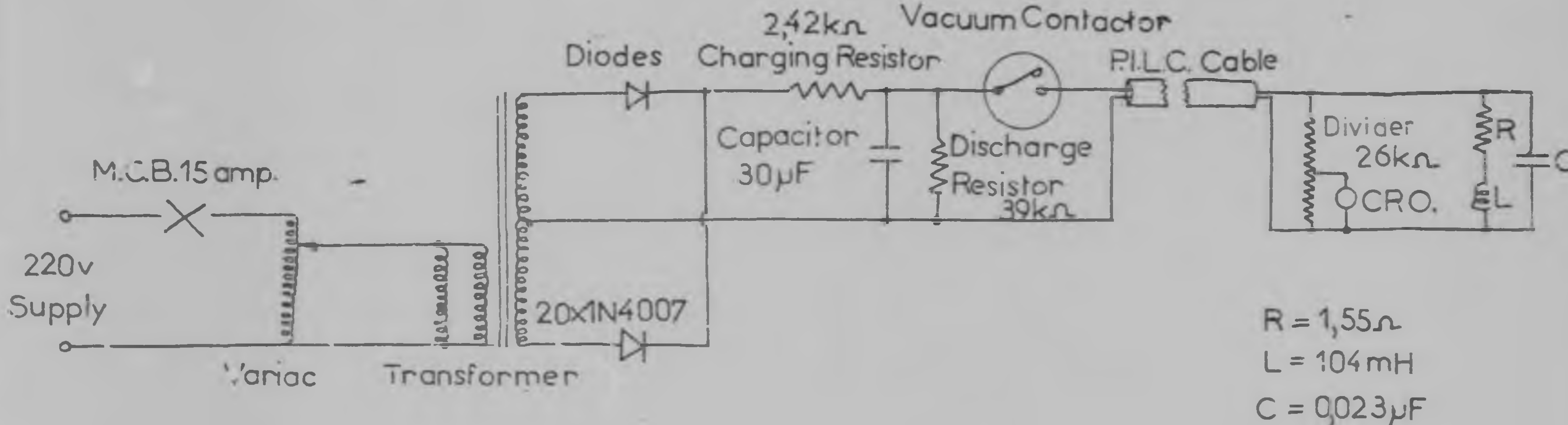
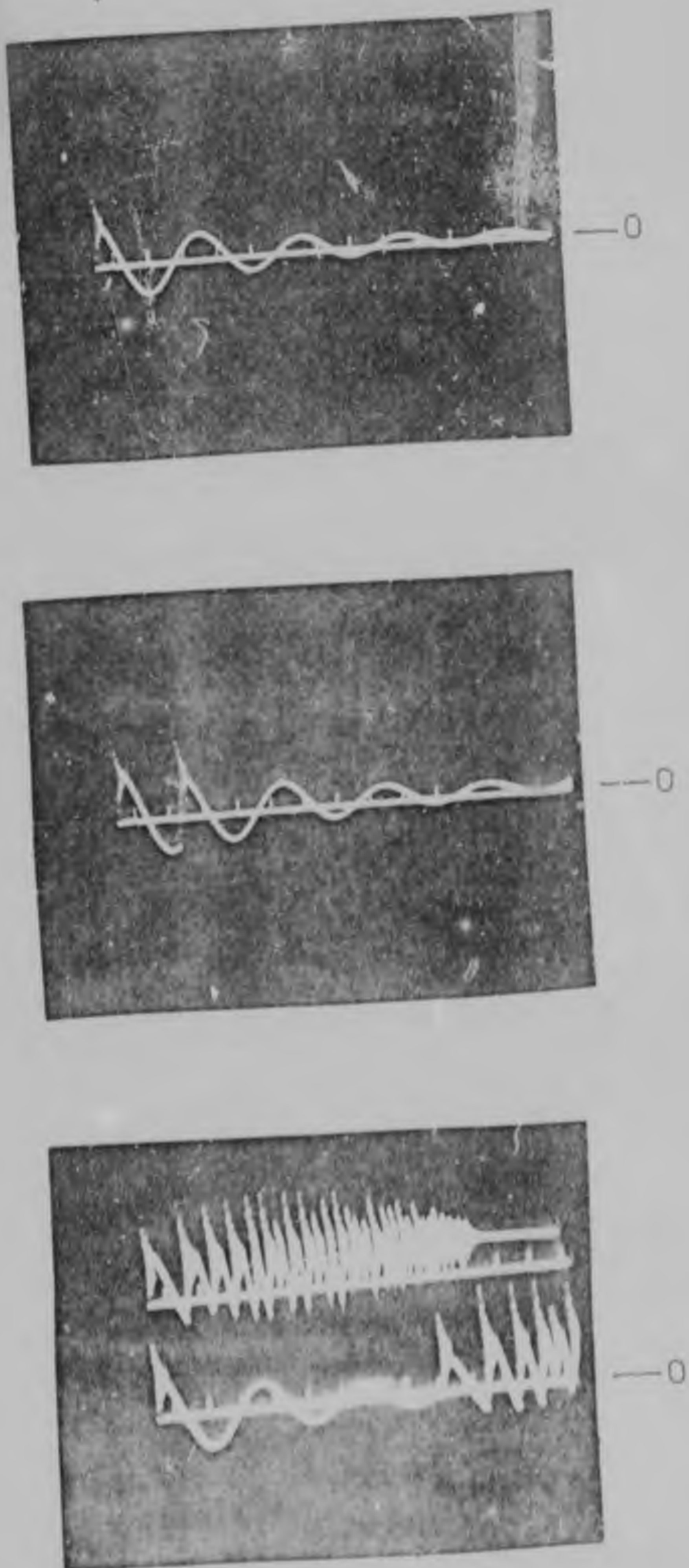


Fig.4.2. Single phase motor simulating circuit.

with 18m. of cable



1 p.u./cm.

100 µsec/div.

1 p.u./cm.

100 µsec/div.

1 p.u./cm.

100 µsec/div.

Top trace:-"normal" prestriking

Bottom trace:- early prestriking

Fig 4.3. Early prestrikes.

contact material which were burnt-off during the brief flow of current, thereby restoring the gap strength. Also clearly shown are the circuit recovery voltages. Referring to figure 4.1 it is interesting to note the switch's ability of subsequently supporting a higher voltage than that which initially precipitated the pre-strike, in spite of the progressive reduction of gap. This "under-shoot" results in surges larger than 2,0 p.u. occurring contrary to published information[45, 46] which stated that the magnitude of these prestrikes is limited to only the 2,0 p.u. which occurs because of voltage reflection.

Measurements were made of the voltage withstand capabilities of a 6,6 kV GEC vacuum contactor as a function of opening distance with three forms of voltage.

(a) 50 c/s alternating current.

(b) Direct current.

(c) A 1/50 µsec. impulse.

These are illustrated in figure 4.4 and as can be seen the dielectric strength is greater for steeper rates of rise in the small distance during which prestriking occurs. Hence in a pre-strike transient, the initial strike occurs at 50 c/s and is relatively small. Succeeding restrikes occur at the frequency of the recovery voltage, which is in most practical circuits of the order of 10 kHz, and hence the dielectric strength is greater and breaks down at higher voltages.

4.2 PARAMETERS OF PRESTRIKES

The amplitude, duration and frequency of the prestrike transients are determined by:-

(a) Supply capacitance.

(b) Cable capacitance.

(c) Load side inductance e.g. motor stalled inductance.

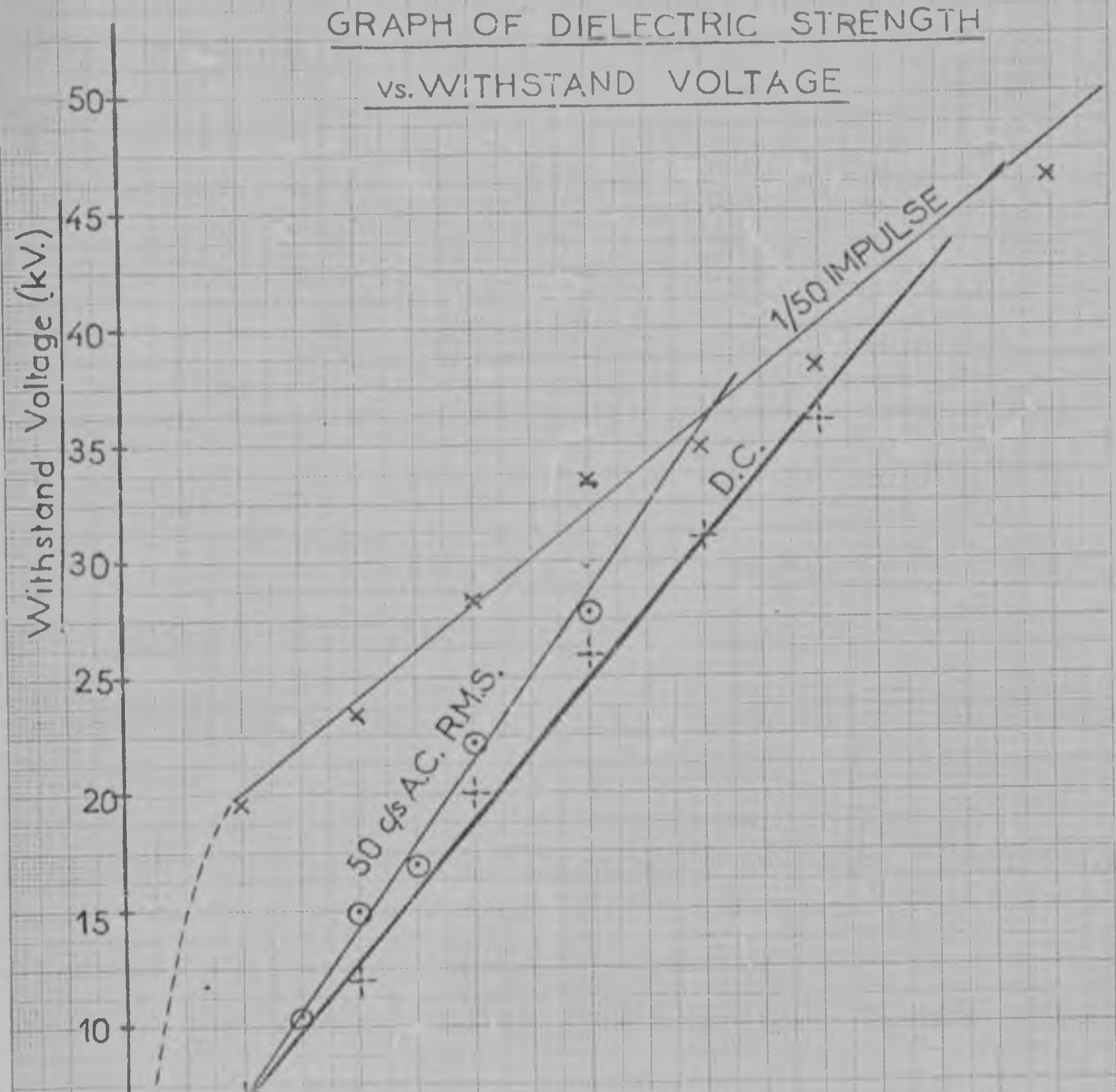

GRAPH OF DIELECTRIC STRENGTH
vs. WITHSTAND VOLTAGE
Withstand Voltage (kV.)
50
45
40
35
30
25
20
15
10
5
0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
1/50 IMPULSE
D.C.
50 c/s A.C. R.M.S.
Opening Distance of Contacts (mm.)

Fig. 4.4.

(d) Point on supply wave at which the closure occurs.

(e) Physical condition of the contacts and the vacuum bottle.

(f) Speed of closure of the contacts.

4.3 SIMULATED TEST RESULTS

Since the prestrike transients are at high frequency for a very short time, typically less than 1msec., the energy to produce them is supplied by the capacitance on the source side of the contactor, such as connected cables and/or power factor correction capacitors. They are therefore likely to be greatest when such capacitance is significant. Initial tests were therefore carried out using a d.c. charged capacitor as shown in figure 4.2.

In the single phase simulated circuit, the maximum recorded voltage across the coil simulating the motor's standstill inductance with 18m. of cable was 2,7 p.u. to earth (maximum voltage swing 4.0 p.u.) with an average maximum peak of 2,4 p.u. (average max. voltage swing 2,7 p.u.) It must be emphasised however, that this circuit simulates always switching on a voltage peak.

The single phase simulated circuit was found to be useful in determining the effect of varying the various parameters involved, e.g. inductance of motor, inductance in supply circuit, lengths of cable, RC suppressors across the coil, etc. A record of a prestrike transient with 100m. of simulated cable using the single phase simulated circuit is shown in figure 4.1.

4.4 EFFECT OF CABLE LENGTH

Figure 4.5 shows a table of the results of varying lengths of simulated cable using the single phase motor simulating circuit.

Length of cable	Max. Volt. Peak	Ave. Max. Volt. Peak	Max. Volt. Swing	Ave. Max. Volt. Swing	Max. No. of Peaks	Ave. No. of Peaks.	Max. Duration Time	Ave. Duration Time
50 m.	2,6 P.U.	2,1 P.U.	3,4 P.U.	2,6 P.U.	23	16	1120 μs.	820 μs.
100 m.	3,3 P.U.	2,4 P.U.	5,0 P.U.	2,9 P.U.	22	14	1500 μs.	880 μs.
150 m.	3,1 P.U.	2,2 P.U.	4,4 P.U.	2,6 P.U.	16	12	1400 μs.	850 μs.
218 m.	3,4 P.U.	2,4 P.U.	5,0 P.U.	2,9 P.U.	15	11	1350 μs.	925 μs.

Fig.4.5. Table of results.

Figure 4.6 and figure 4.7 show the effect on magnitudes and rates of rise. Whilst the duration and number of spikes might be comparable with an actual on site case, the rates of rise and magnitudes have been found to be lower and higher respectively than in practice. This is due to the difference of "lumped" capacitance in the case of the simulated circuit and the distributed capacitance with an actual cable and motor.

It is interesting to compare the results of this test with those reported by Smith [15], shown in figure 4.8. Ignoring the effects of capacitors for the time being, it can be seen that the general trend is for the magnitudes to increase till approx. 100m. of cable then level off. The results obtained by the author show a very similar trend.

4.5 ACTUAL TESTS ON A MOTOR

4.5.1 DESCRIPTION OF TESTS

The test circuit was the same as that shown in figure 3.21. These were three phase tests at 6,6 kV using a 6,6 kV GEC vacuum contactor, 18 and 90 meters of P.I.L.C. cable and a 6,6 kV, 200 kW motor. Thirty μF capacitors were connected on the supply side on each phase and the neutral was earthed.

The tests were done in collaboration with the C.S.I.R. using their monitoring equipment. This included 3 H.V. potentiometers, 2 digital oscilloscopes (Gould Advance Type OS4000) tape recorder (Philips Analog 7) and 2 oscilliscopes (Tektronix 556).

4.5.2 RESULTS

Twelve switch-on operations were recorded, using 18m. of

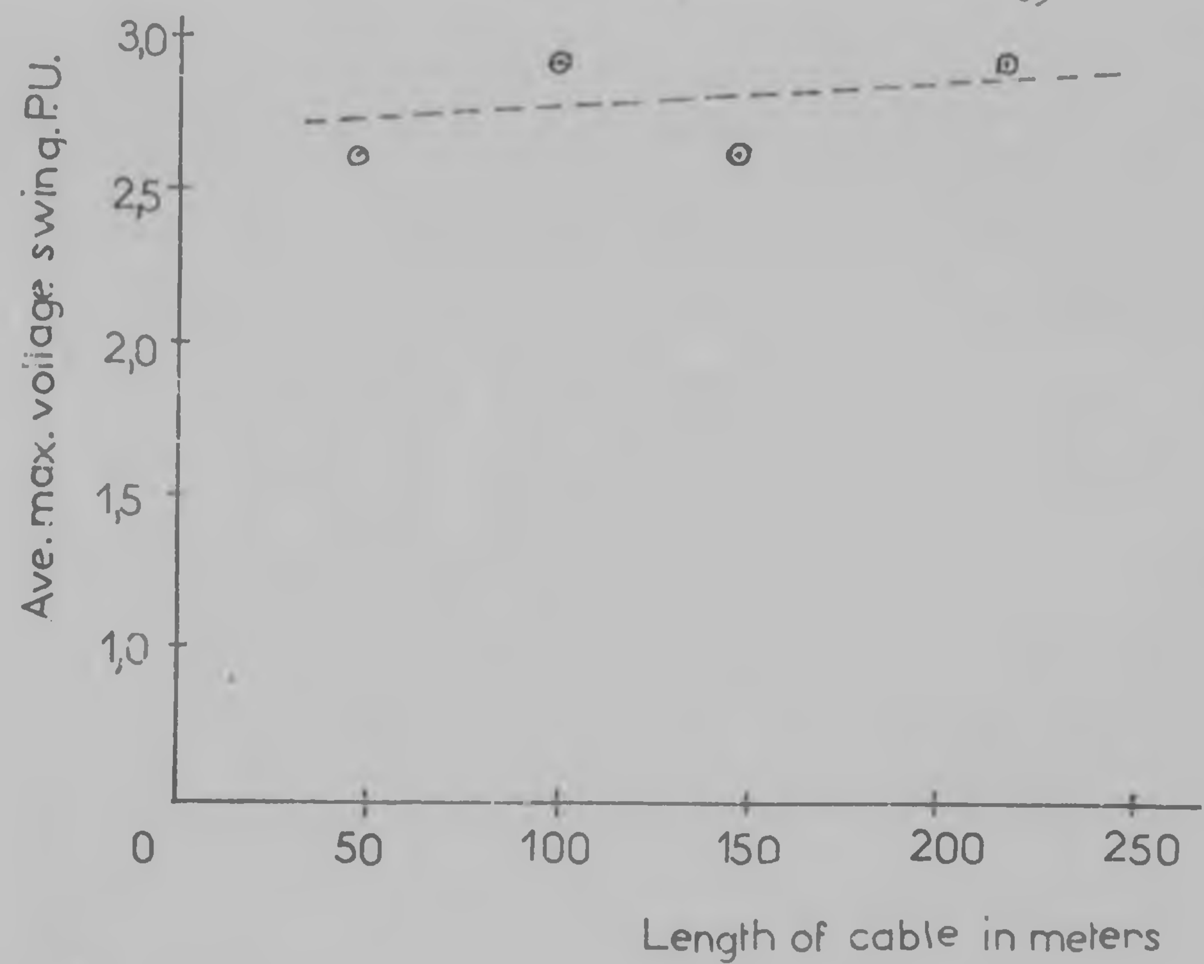


Fig.4.6. Effect of cable length on the magnitude of the average maximum voltage swings.

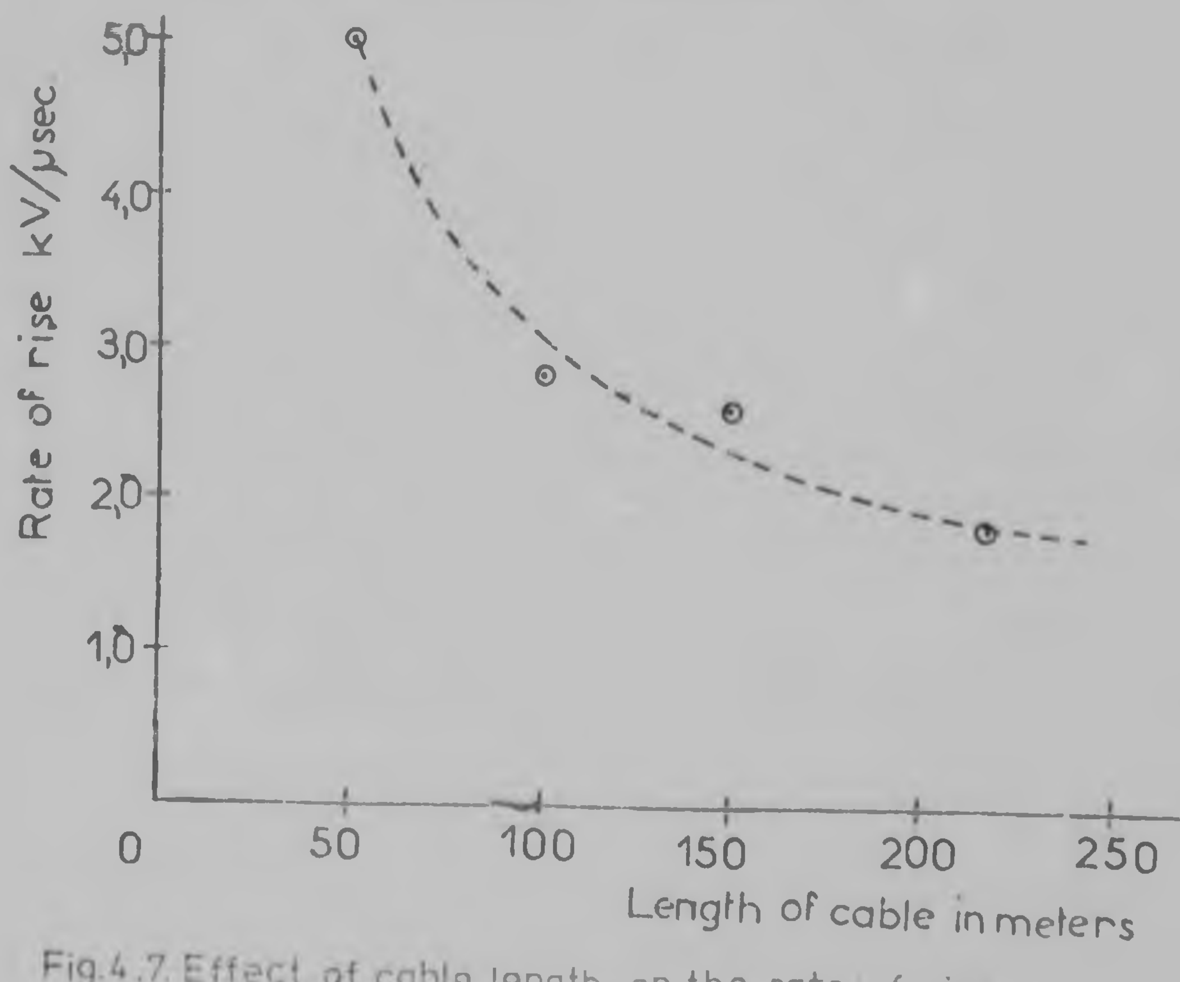


Fig.4.7. Effect of cable length on the rate of rise.

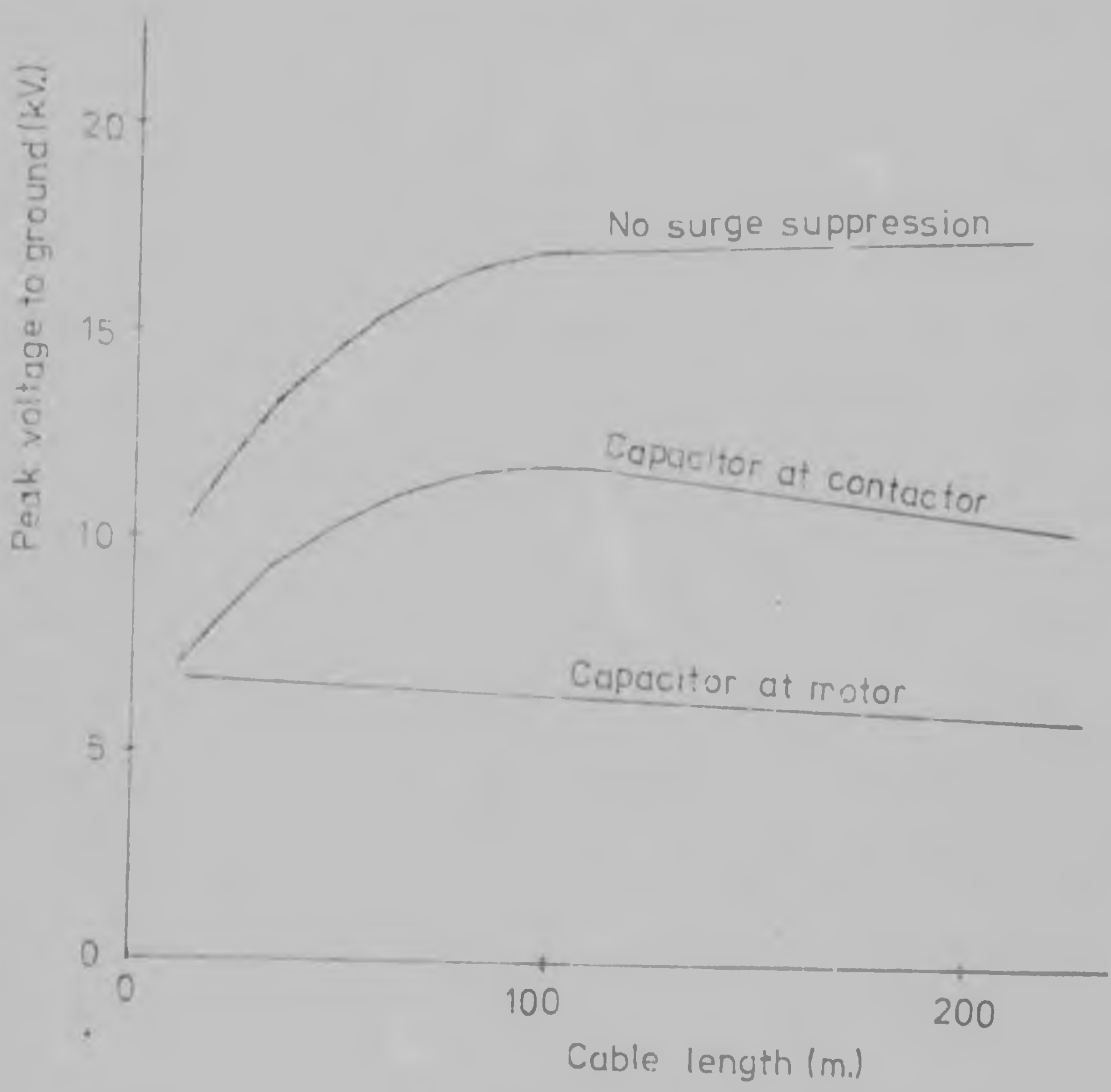


Fig 4.8. Effect of 0,3 μF surge suppression capacitor with 300 Ω damping resistor.

cable between the contactor and the motor. All three phases were monitored yielding 36 records of prestrike transients. The average max. voltage swing recorded was 1,7 p.u., whilst the maximum was 3,1 p.u. The average number of major strikes was 25 with a max. of 40. The average duration time was 880 µsec. with a max. of 1300 µsec.

A typical record is shown in figure 4.9 and the histogram of the max. voltage swings is shown in figure 4.10. The max. rate of rise of the transients is of the order of 1,4 p.u. in 0,3 µsec. i.e. 25 kV/µsec.

The probability of magnitude of any one strike in a prestrike transient with 18m. of cable is shown in figure 4.11.

Three operations were recorded of switch-ons with 90m. of cable between the contactor and the motor. All three phases were monitored yielding 9 transients.

The average max. voltage swing was 2,1 p.u. with a max. recorded of 3,5 p.u. Typical records are shown in figure 4.12 and 4.13. The similarity between these transients and those recorded using the simulated single phase test set, figure 4.1, is noticeable. The max. rate of rise recorded was 3,0 p.u. in 1,5 µsec., i.e. 10,8 kV/µsec. (approx.).

4.6 ACTUAL TESTS ON TRANSFORMER

4.6.1 ARC FURNACE TRANSFORMER SWITCHING

On site measurements were conducted on a 6,6 kV GEC vacuum contactor switching a 2000 kVA arc furnace transformer. The circuit diagram is shown in figure 4.14 and a typical switch-on transient is shown in figure 4.15.

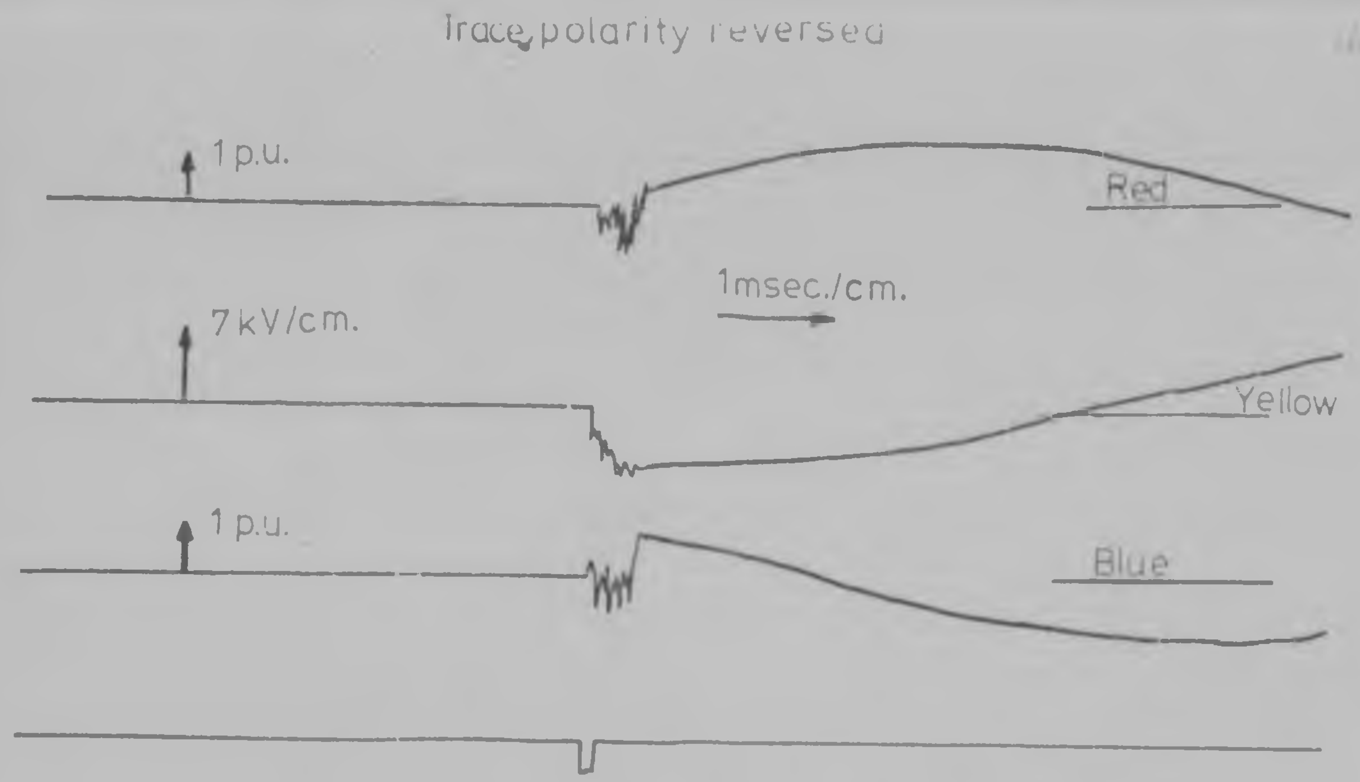
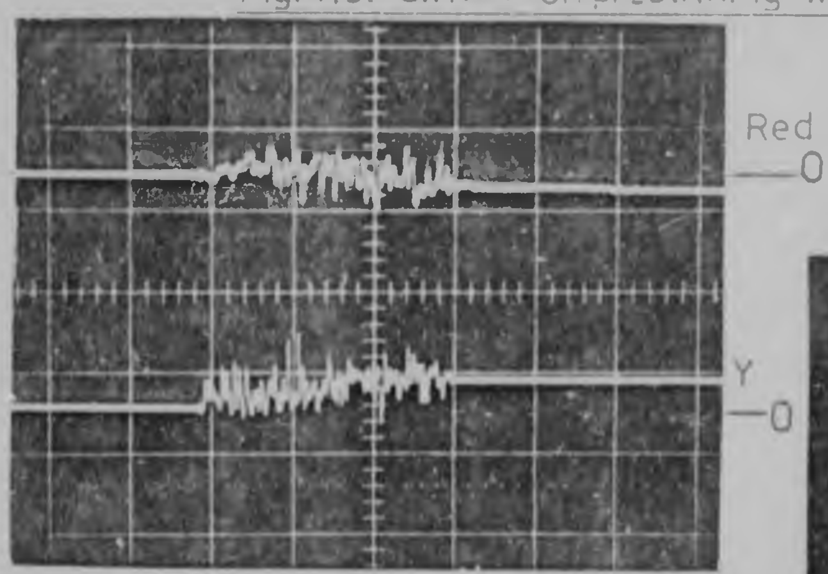
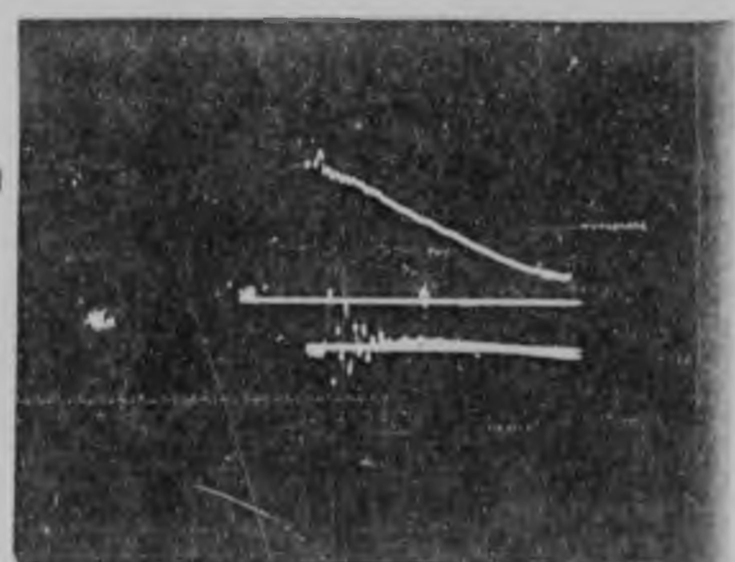
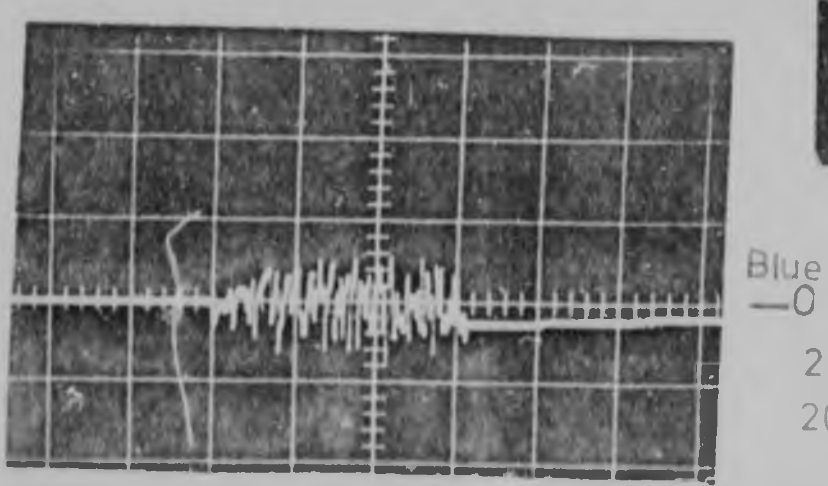


Fig. 4.9. Switch-on prestriking with 6,6 kV motor.







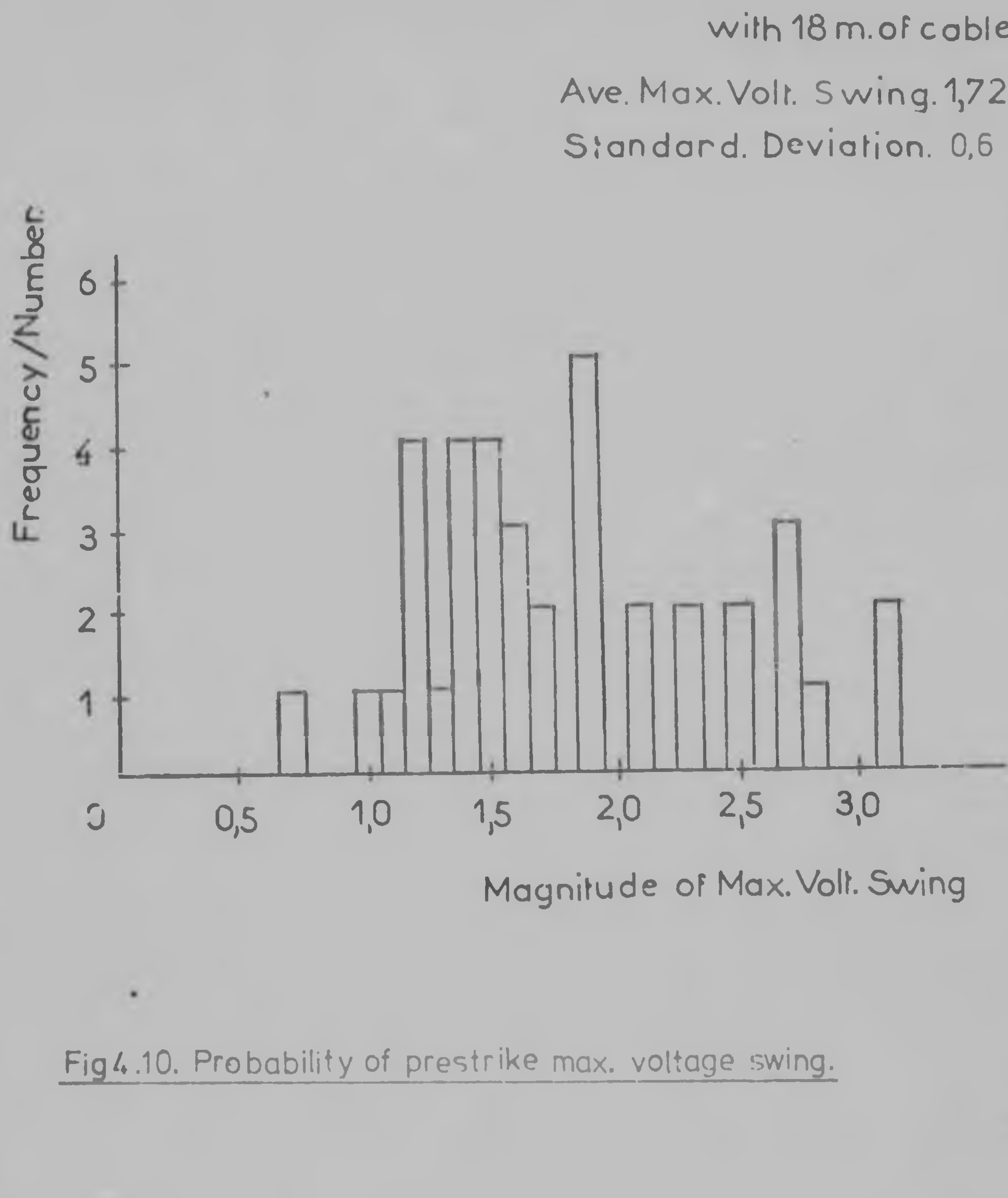


Fig 4.10. Probability of prestrike max. voltage swing.

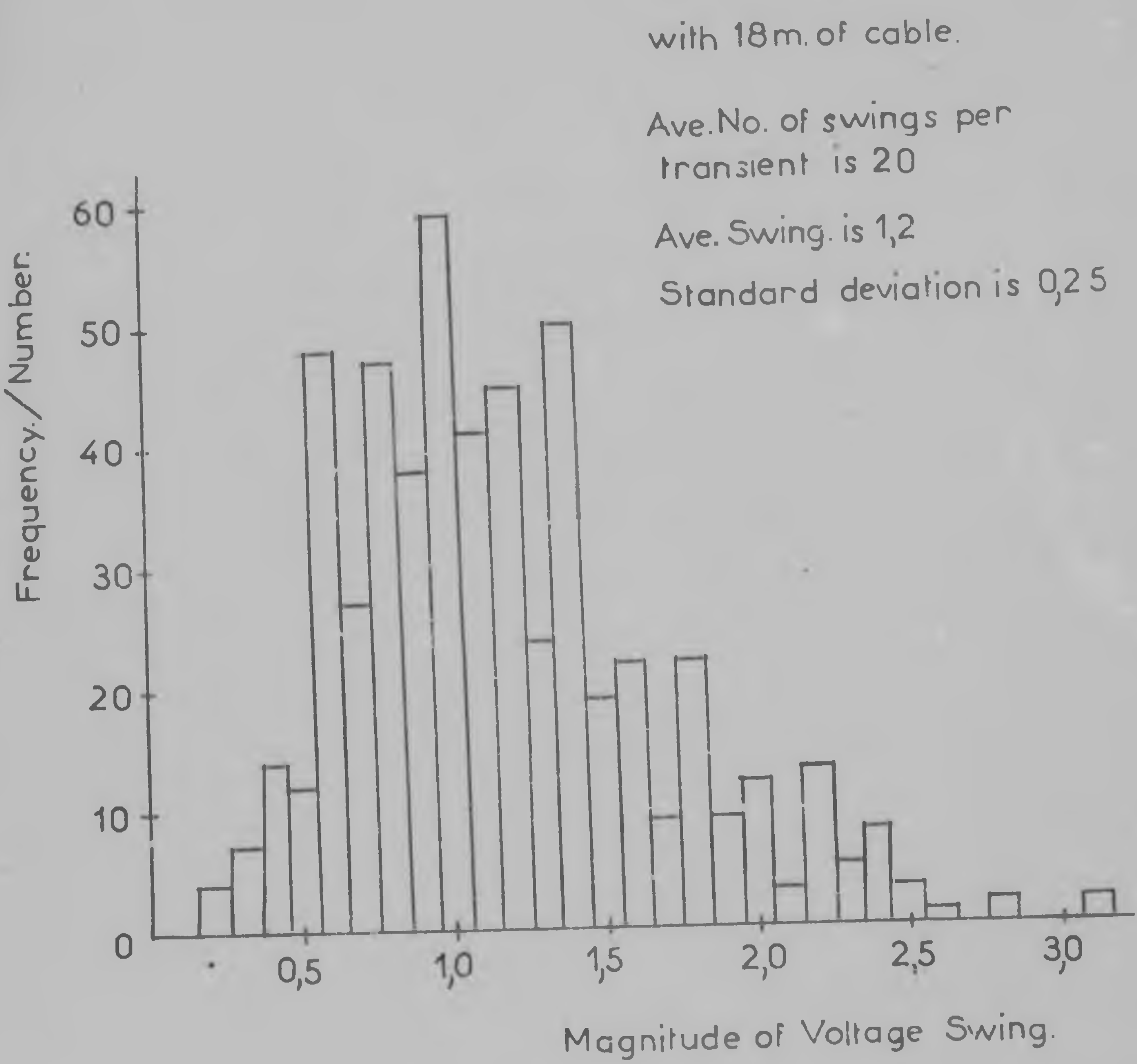


Fig.4.11. Probability of voltage swing in a prestrike transient.

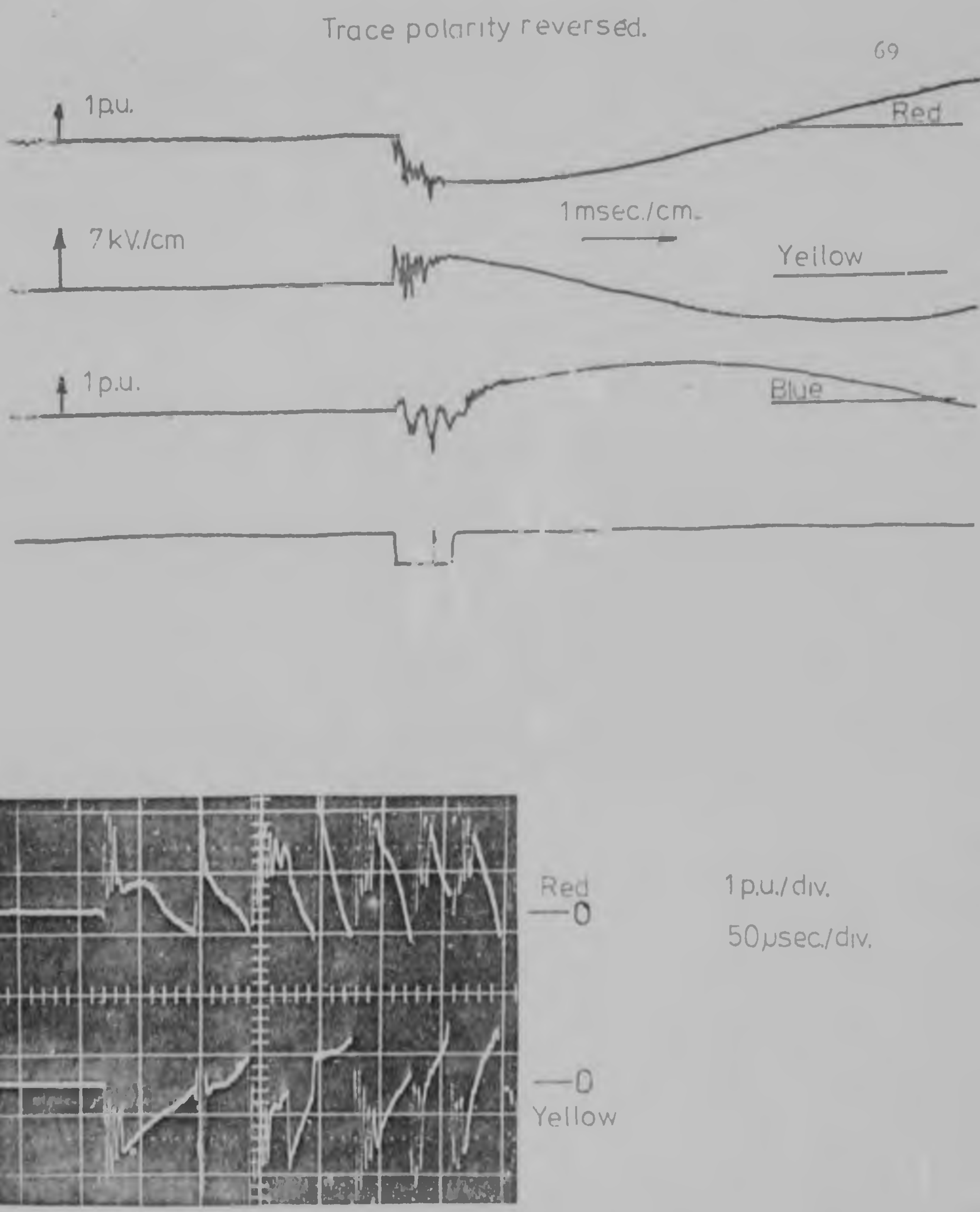
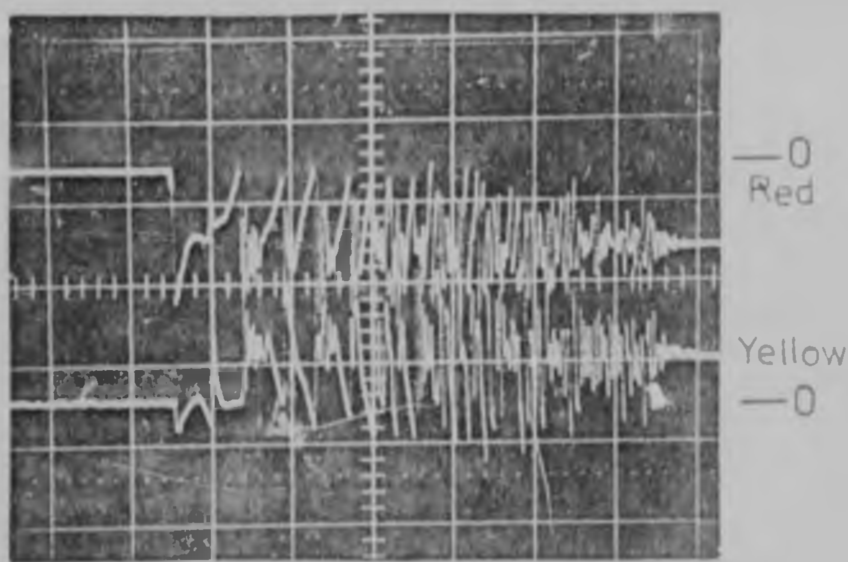
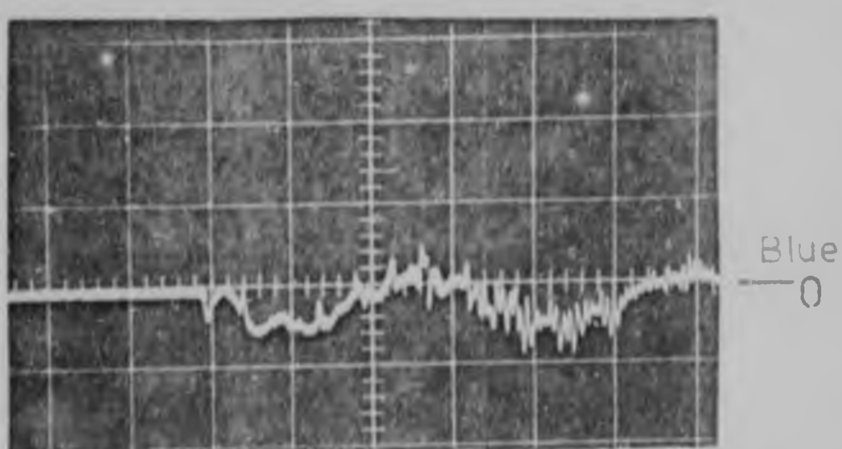


Fig.4.12. Switch-on prestriking with 6,6kV motor.



1 p.u./div.

100 μsec./div.



1 p.u./div.

100 μsec./div.

Fig.4.13. Switch-on prestriking with 6,6 kV motor.

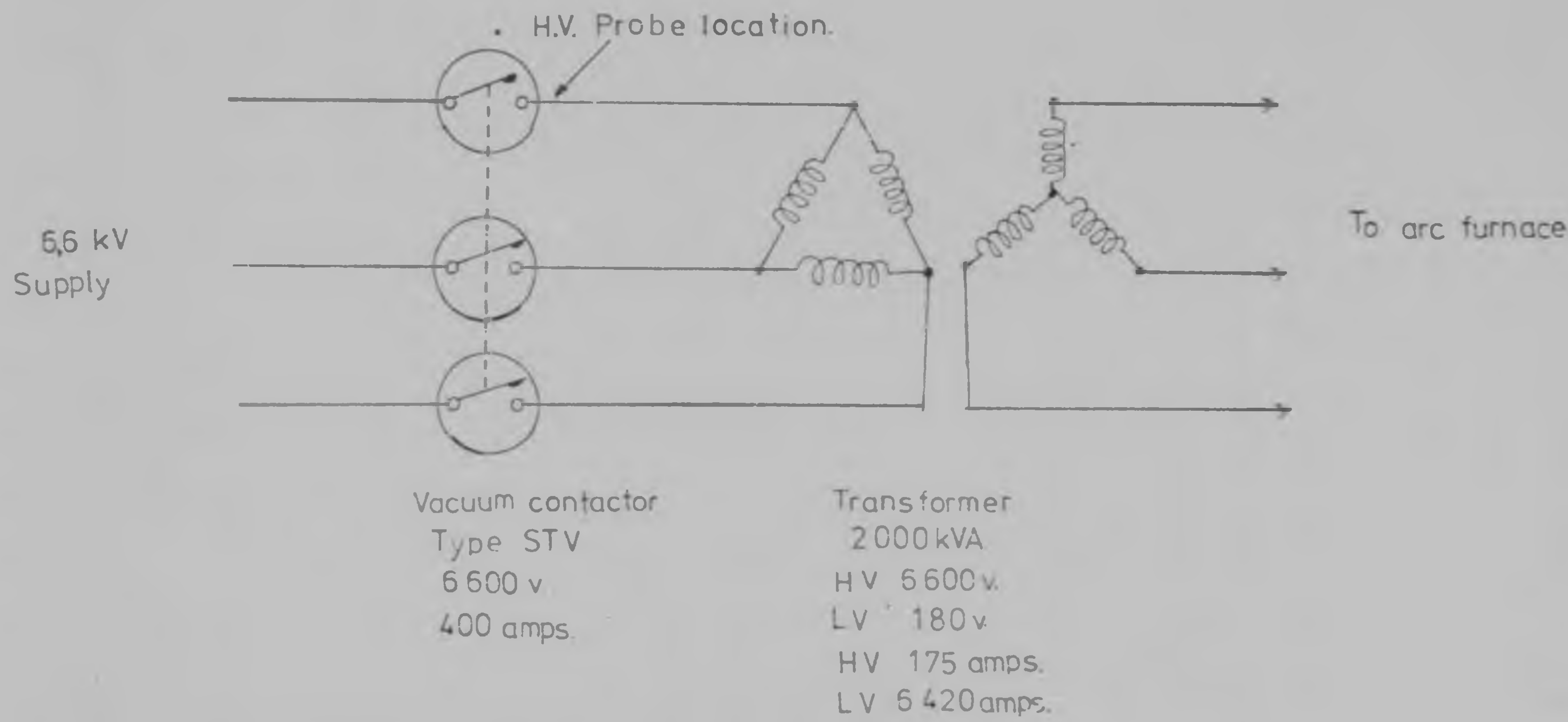


Fig 4.14. Circuit of arc furnace transformer.

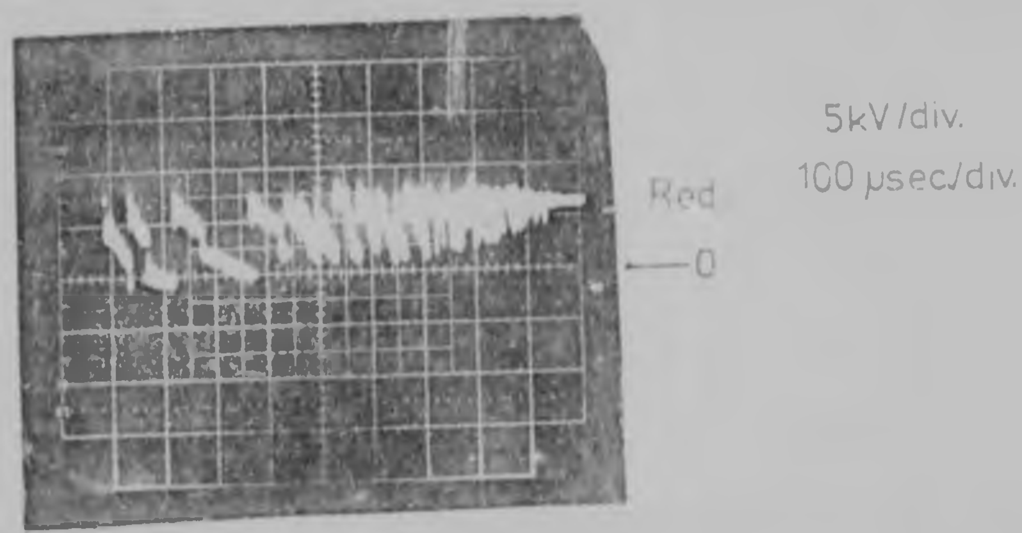


Fig.4.15 Switch-on transient with 2000kVA arc furnace transformer.

As can be seen the magnitudes of the transient are modest (max. 1,7 p.u.). Approx. 30 switch-ons were monitored, m on the red phase, and no voltage swing greater than 1,7 p was monitored.

[illegible] VACUUM CONTACTOR SWITCHING A 350 KVA TRANSFORMER

The test circuit was as for figure 3.24 and has already been partly described in 3.10. Six circuit configurations were inv stigated and they are listed below:

A. Power factor correction capacitors connected to the supply, RC surge suppressor disconnected, short cable (16m.) between transformer and contactor panel and no supply cable i.e. the supply was connected to the contactor by short, direct, single core cables. Eleven switch-on operations were recorded, and measurements made of max. overvoltage, max. voltage swing, number of strikes and duration of transient for each operation and in each phase. The results are shown in figure 4.16 and a typical switch-on is shown in figure 4.17.

	Switch ON
Max. overvoltage recorded (p.u. peak) Average max. overvoltage (p.u. peak) Standard deviation	2,00 1,14 0,41
Max. voltage swing recorded (p.u. peak-peak) Average max. voltage swing (p.u. peak-peak) Standard deviation	2,00 1,18 0,47
Max. number of strikes recorded Average number of strikes Standard deviation	4,00 2,22 1,07
Max. duration of transient (ms) Average duration of transient (ms) Standard deviation	2,18 1,09 0,57

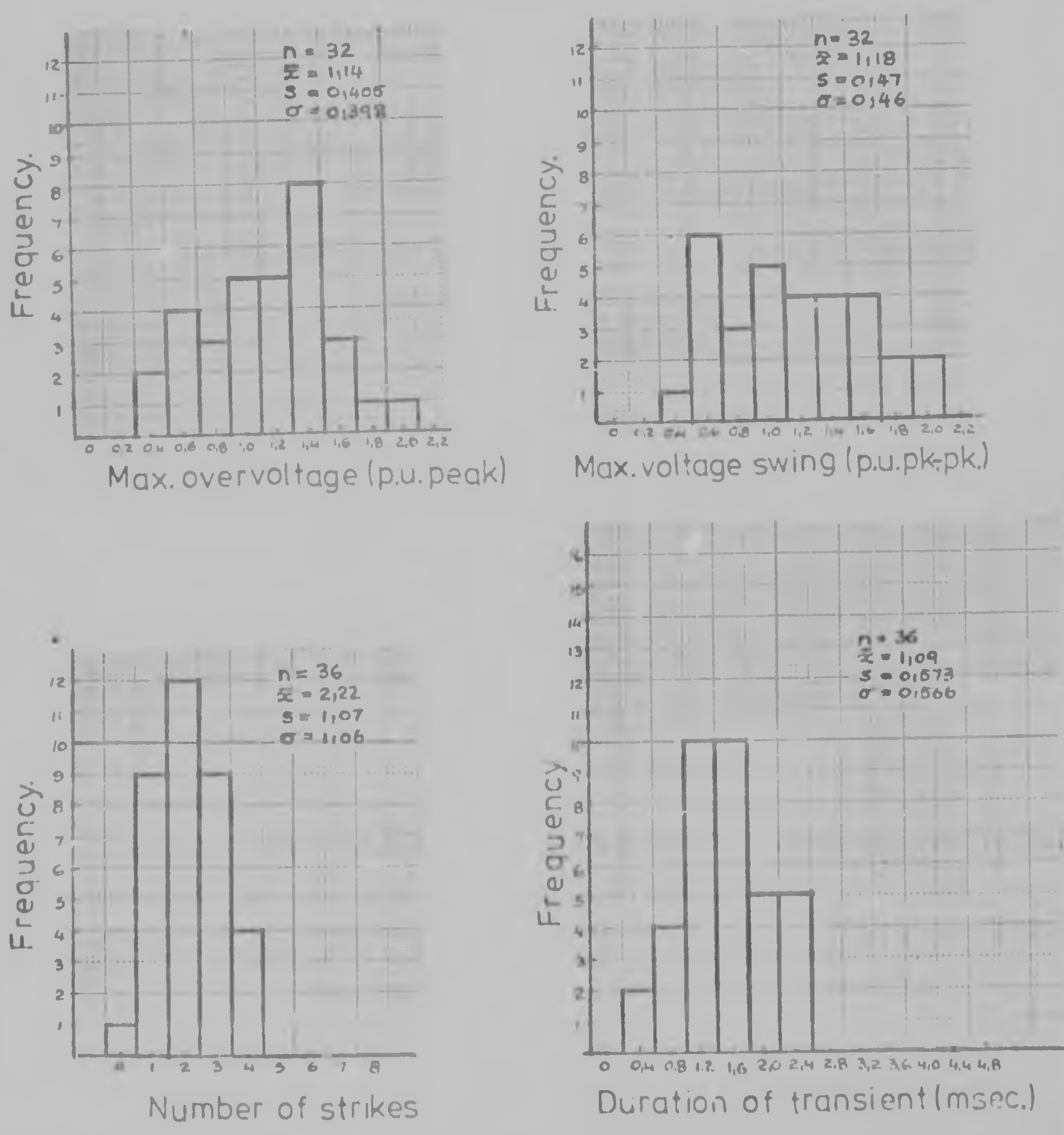


Fig. 4.16. Results of transformer switch-on tests A.

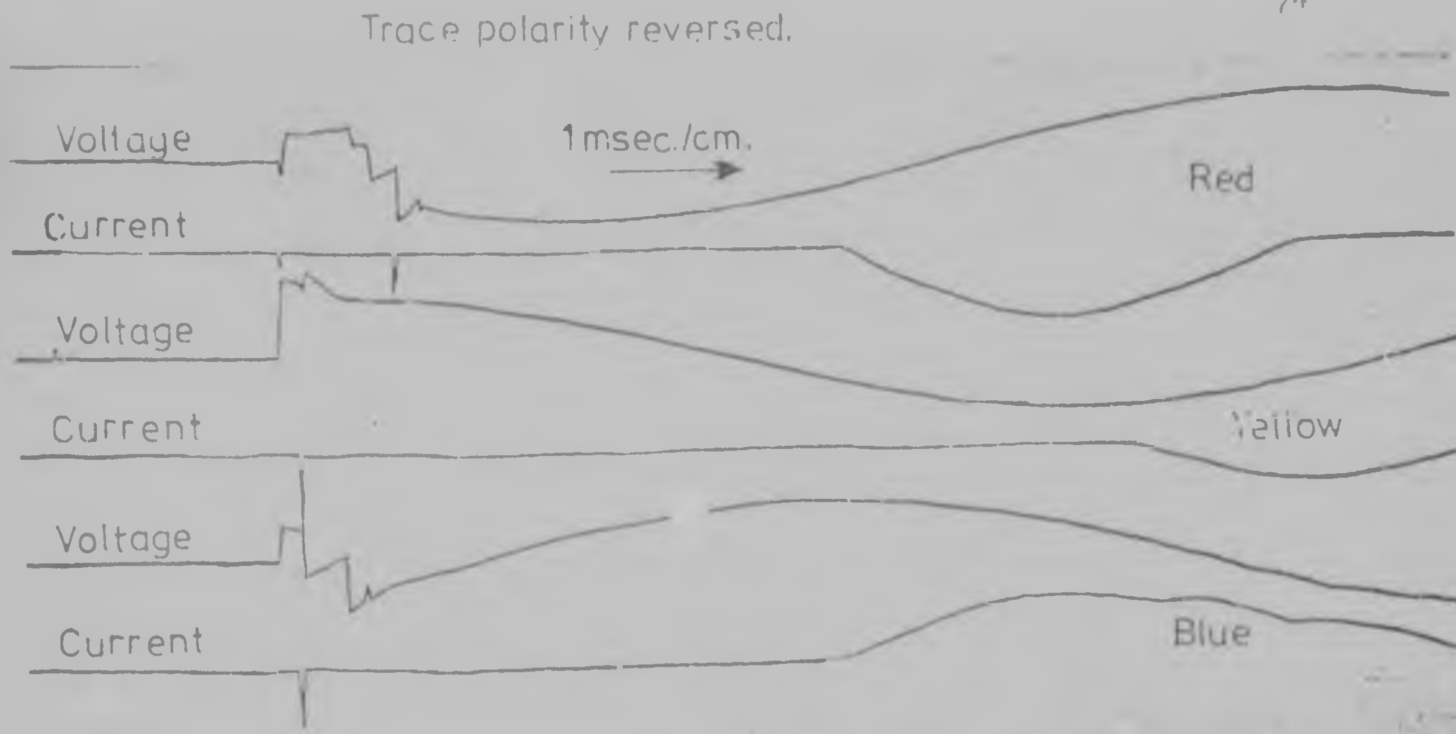
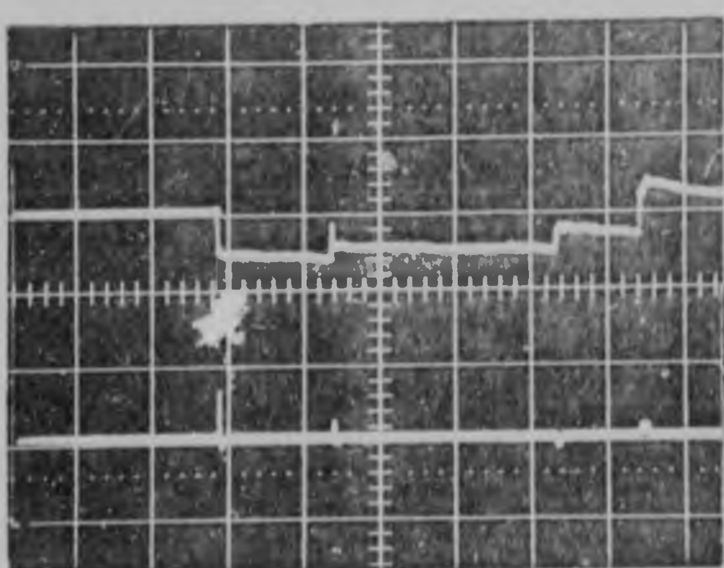
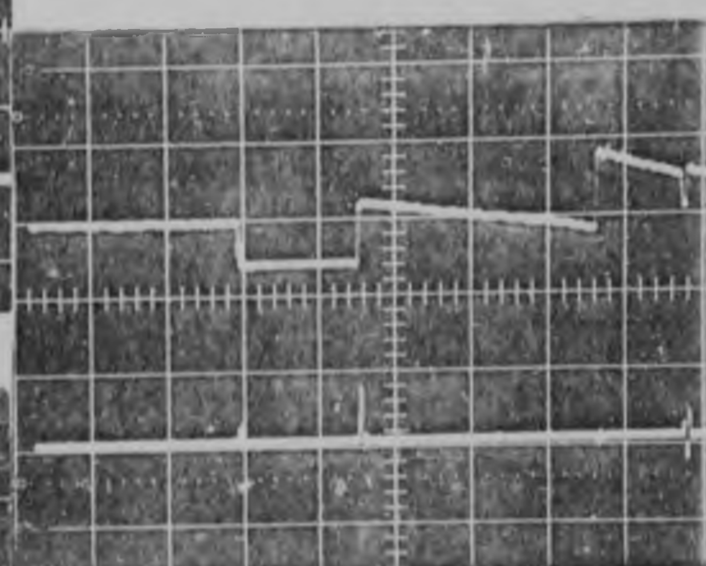


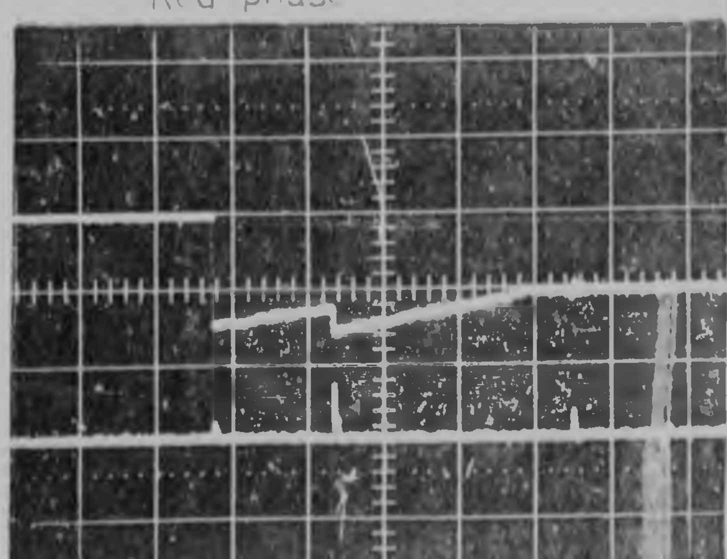
Fig.4.17. Transformer switch-on transients. A.



Red phase



Blue phase



Yellow phase

Voltage: 1 p.u./div. (Top trace)

Current: 50 A./div. (Bottom trace)

Time: 200 μsec./div.

B. Without power factor correction capacitors connected to the supply, without RC surge suppressor, short load cable and no supply cable. Eleven switch-on operations were recorded of voltage and current in each phase. The results are shown in figure 4.18 and a typical recording of the switch-on is shown in figure 4.19.

C. No power factor correction capacitors, long load cable (90m.), between contactor and transformer, short supply cable, RC surge suppressor disconnected. Ten switch-on recordings of voltage and current in each phase were taken. The results are shown in figure 4.20 and a typical recording in figure 4.21.

D. As for C but with power factor correction capacitors connected to the supply. Measurements were made of the transients generated in each phase for 11 switch-on operations. The results are given in figure 4.22 and a typical transient is shown in figure 4.23.

E. With power factor correction capacitors connected, short load cable, long supply cable, no RC suppressor. Measurements were made of the transients generated in each phase for 11 switch-on operations. The results are shown in figure 4.24 and a typical transient is shown in figure 4.25.

F. Without power factor correction capacitors, short load cable, long supply cable, no RC suppressor. Measurements were made of the transients generated in each phase for 10 switch-on operations. The results are given in figure 4.26 and a typical transient is shown in figure 4.27.

4.7 SUMMARY AND DISCUSSION

The simulated test results were a useful way of starting the investigation into prestrikes. The mechanism, and what contributes to it's form, can be easily studied. In fact it was only during these tests that the phenomena of very early prestrikes due to whiskers, were recorded. At no stage during any motor or transformer switching were early prestrikes ever again recorded. It

	Switch ON
Max. overvoltage recorded (p.u. peak)	1.2.
Average max. overvoltage (p.u. peak)	0.81
Standard deviation	0.28
Max. voltage swing recorded (p.u. peak-Peak)	1.6
Average max. voltage swing (p.u.peak-peak)	0.89
Standard deviation	0.42
Max. number of strikes recorded	4
Average number of strikes	1.93
Standard deviation	1,26
Max. duration of transient recorded (ms)	2.03
Average duration of transient recorded (ms)	1.03
Standard [illegible]	0.58

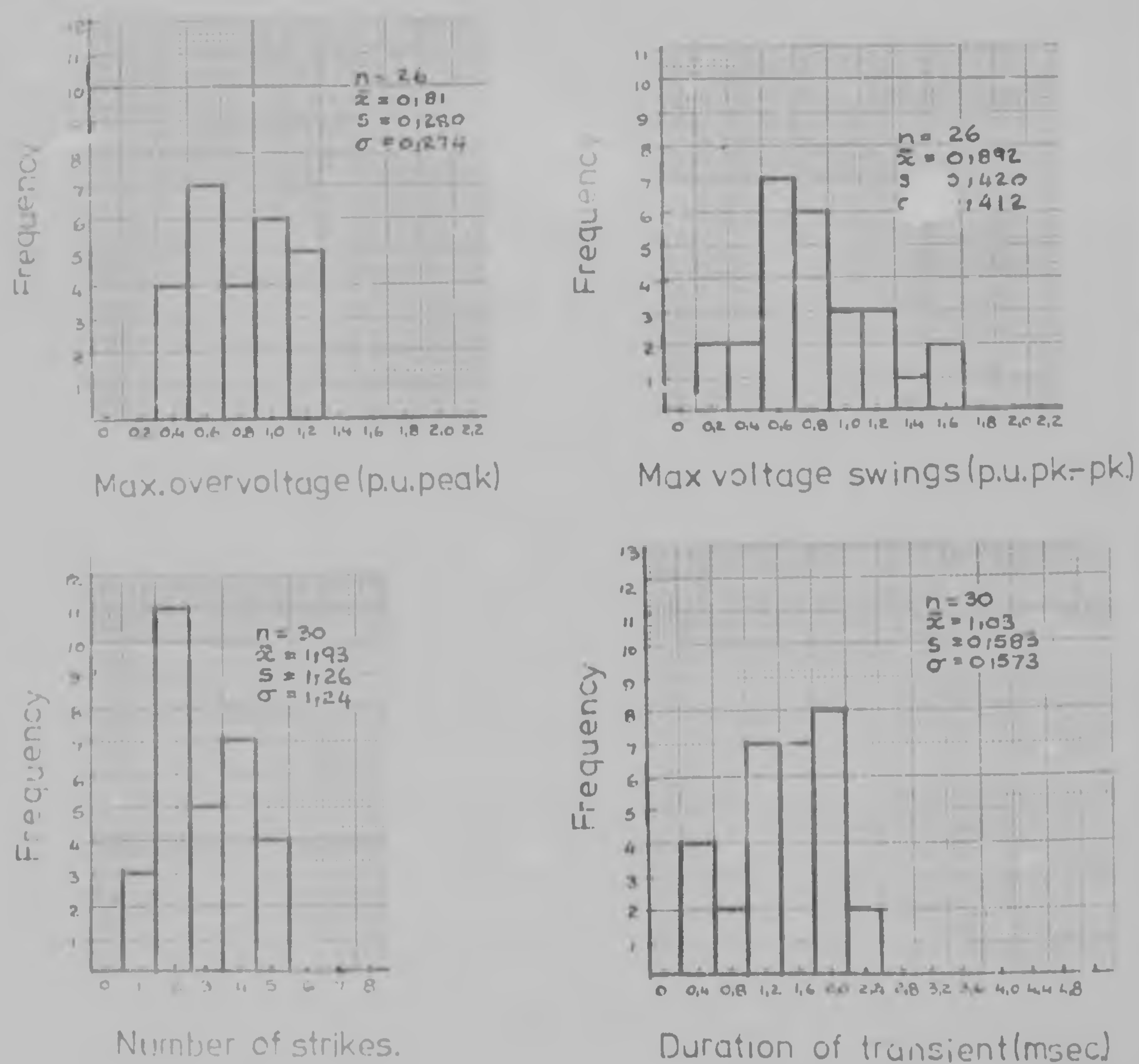


Fig.4.18. Results of transformer switch-on tests B.

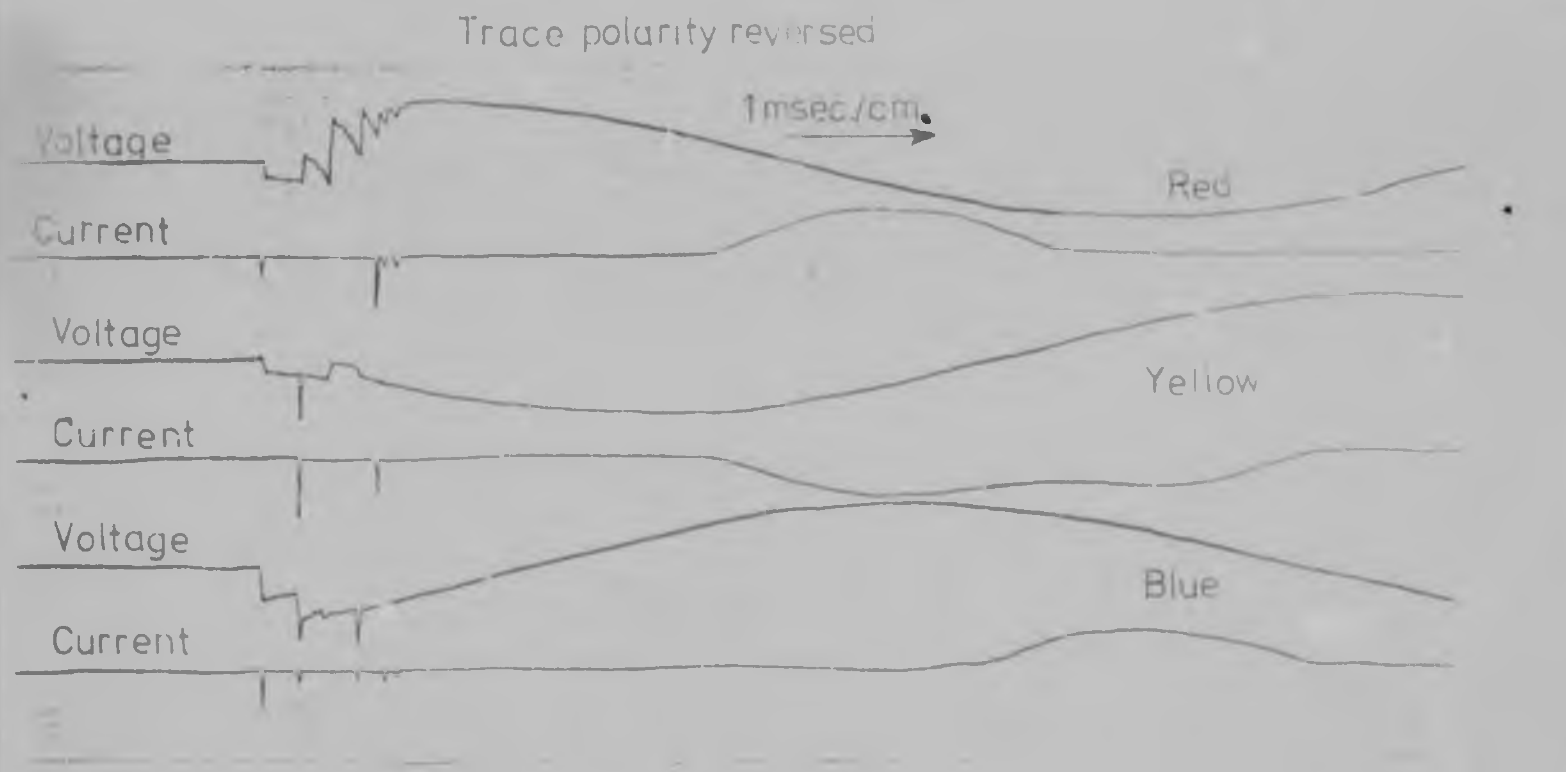
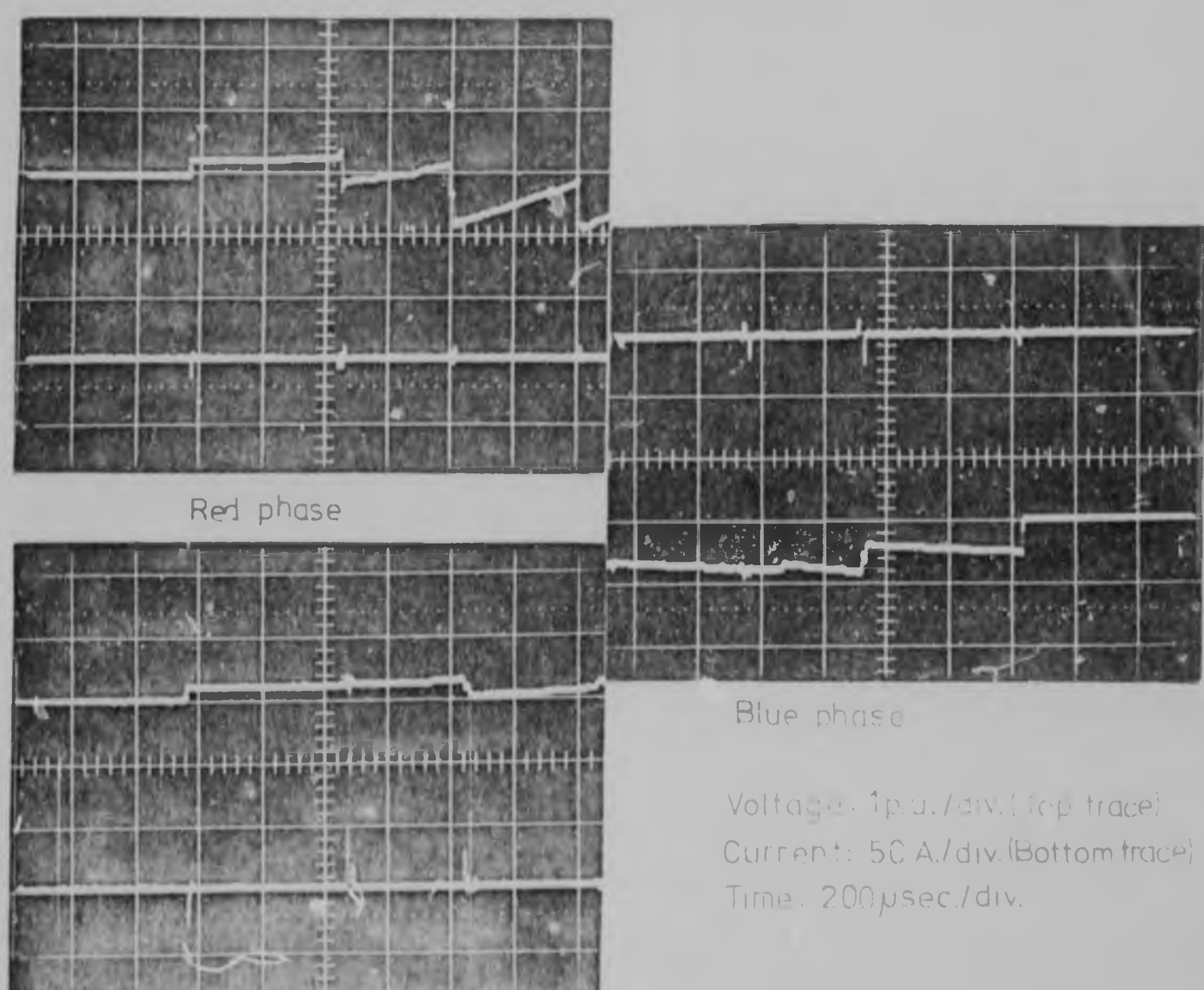


Fig 4.19. Transformer switch-on transients B



Red phase

Yellow phase

Blue phase

Voltage: 1p.u./div.(Top trace)
Current: 50 A./div.(Bottom trace)
Time: 200μsec./div.

	Switch On
Max. Overvoltage recorded (p.u.Peak) Average Max.Overvoltage (p.u.peak) Standard Deviation	1.4 0.81 0.33
Max. Voltage Swing recorded (p.u. peak-peak) Average max.voltage swing (p.u. peak-peak) Standard Deviation	1.4 0.88 0.38
Maximum number of strikes recorded Average number of strikes Standard Deviation	3 1.63 0.67
Max. Duration of Transient recorded (ms) Average Duration of Transient (ms) Standard Deviation	2.19 0.97 0,63

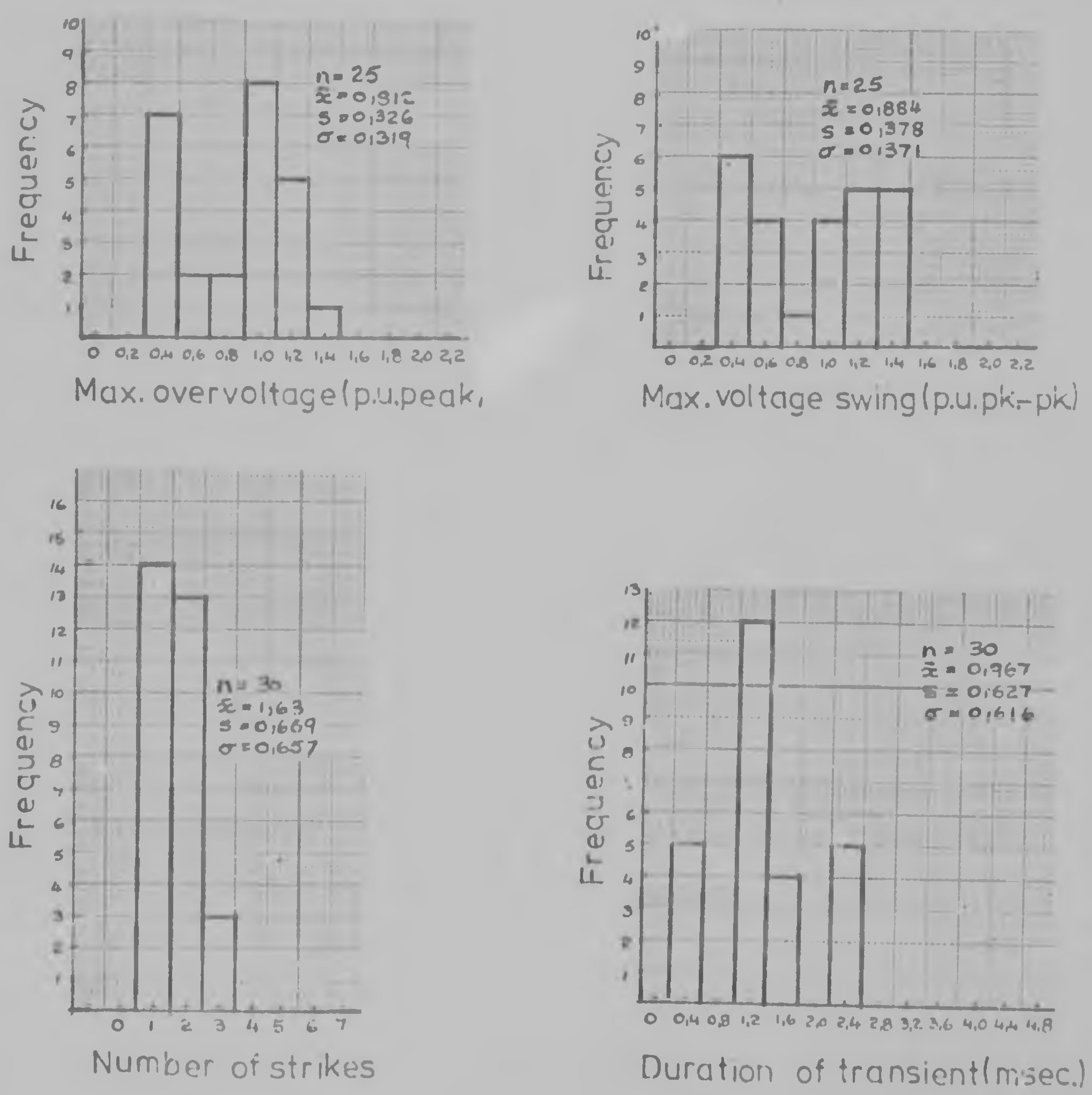


Fig. 4.20. Results of transformer switch-on tests C

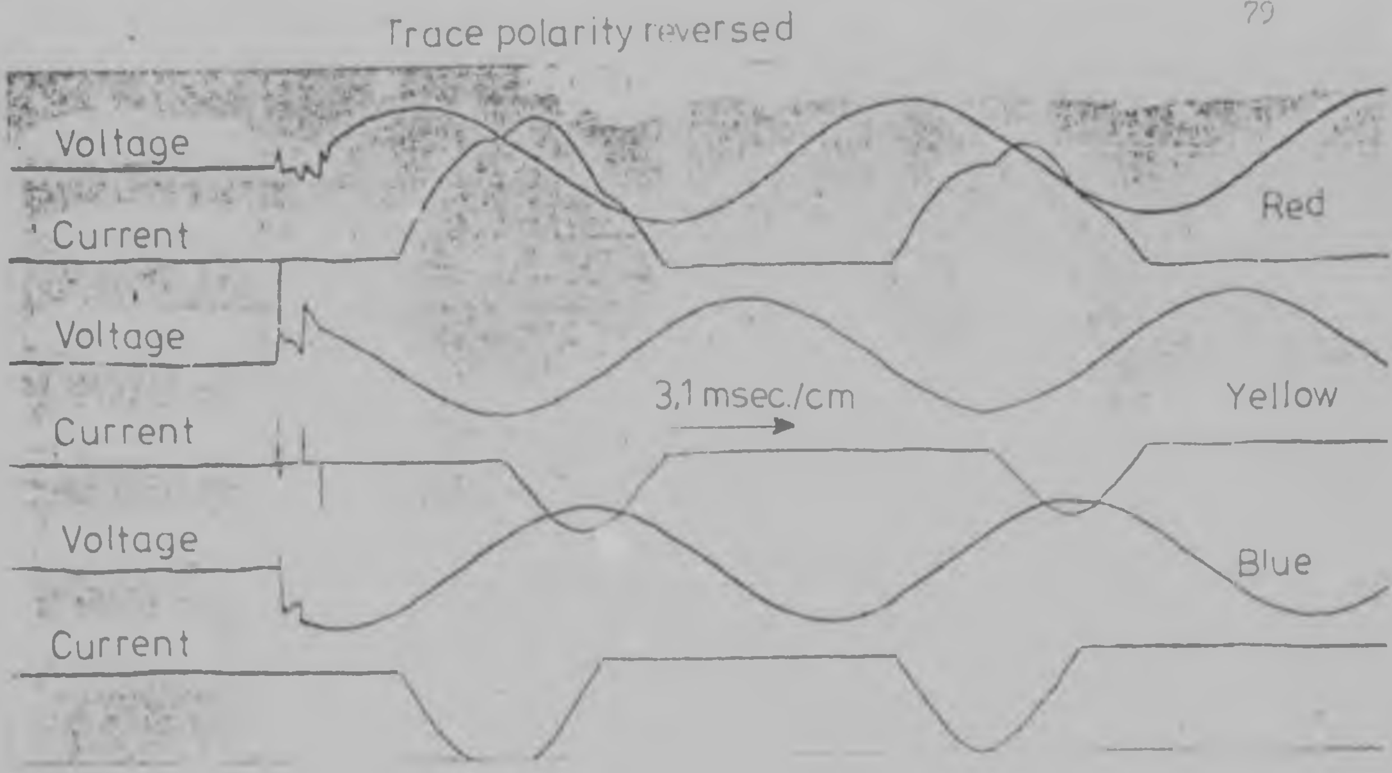
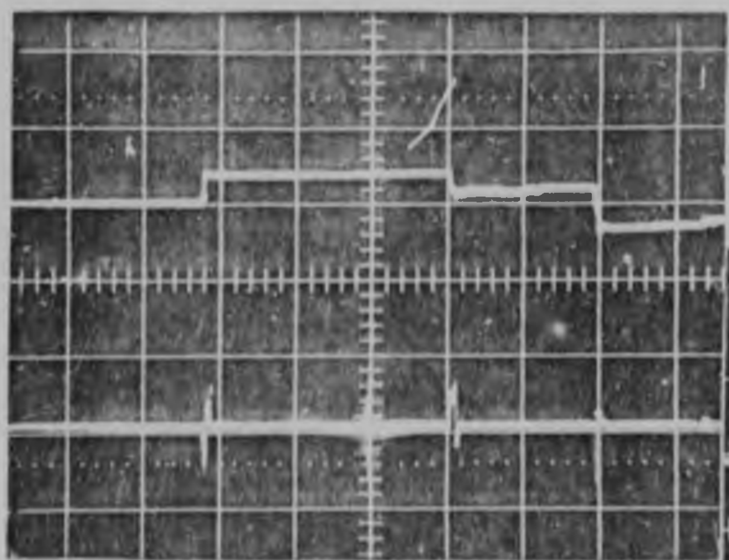
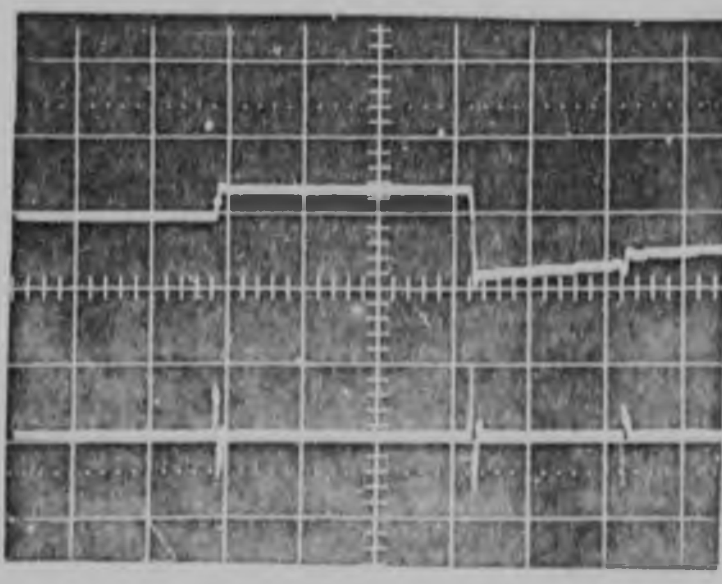


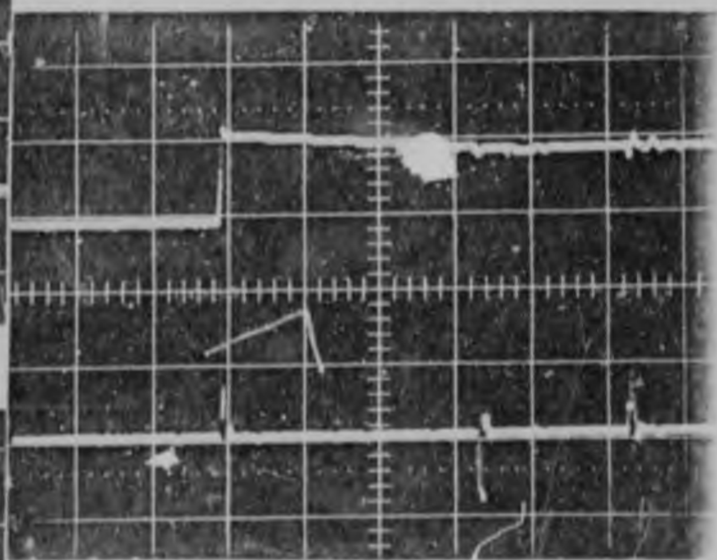
Fig.4.21. Transformer switch-on transients C



Red phase



Yellow phase



Blue phase

Voltage: 1 p.u./div. (Top trace)

Current: 50 A /div.(Bottom trace)

Time: 200 μsec./div.

	Switch ON
Max. Overvoltage recorded (p.u. pk) Average overvoltage (p.u. pk) Standard Deviation	2.0 1.32 0.95
Max. Voltage swing recorded (p.u. pk-pk) Average Voltage Swing (p.u. pk-pk) Standard Deviation	2.0 1.09 0.44
Max. Number of strikes recorded Average number of strikes Standard Deviation	3 1.3 0.81
Max. Duration of Transient Recorded (ms) Average Duration of Transient (ms) Standard Deviation	1,88 0,61 0,51

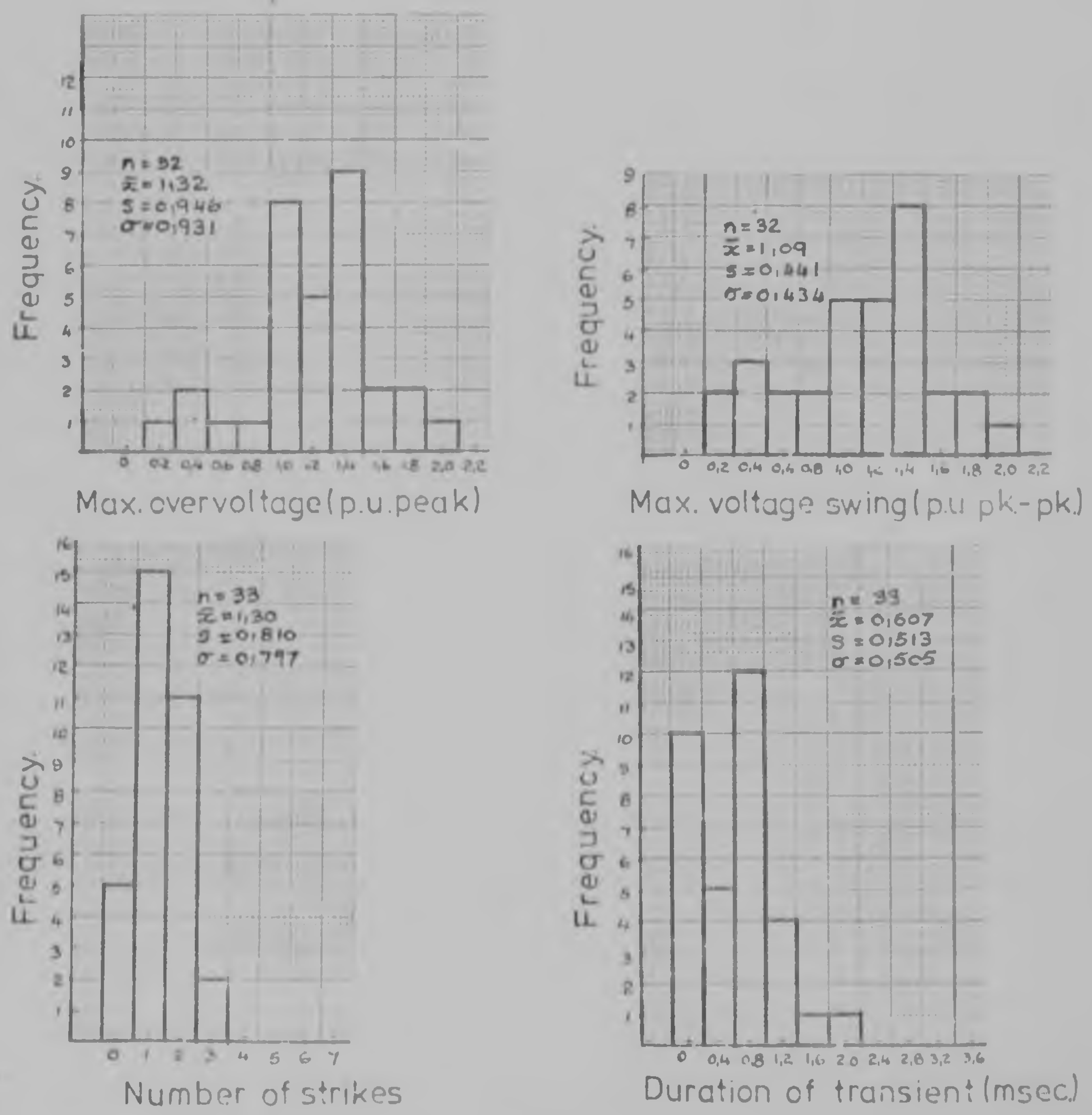


Fig. 4.22. Results of transformer switch-on tests D.

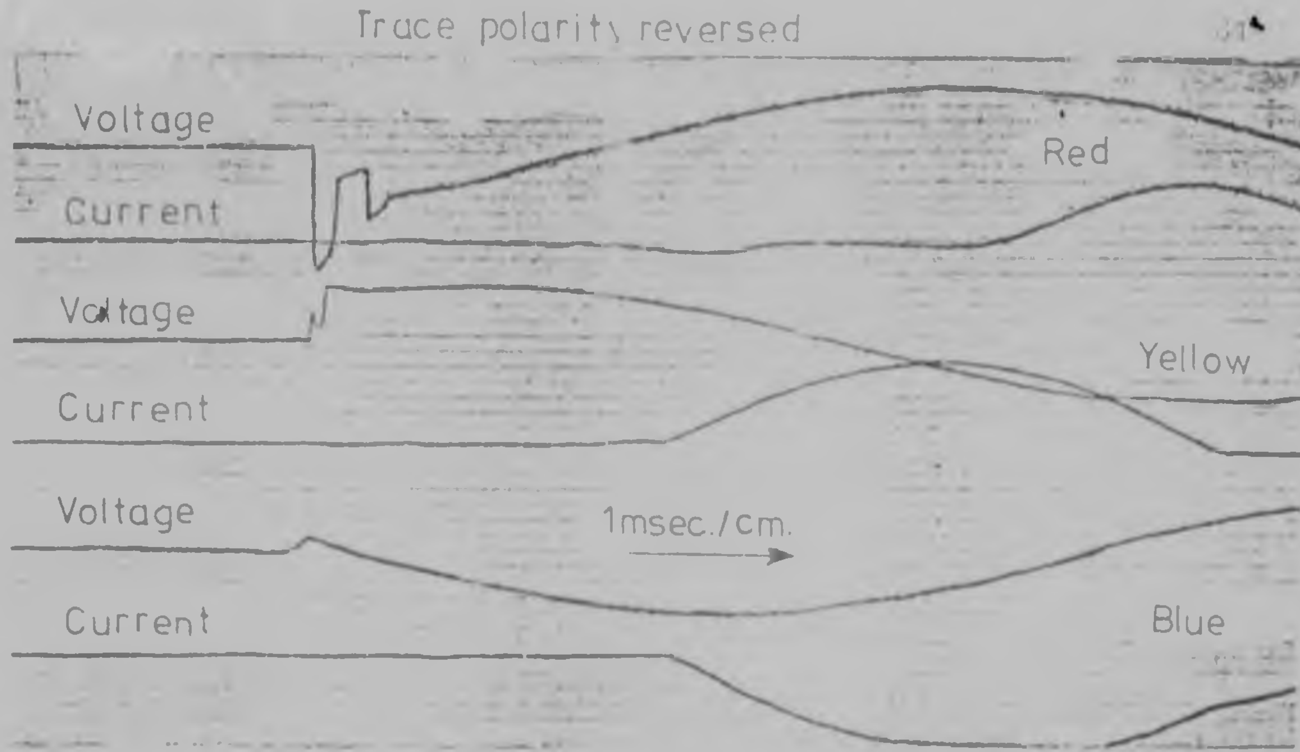
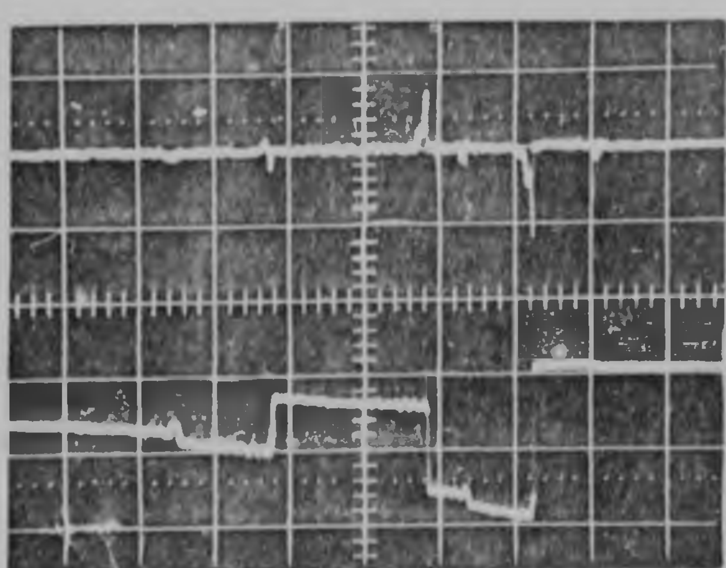
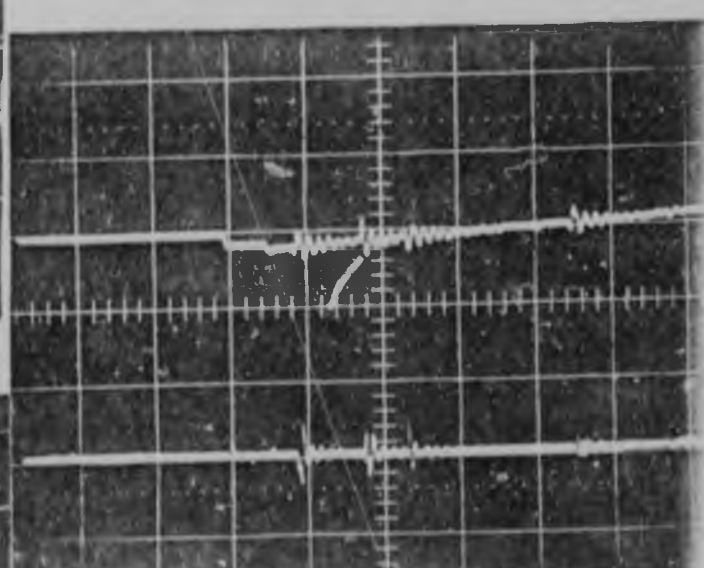


Fig. 4.23. Transformer switch-on transients D

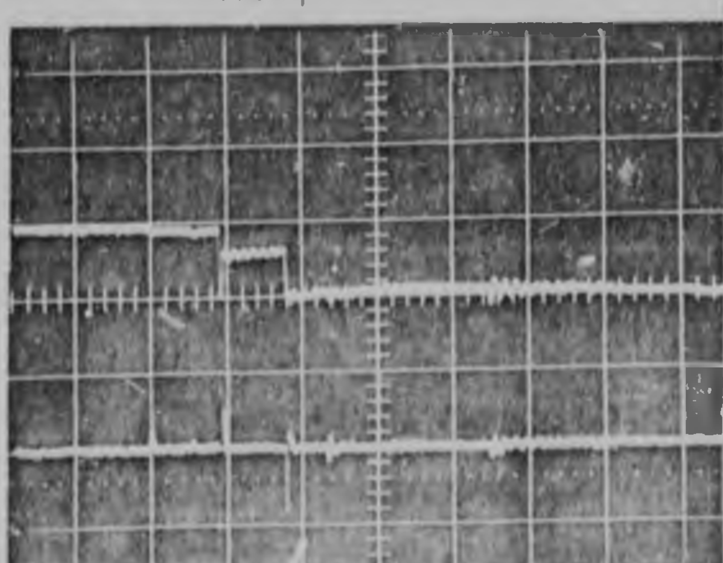


Red phase



Blue phase

Voltage: 1 p.u./div.(Top trace)
Current: 50 A./div.(Bottom trac
Time: 200 µsec./div.



Yellow phase

	Switch ON
Max. Overvoltage Recorded (p.u. peak) Average Overvoltage (p.u. peak) Standard Deviation	1.4 0.87 0.28
Max. Voltage Swing Recorded (p.u.pk-pk) Average Voltage Swing (p.u. pk-pk) Standard Deviation	1.7 0.90 0.36
Max. Number of strikes recorded Average number of strikes Standard Deviation	4 2.18 1.07
Max. Duration of Transient recorded (ms) Average Duration of Transient (ms) Standard Deviation	2.03 0.85 0.61

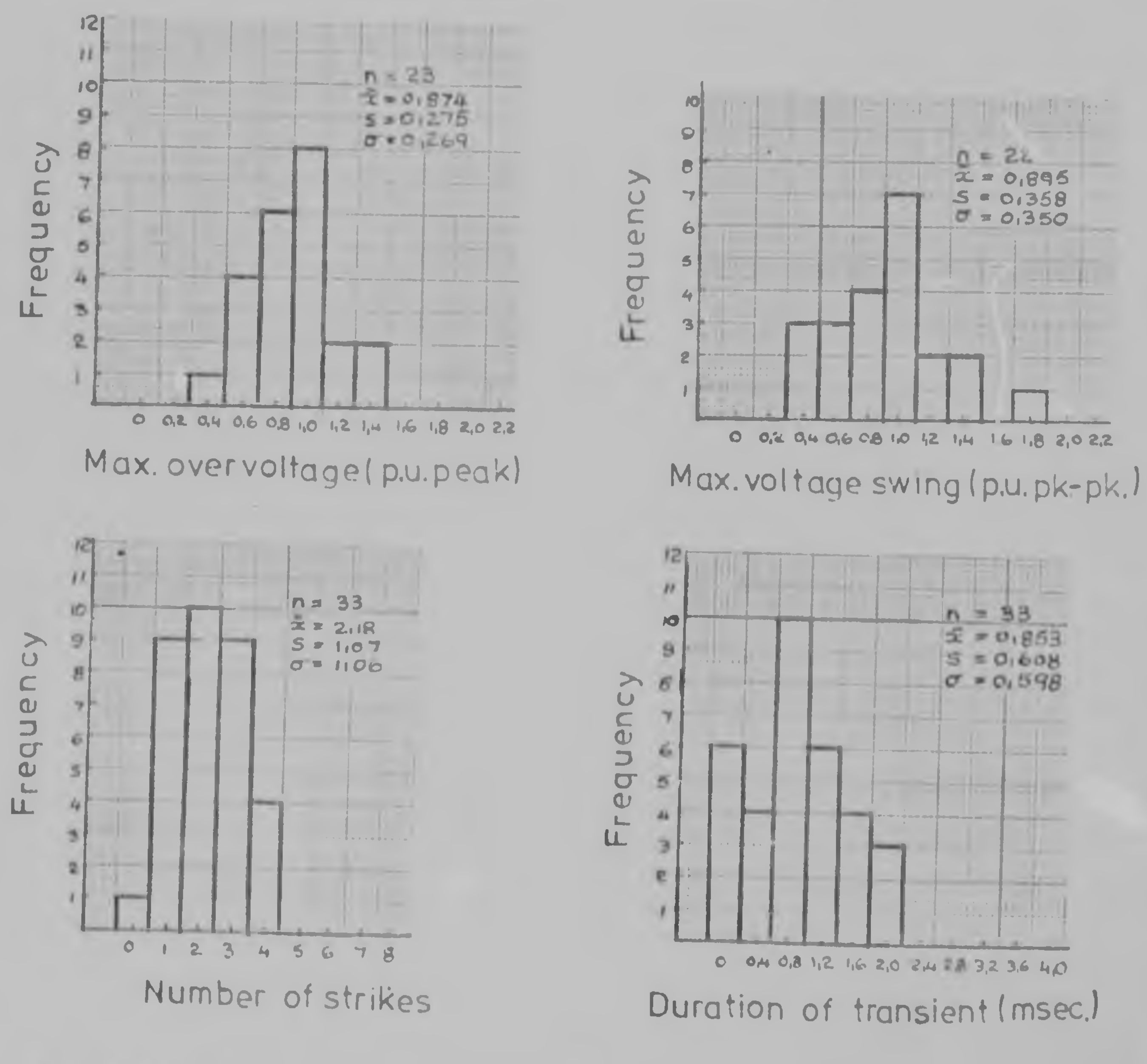


Fig.4.24. Results of transformer switch-on tests E.

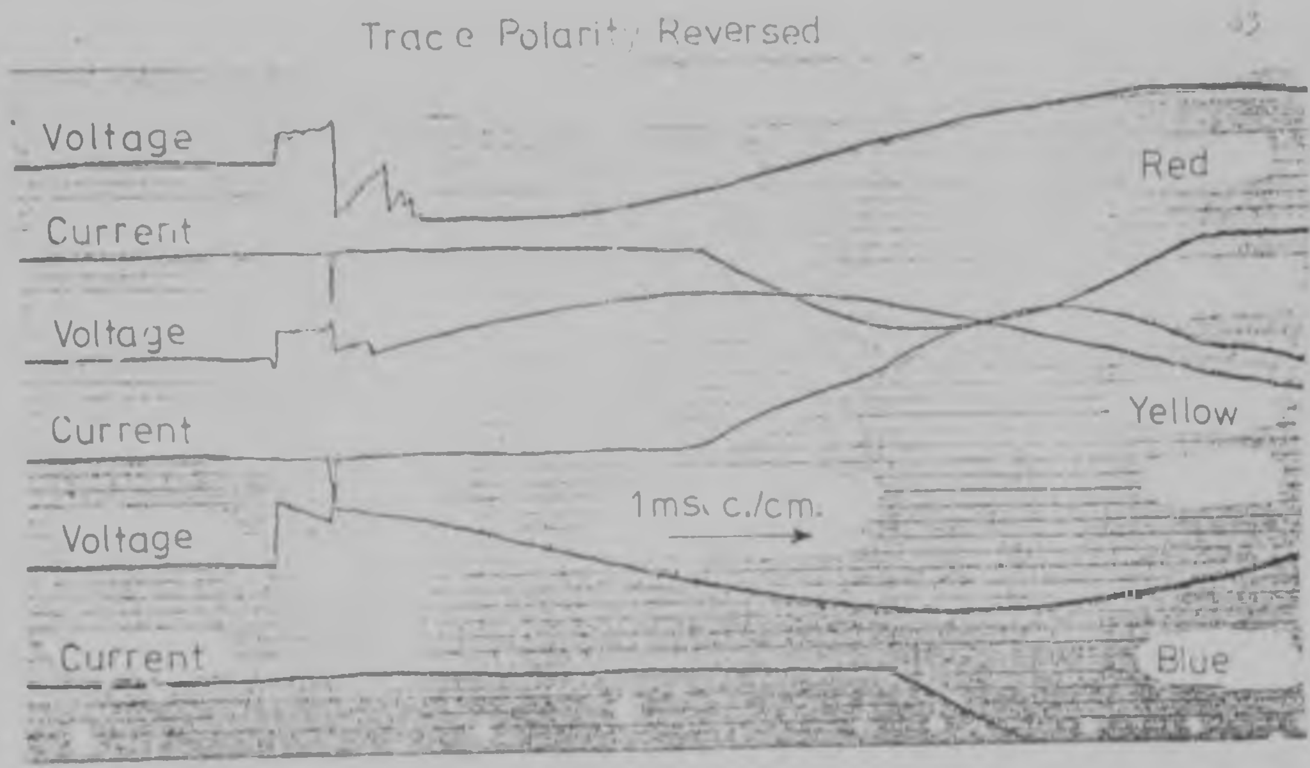
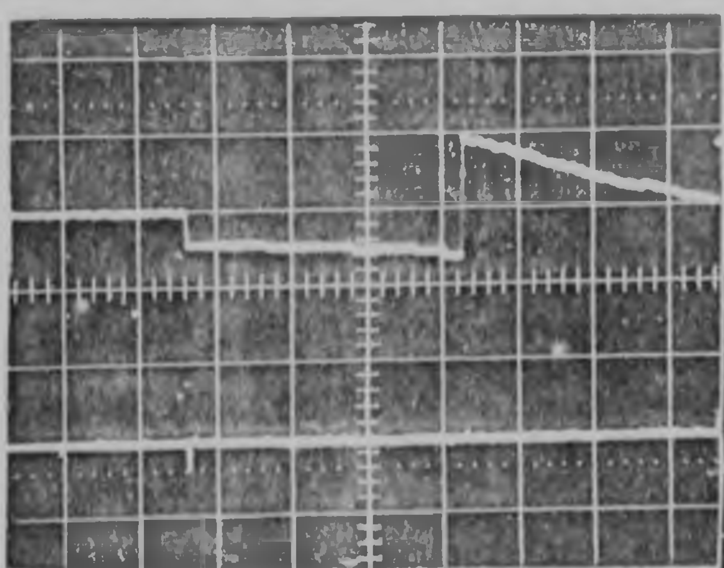
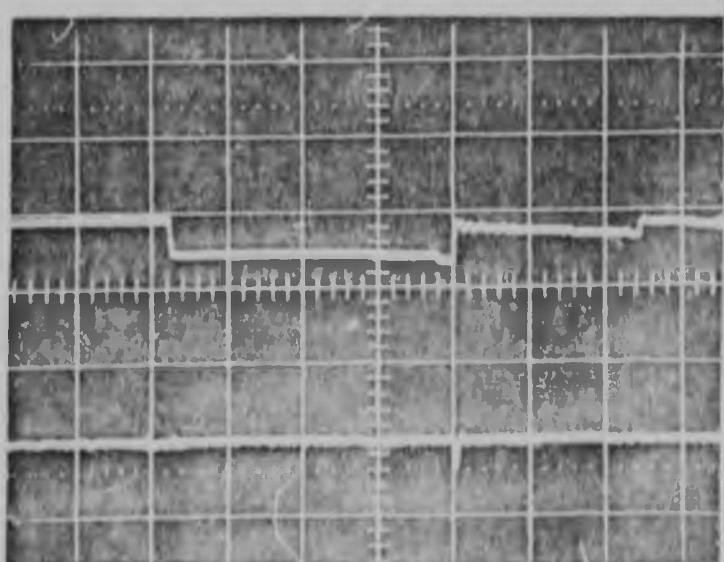


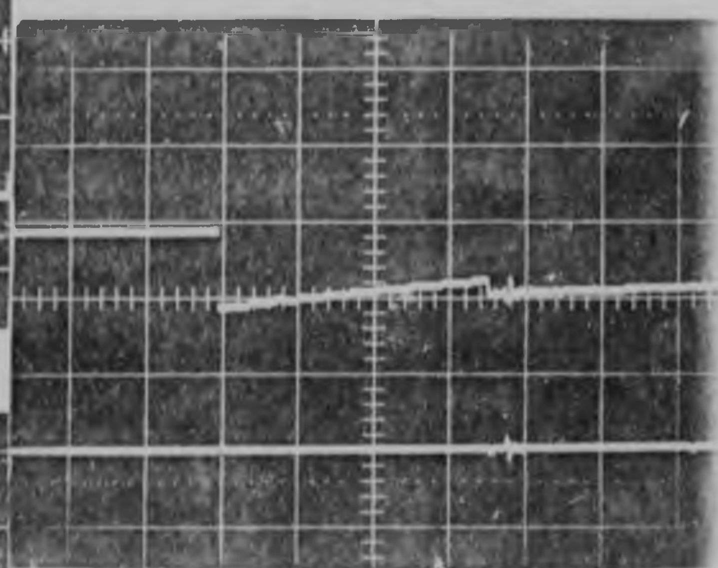
Fig.4.25. Transformer switch-on tests E.



Red phase



Yellow phase



Blue phase

Voltage: 1 p.u./div. (Top trace)

Current: 50 A./div. (Bottom trace)

Time 200 μsec./div.

	Switch ON
Max.Overvoltage recorded (p.u. peak) Average Max.Overvoltage (p.u. peak) Standard Deviation	1.2 0.79 0.25
Max.Voltage Swing Recorded (p.u. peak-peak) Average Max.Voltage Swing (p.u. peak-peak) Standard Deviation	1.4 0.88 0.32
Max.Number of strikes recorded Average number of strikes Standard Deviation	5 2.75 1.36
Max.Duration of Transient Recorded (ms) Average Duration of Transient (ms) Standard Deviation	2.03 1.2 0.67

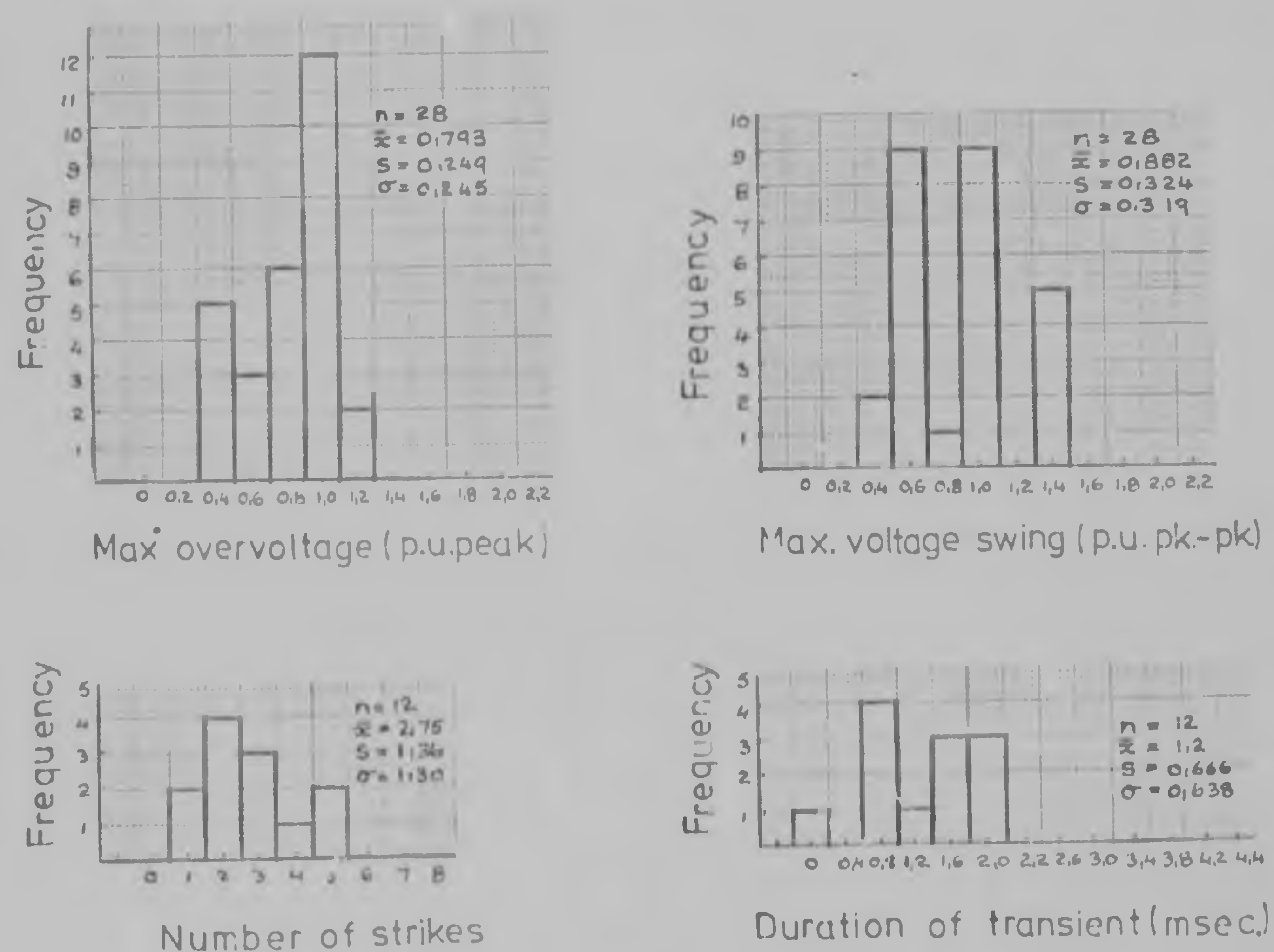


Fig. 4.26. Results of transformer switch-on tests F

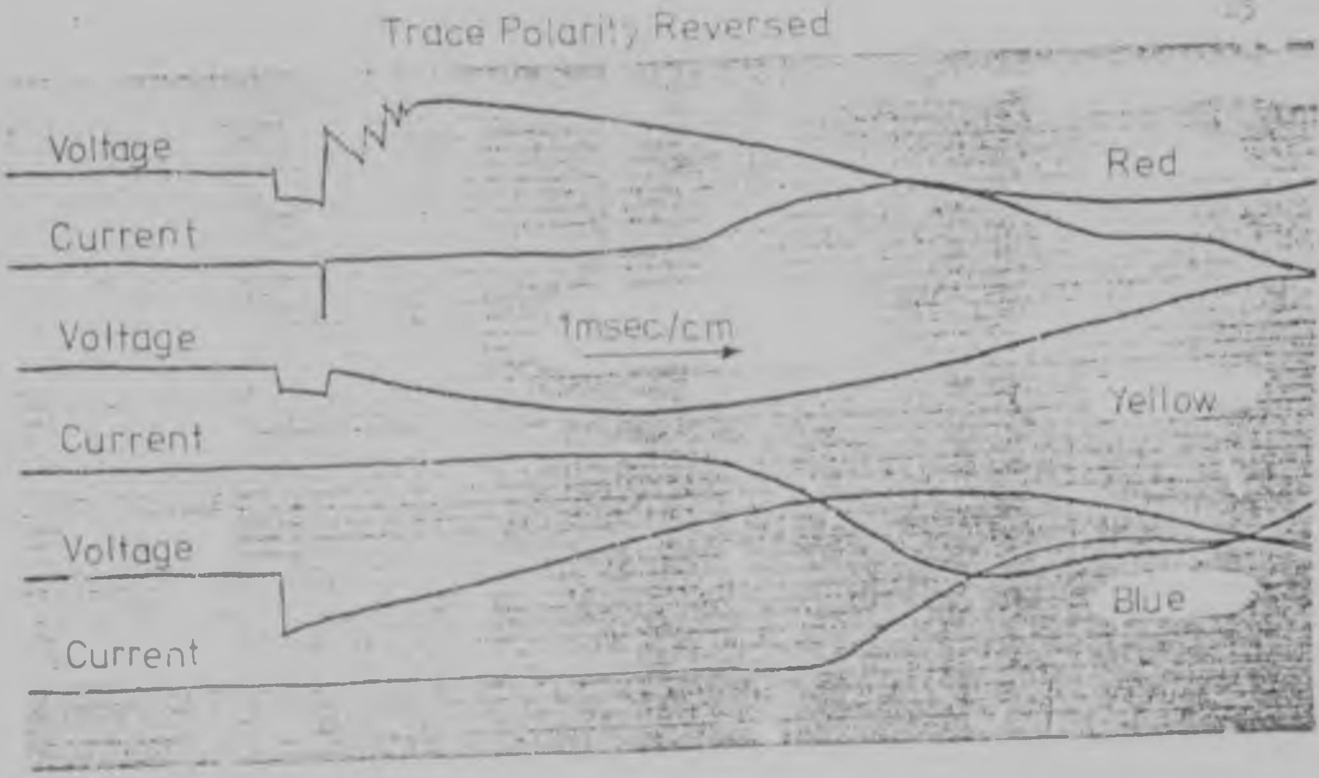
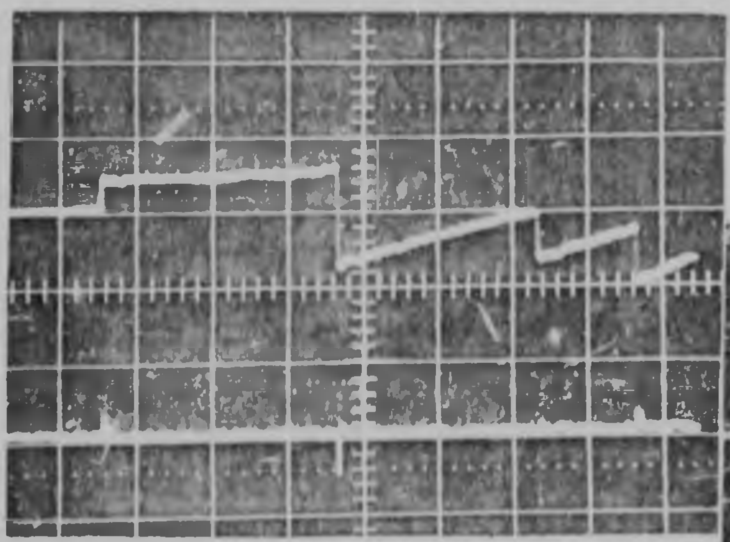
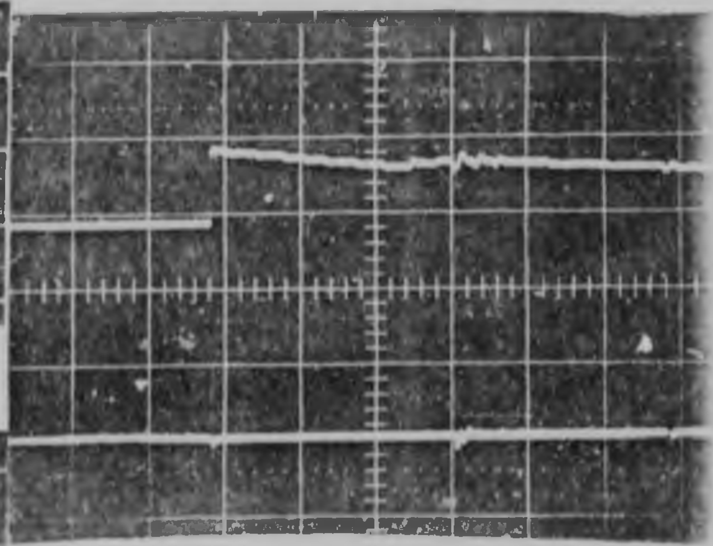


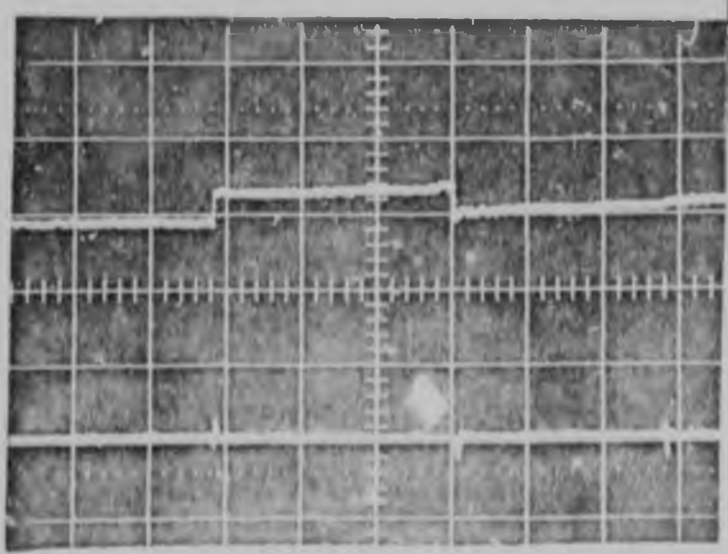
Fig.4.27 Transformer switch-on transients F



Red phase



Blue phase



Yellow phase

Voltage: 1 p.u./div. (Top trace)

Current: 50 A /div.(Bottom trace)

Time: 2 00 μsec./div.

was also on the simulated circuit that transients were observed to exceed 2,0 p.u. contrary to what had been published. The form of these transients is also very amenable to analysis, and the various frequencies present can be attributed to various oscillations taking place in the circuit. Also clearly discernable is the manner in which the strikes are doubled due to mismatch of circuit surge impedances.

However, the only true way of determining prestriking phenomena is with actual circuit elements. For this reason over 200 switch-on operations were monitored switching an actual motor and transformer, under various circuit configurations.

The rates of rise of prestrikes as measured at the motor terminals was greatest for short cables, and a value of 25 kV/µsec. was recorded for one switch-on transient. This was for a practically worst case, as supply capacitance was in abundance and there was no supply cable to speak of. Also the motor switched was of relatively high surge impedance (2,2 kohm.).

Only voltage swings are shown recorded for the motor tests. As with restrikes, it is only the rates of rise which are really important, as it is these which can lead to turn to turn insulation failure.

Prestrike transients, in the worst case, can be considered to involve 20 major strikes, with swings at or just about 3,0 p.u. The rise times will not be less than 0,5 µsec. With longer cables, or higher impedance supplies, rates of rise and numbers of major strikes are reduced.

The above only applies to the GEC contactor switching motors, and other types of contactors may well produce different results.

The rates of rise, however, are a function of the circuit parameters, and any switch which prestrikes will have similar rates of rise.

A summary of the results obtained when switching the 250 kVA transformer is shown in table 4.1. The maximum number of prestrikes recorded was 5 with an average of 2. The largest switch-on overvoltage recorded was 2,0 p.u. with an average of 0,96 p.u. The figures for voltage swing are similar. There was no superimposed "ringing" present on the prestrike transients, except for a very small amount in test series D.

All the transients were of low magnitude and were of no danger to the distribution transformer used in the tests, which had a lightning impulse level of 75 kV (almost 14 p.u.).

The equipment used to monitor the transients was hired, and unfortunately there was a fault in the triggering unit which triggered the oscilloscope used to measure rates of rise. Consequently, no rates of rise of transient voltages or currents were measured.

Referring to table 4.1, a comparison between tests A and B, C and D, E and F shows that the overvoltages generated when there was power factor correction capacitance connected to the supply, were more severe than when this capacitance was absent.

Other less significant conclusions may be drawn by comparison of the test results of the various test circuits.

Comparing tests A with E and B with F indicates that when power factor correction capacitors were connected to the supply, the switch-on overvoltages generated were worse when there was no supply cable i.e. directly connected.

Also, with power factor correction capacitance, a comparison between tests D and E indicates that prestrike overvoltages were

	SWITCH-ON					
	A	B	C	D	E	F
Max.Overvoltage (p.u. peak) Average Overvoltage (p.u. peak) Standard Deviation	2.00 1.14 0.41	1.20 0.81 0.28	1.40 0.81 0.33	2.00 1.32 0.95	1.40 0.87 0.28	1.20 0.79 0.25
Max.Voltage Swing (p.u. pk-pk) Average Voltage Swing (p.u. pk-pk) Standard Deviation	2.00 1.18 0.47	1.60 0.89 0.42	1.40 0.88 0.38	2.00 1.09 0.44	1.70 0.90 0.36	1.40 0.88 0.32
Maximum Number of Strikes Average Number of Strikes Standard Deviation	4.00 2.22 1.07	4.00 1.93 1.26	3.00 1.63 0.67	3.00 1.30 0.81	4.00 2.18 1.07	5.00 2.75 1.36
Maximum duration of Transients (ms) Average Duration of Transien (ms) Standard Deviation	2.18 1.09 0.57	2.03 1.03 0.58	2.19 0.97 0.63	1.88 0.61 0.51	2.03 0.85 0.61	2.03 1.20 0.67

A - With p.f. correction cap. ; short load cable ; no supply cable.
B - Without p.f. correction cap ; short load cable ; no supply cable.
C - Without p.f. correction cap ; long load cable ; short supply cable.
D - With p.f. correction cap ; long load cable ; short supply cable.
E - With p.f. correction cap ; short load cable ; long supply cable.
F - Without p.f. correction cap ; short load cable ; long supply cable.

Table 4.1 Summary of transients measured under various circuit conditions.

larger for the circuit with long load cable and short supply cable. However without power factor correction capacitance, the prestrike overvoltages for the two circuits were similar.

An interesting feature of the transformer tests was the monitoring of the high frequency currents when striking took place. It is difficult from the results to determine the contactors high frequency current interrupting ability. Tests conducted in the U.K. by GEC Industrial Controls yielded a figure of, typically 20 A/µsec. and from what can be d mined from the results this is approx. correct.

It is interesting to compare this figure with those determined by Ismail(for vacuum circuit breaker interrupters. He obtained approx. 250 A/µsec. for the GE interrupter and between 400 and 750 A/µsec. for the V.I.L. interrupter. It is to be expected therefore that the circuit breaker interrupt high frequency currents more easily than the GEC vacuum contactor, and that the contactor will allow more "ringing" to take place before finally interrupting the high frequency current. This is more particularly discernable in the motor and simulated test circuits.

Also of interest, in the transformer tests, are the magnetising inrush currents which can just be seen starting to flow.

CHAPTER 5

RESTRIKE TRANSIENTS

5.1 MECHANISM OF A RESTRIKE

When switching off a stalled induction motor, lightly loaded transformer, or inductor, because of the low power factor, current zeros approach co-incidence with supply system peak voltages. Immediately following arc interruption, the switch gap is called upon to withstand a high voltage. If the switch gap is very small, at this instant in time, it may break down, and with suitable circuit constants, initiate a restrike transient. The transient is similar to the previously described prestrike transient with the important difference that the gap is increasing and with the switch breakdown strength growing, the magnitude of successive restrikes will increase.

At each reignition, some of the energy stored in the load is returned to the source. Because of this, the prospective voltage to which the transient is attempting to rise, diminishes with each successive reignition and the energy in the load decreases[47]. However, as mentioned, the voltage of each successive reignition increases as the gap separation is increasing and can support increasingly higher voltage. See figure 5.1 (a) and (b).

5.2 RELATIONSHIP TO CURRENT CHOPPING

The initial prospective overvoltages in figure 5.1 (a) and (b) are determined by the current chopped and the surge impedance of the circuit as shown in paragraph 3.6. Thus for identical circuits,

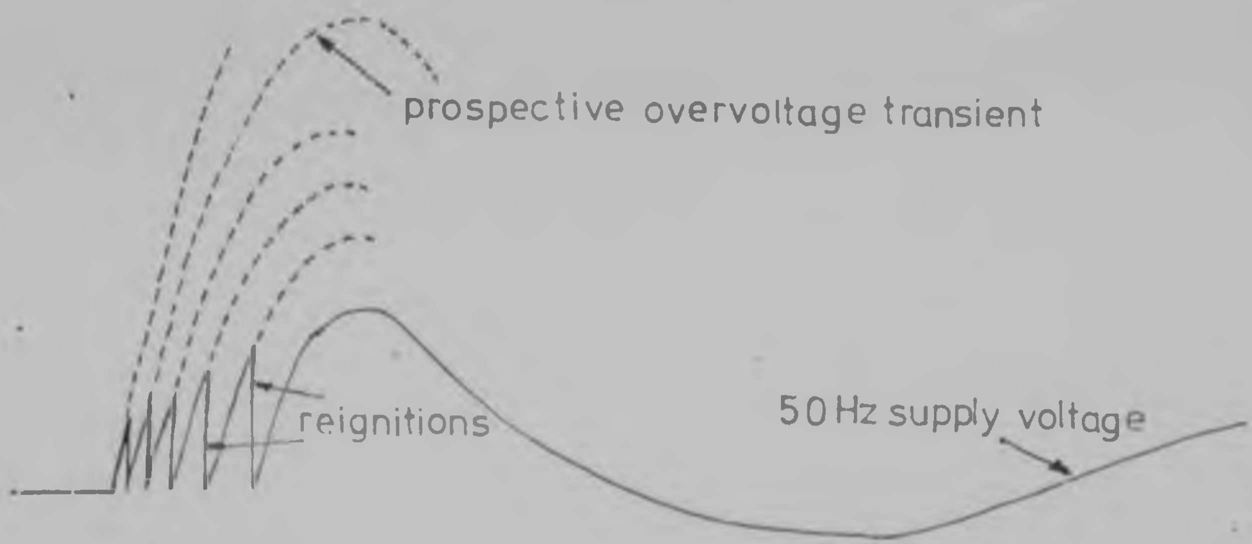


Fig.5.1.(a). Voltage across contacts.

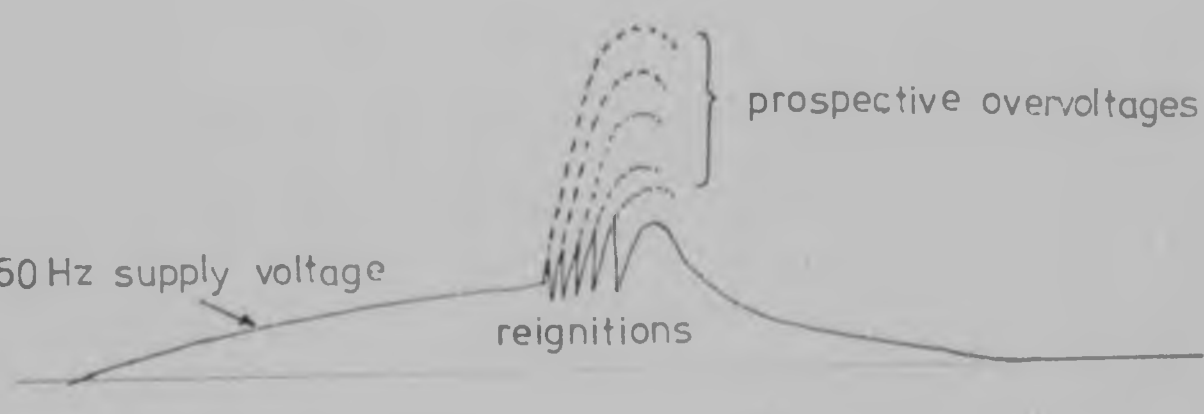


Fig.5.1.(b). Load voltage.

switches having higher chopping current levels than others, will breakdown relatively earlier than those with low current chopping levels. The magnitude of the restrikes however is primarily determined by the dielectric strength of the individual switches as discussed further in 5.4.

5.3 ACTUAL TESTS ON A MOTOR

No restriking can occur when a motor is switched off at full speed or near full speed. The reason for this is that the motor is still generating back emf. and there exists very little potential difference across the contactor once interruption occurs. However, as can be seen by the following tests, there is a very good probability of restriking occurring when the motor is switched off at standstill, or very near to standstill, as would occur when inching a motor for example.

The tests were conducted on the same circuit as that for 3.7 and 4.5 and is as shown in figure 3.20. One hundred and two switch-off operations whilst drawing starting current (no back emf.) were recorded, using the 6,6 kV GEC vacuum contactor with 18m. of cable connected between the contactor and the motor. All three phases were monitored, yielding a total of 185 transients.

Thirty-three per cent of the transients were "clean" breaks with only current chopping occurring as can be seen in figure 5.2. Thirty-six per cent included unsuccessful attempts to break the current with restriking occurring. A typical record of this is shown in figure 5.3. Thirty-one per cent were of the type where restriking occurred, but the current was cut off and current chopping eventually occurred. A typical record of this is shown in figure 5.4.

The average max. voltage swing of all these transients was 1,67 p.u. with a standard deviation of 0,63 p.u. and a maximum recorded of 3,6 p.u. The greatest rate of rise that could be recorded with these transients was 3,0 p.u. in 1 μsec., i.e. 16,2 kV/μsec. (approx.) and the frequency of the current chopping was 10 kHz as before.

The histogram of these results is shown in figure 5.5. Fifty-five switch-off operations were also recorded with 90m. of cable

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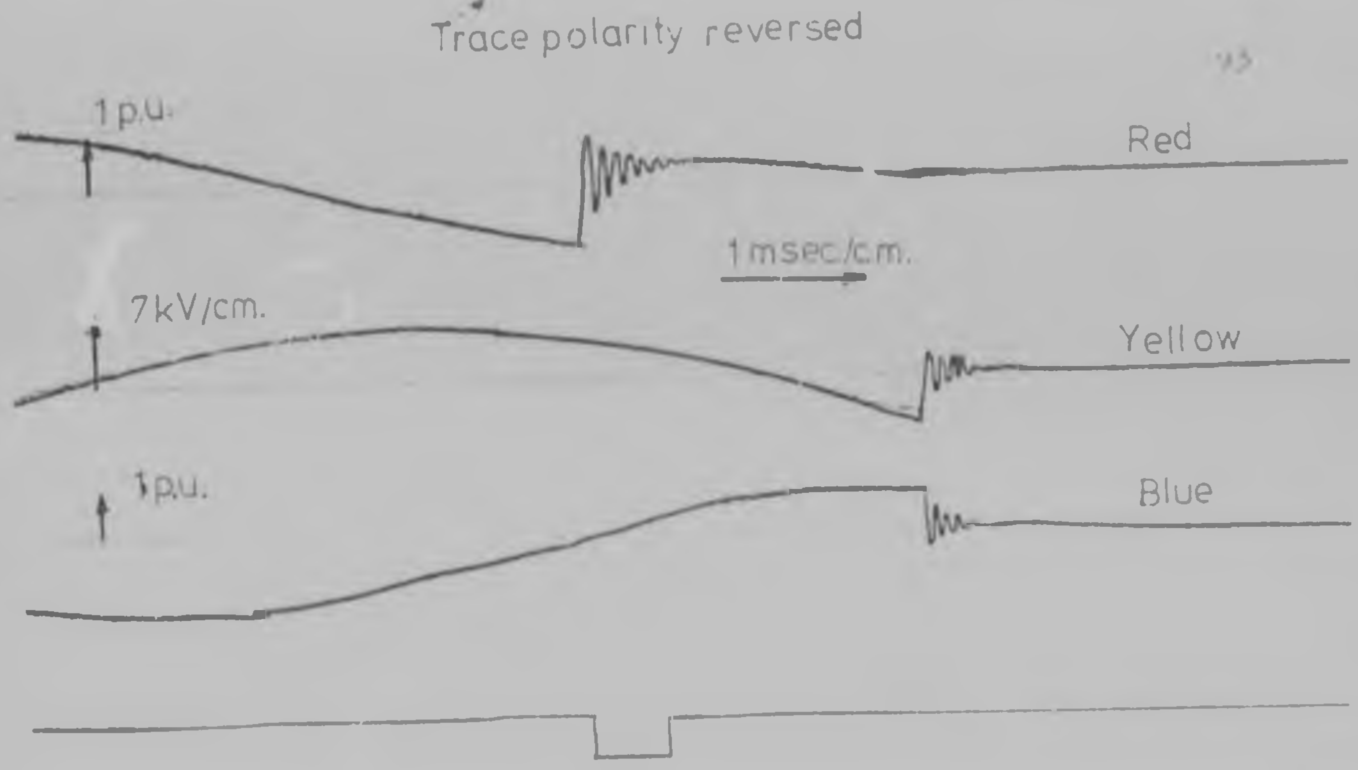
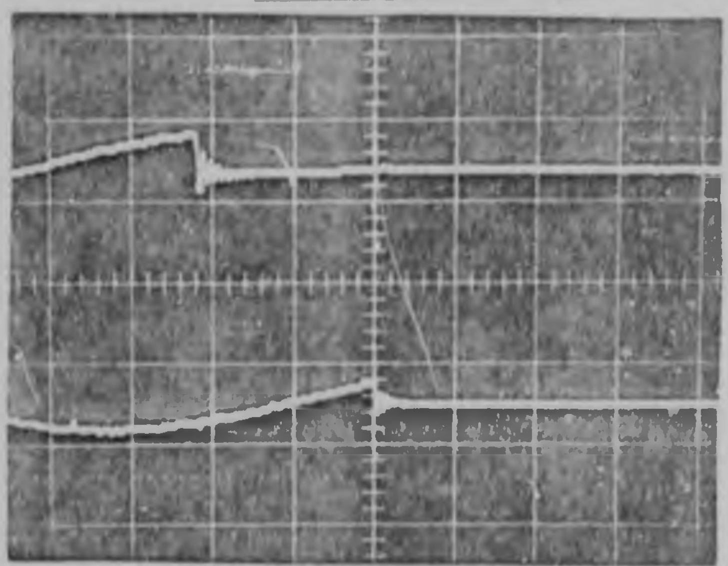
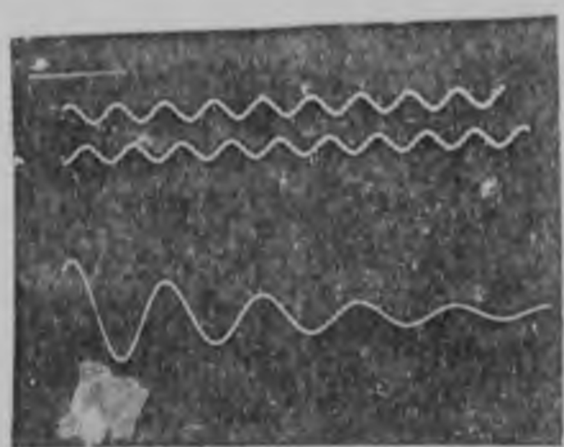
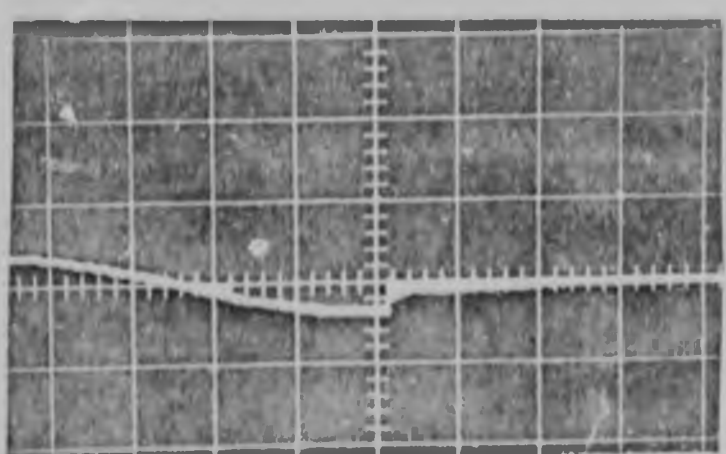


Fig.5.2. Motor switch-off transient.



2,5 p.u./div.
2 msec./div.
Red 0
Yellow 0





2,5 p.u./div.
2 msec./div.
Blue — 0

Top two traces 7 p.u./cm.
3 0 msec./cm

Bottom trace 1,5 p.u./cm.
150 μsec/cm.

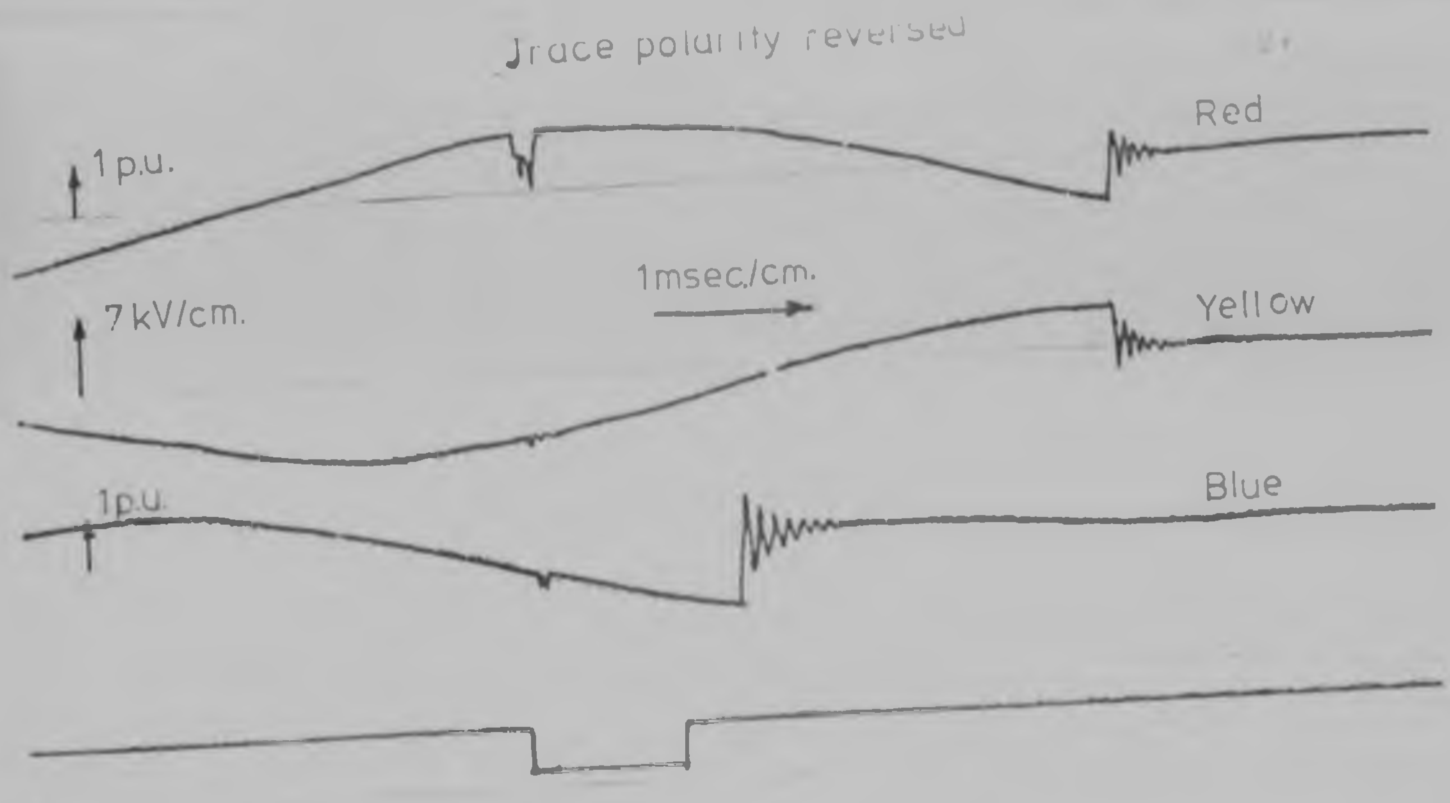
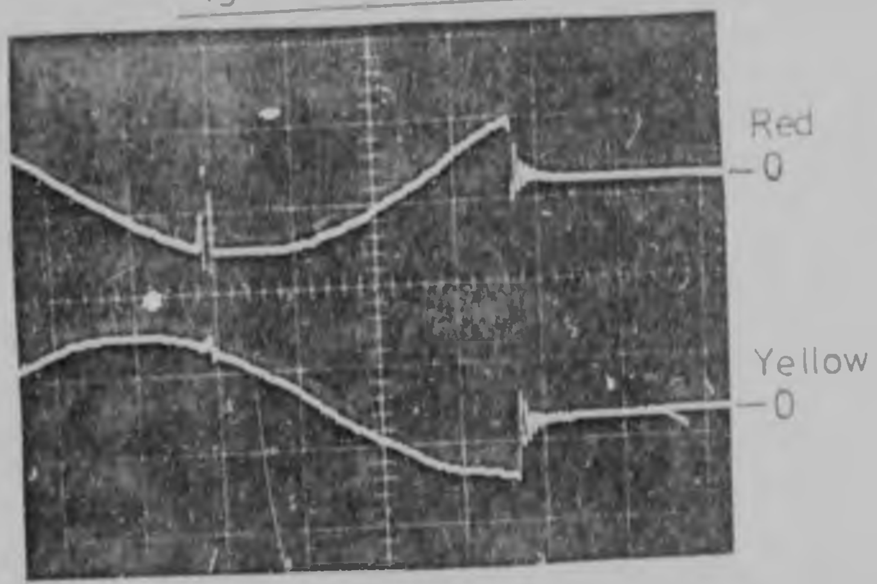
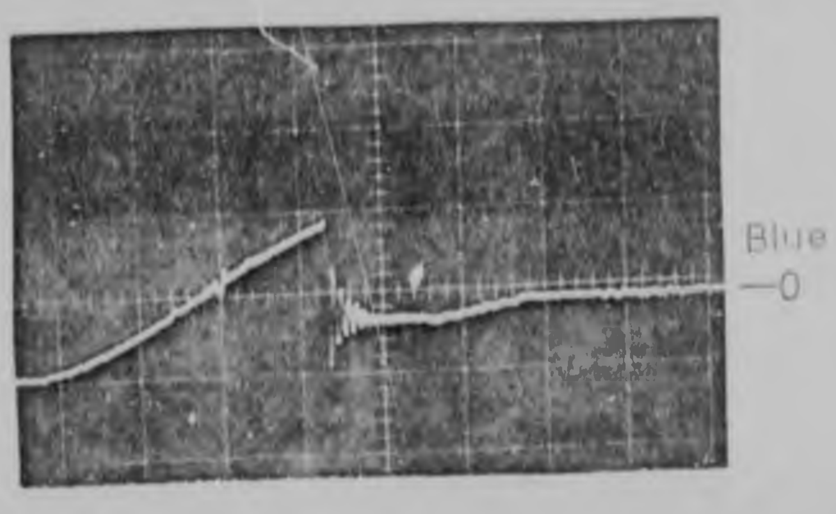


Fig.5.3. Motor switch-off transient.



1p.u./div.
2msec./div.



1p.u./div.
2msec./div.

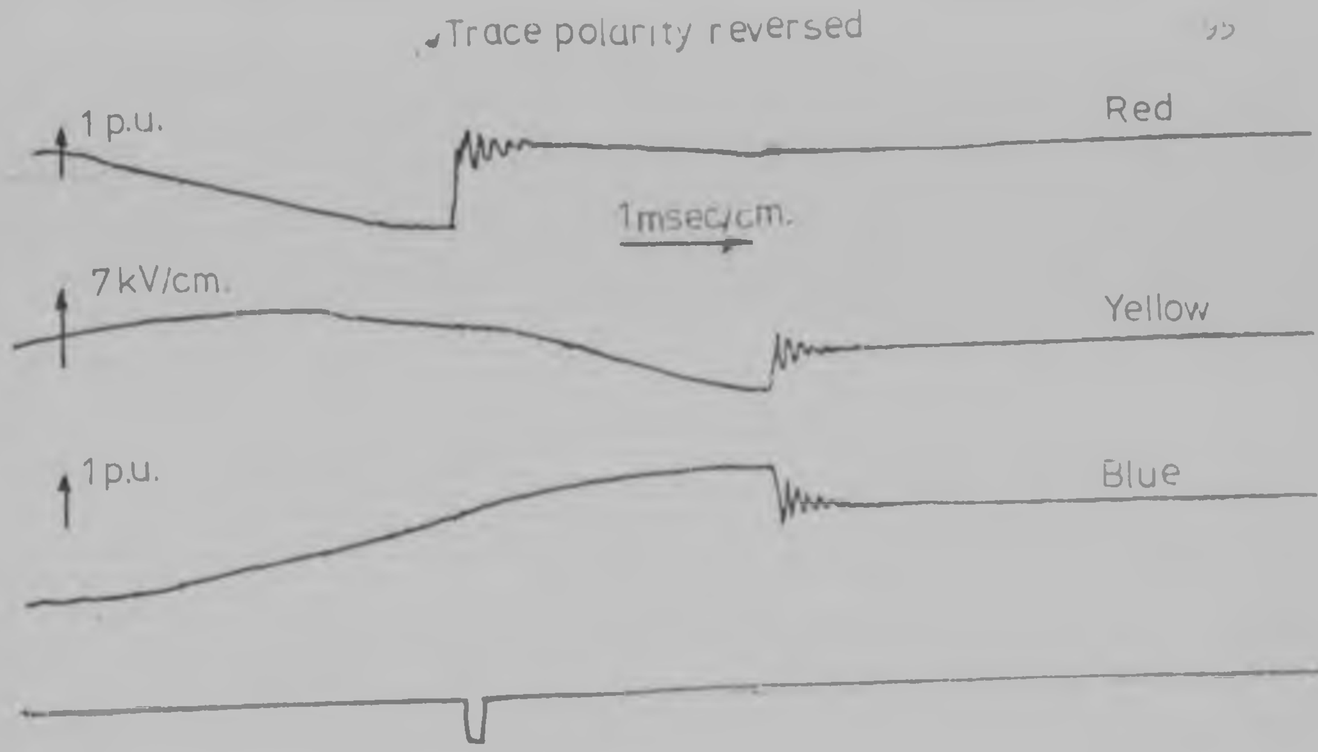
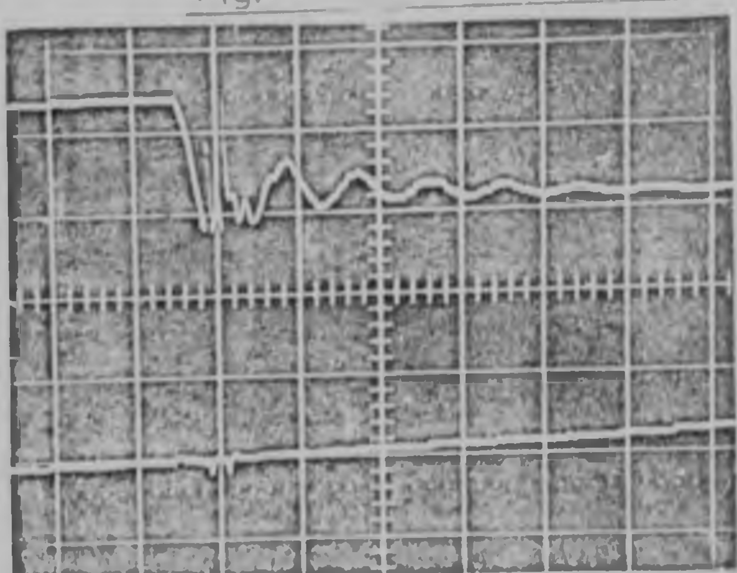
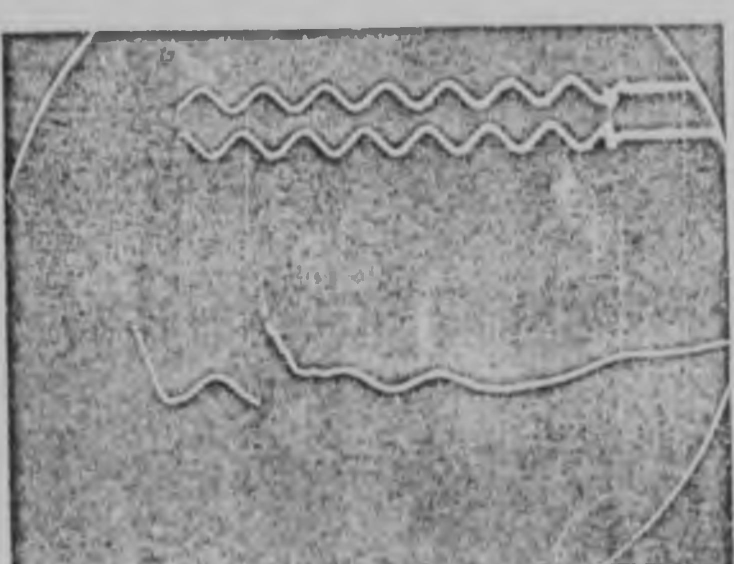


Fig.5.4 Motor switch-off transient.





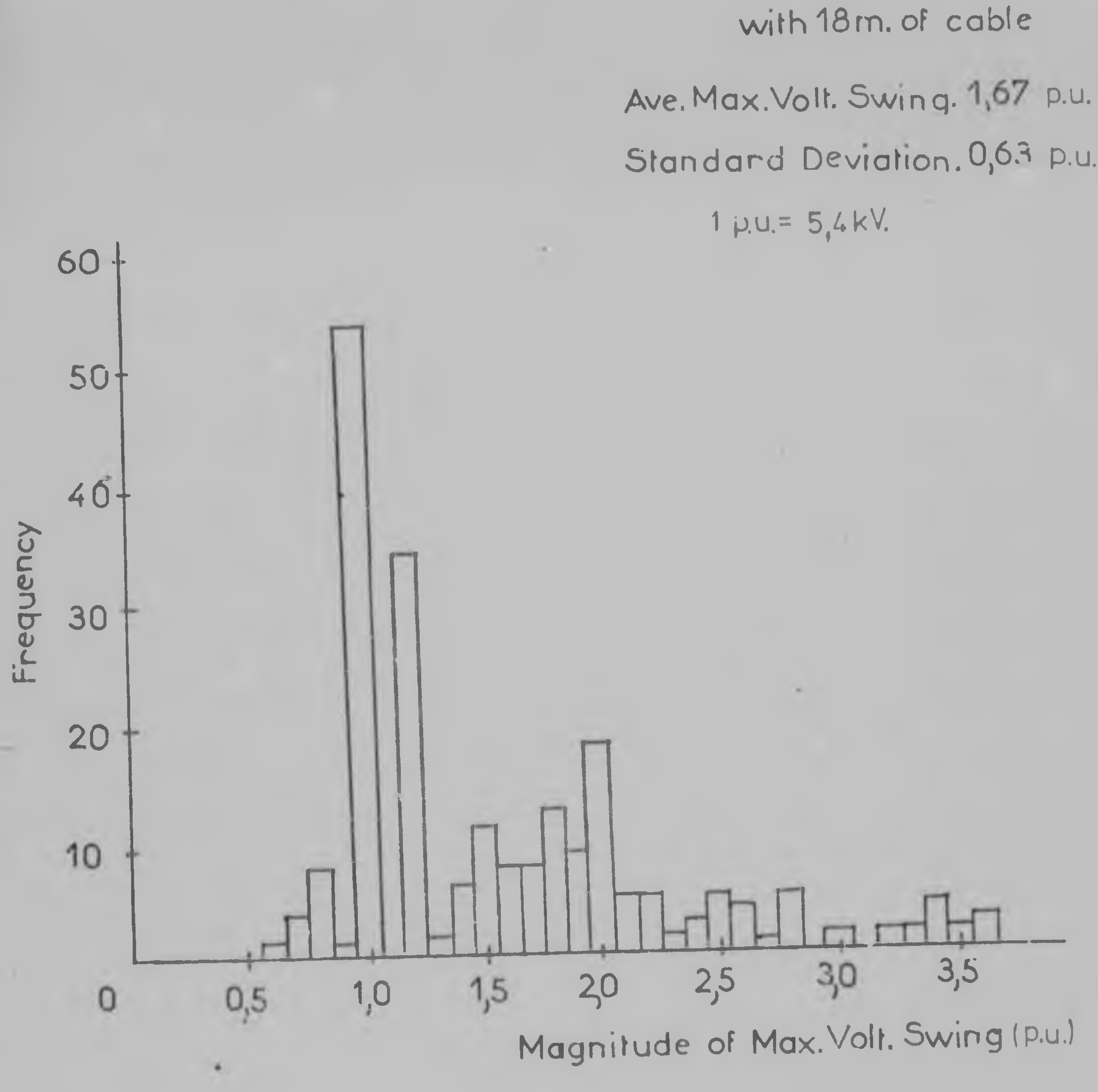


Fig.5.5. Probability of switch-off at start max. voltage swing

between the contactor and the motor. All three phases were again monitored yielding a total of 132 transients. The average max. voltage swing was 2,19 p.u. with a standard deviation of 1,23 p.u. and a max. recorded of 7,5 p.u. This very large transient is shown in figure 5.6 and 5.7. The max. voltage above earth was 4,5 p.u. This transient had a rate of rise of 40,0 kV in 4 µsec., i.e. 10 kV/µsec. This was also the largest rate of rise recorded for this test. The frequency of the current chopping with the longer cable was found to have dropped to 3,5 kHz. The histogram is shown in figure 5.8.

A typical record of voltage escalation occurring at switch-off at start is shown in figure 5.9. The probability of a max. voltage swing occurring above 5,0 p.u. with 18m. of cable was estimated to be approximately zero. The probability of a max. voltage swing above 7,0 p.u. with 90m. of cable at switch-off on start was estimated from the results as being 1 in 2000 operations.

5.4 COMPARISON WITH THEORY

5.4.1 INTRODUCTION

A restrike occurs in a vacuum switch when the recovery voltage across the switch exceeds the dielectric strength after current extinction has occurred. This section uses measurements of dielectric strength and opening speeds of a 6,6 kV GEC vacuum contactor to determine the relative values of restrikes which would occur with different lengths of cable i.e. 18 and 90m., switching a standstill motor. The motor switched by the contactor was assumed to be 225 kW. The cable used in the calculations is 6,6 kV P.I.L.C. 16mm.^{2} x 3 core.

A simplified parallel C and LR circuit is used to calculate polarity reversed

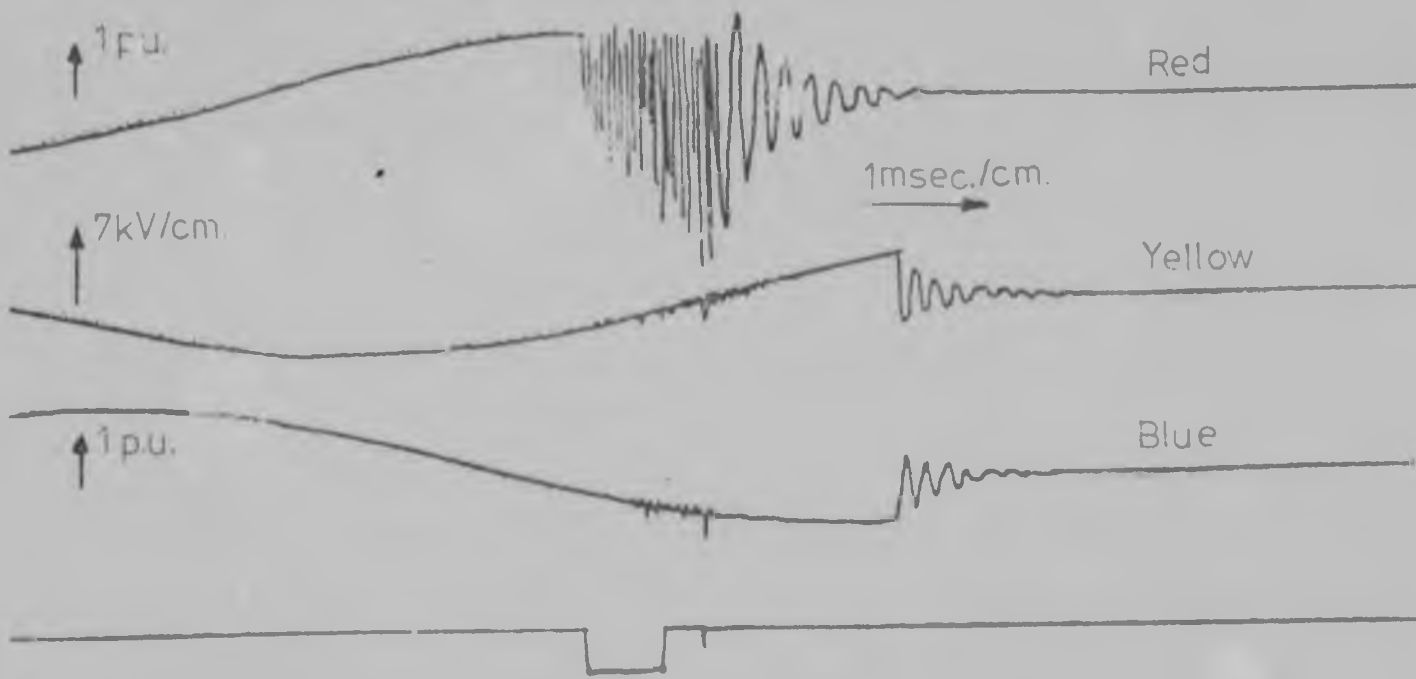
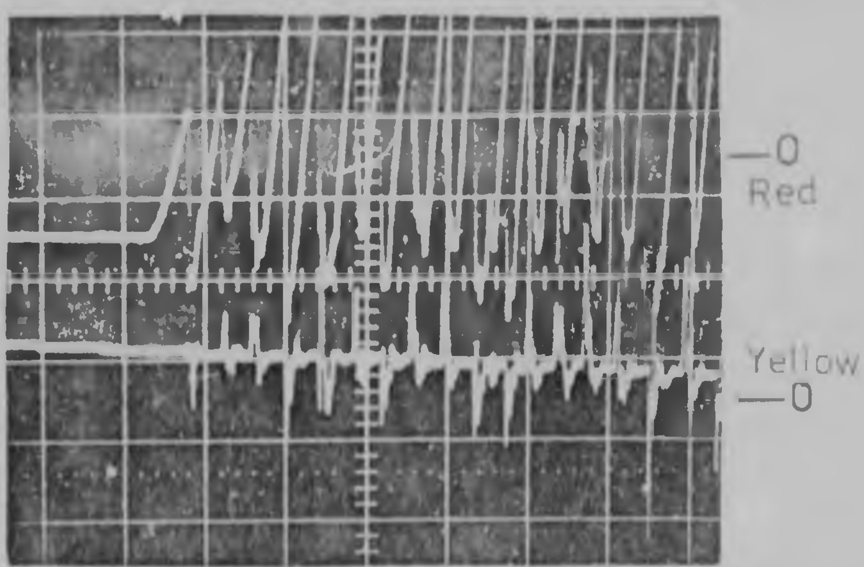
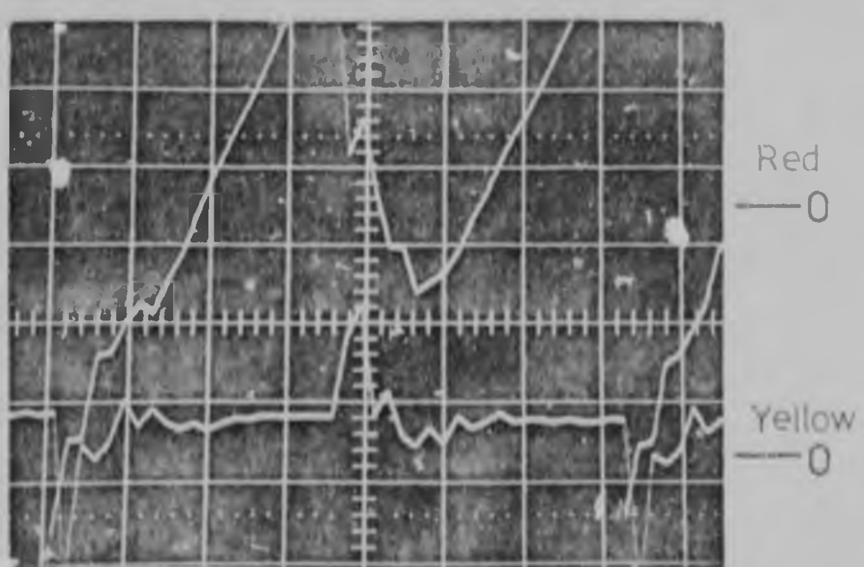


Fig.5.6. Motor switch-off transient



1 p.u./div.
200 μsec./div.



1 p.u./div.
25 μsec/div.

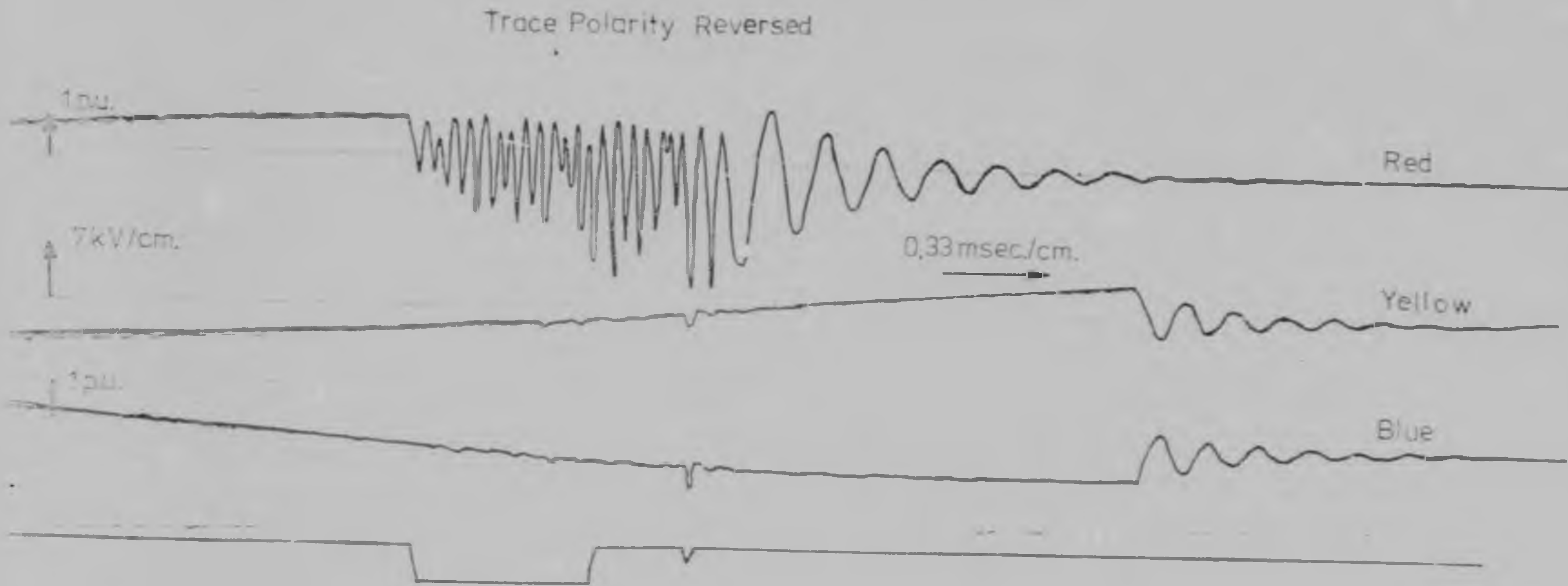


Fig.5.7. Motor switch-off transient.

with 90m of cable

Ave. Max. Voltage Swing. 2,19 p.u.

Standard Deviation. 1,23 p.u.

1 p.u. = 5,4 kV.

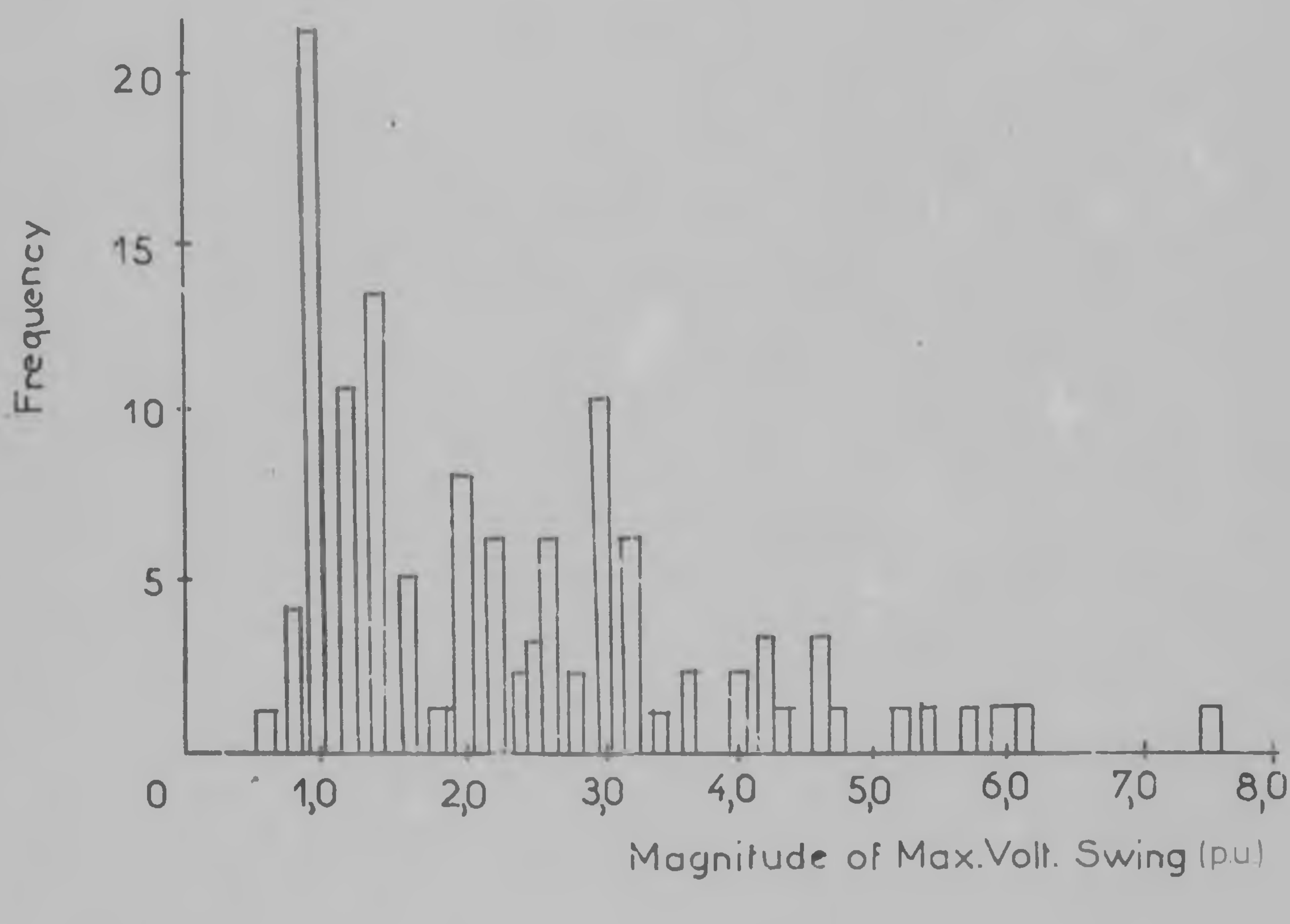


Fig.5.8. Probability of switch-off at start max. voltage swing.

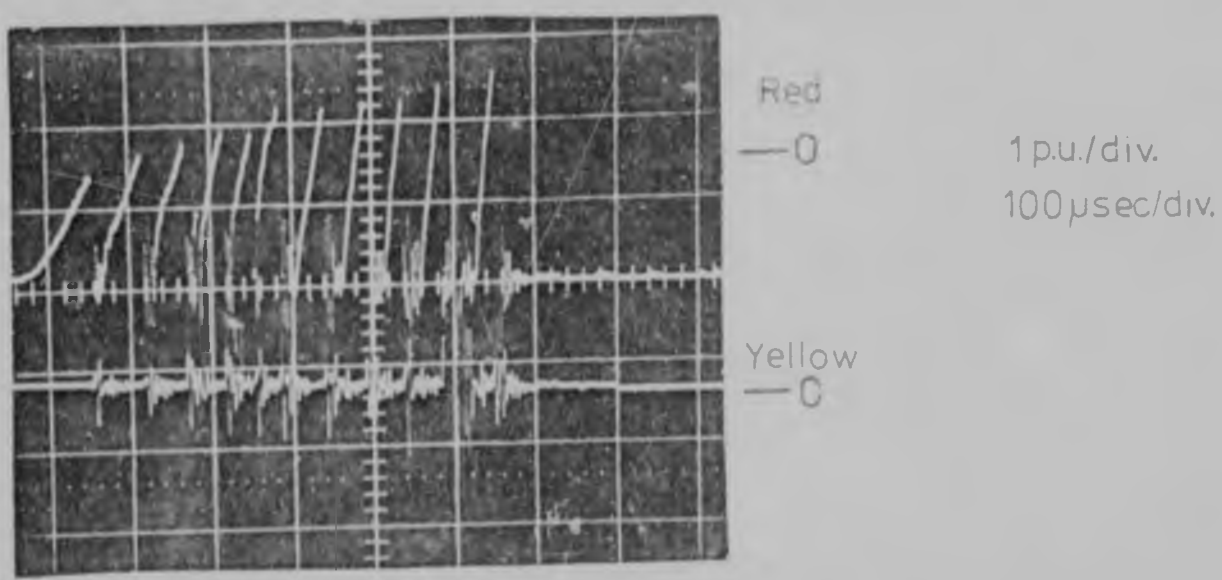


Fig.5.9. Typical voltage escalation on switch-off.

the recovery voltage using the Laplace transform.

Finally, curves are plotted for various times that the contacts open before arc extinction occurs, to show the effects of longer cables on the magnitudes of the restrike overvoltages and the probability of a restrike.

5.4.2 FUNDAMENTAL THEORY

Figure 5.10 shows the general pattern of the restrike phenomenon of a vacuum switch. Once a current extinction occurs, a finite time elapses for the dielectric to recover. The value to which the dielectric recovers, is dependent upon the instant of opening of the contacts before a current zero. The dielectric strength of the contactor has already been shown in figure 4.4. As the frequency of the recovery voltage is high, kHz, the 1/50 impulse strength is used in the calculations and not the 50 c/s dielectric strength, which would produce incorrect results.

The dielectric recovery times in these calculations were taken as for silver contacts in vacuum of 1,27cm. diameter. These are taken from Rich and Farrall [48], and are shown in figure 5.11. In their paper, they state that the recovery time of the dielectric is partly proportional to the number density of the vapour arc. This in turn, is proportional to β where β is given by:-

$$\beta = \frac{M}{2kT}$$

where M = mass of the gas atom

k = Boltzmann constant

T = temperature of the gas.

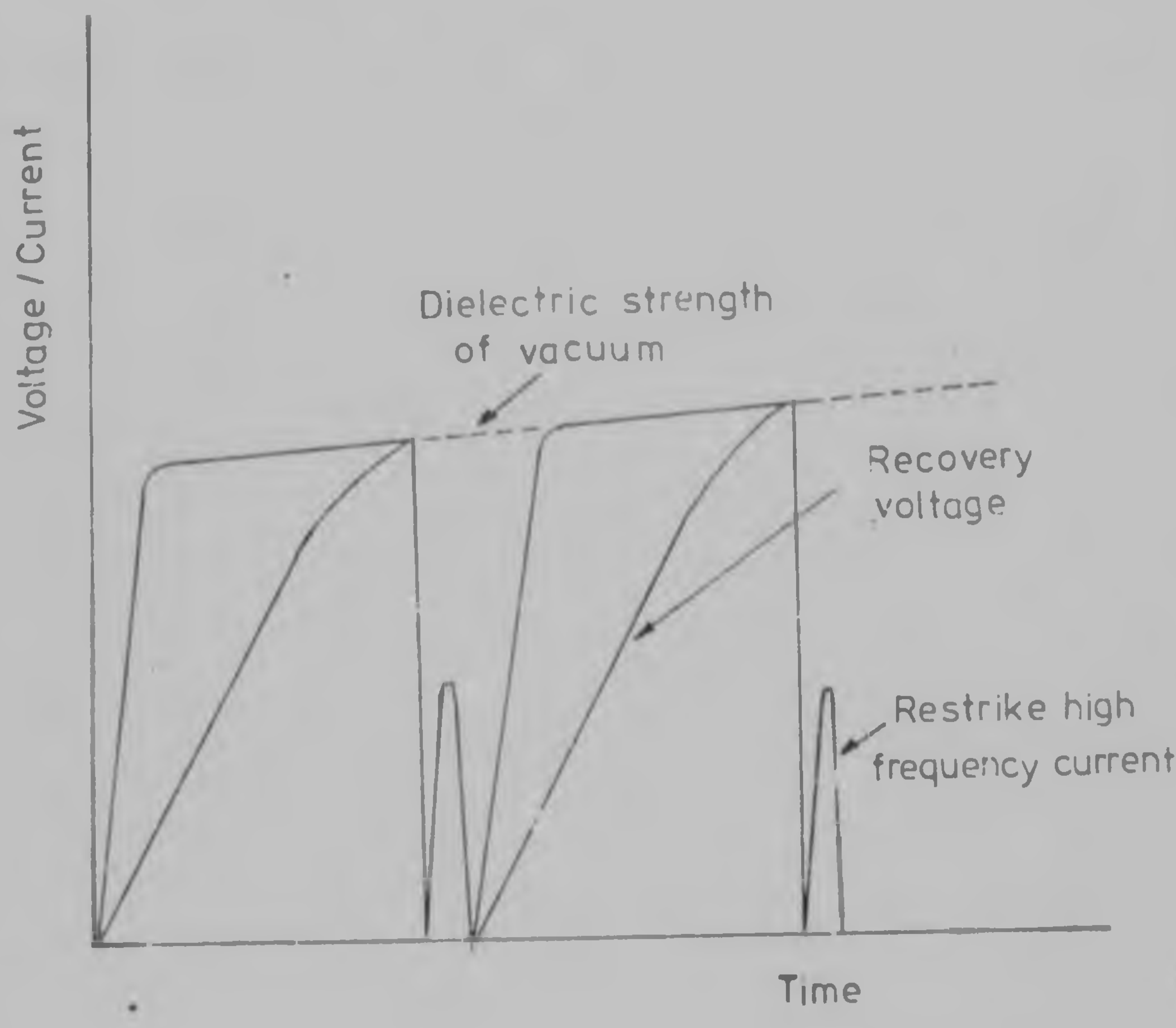


Fig.5.10. General simplified pattern of restriking

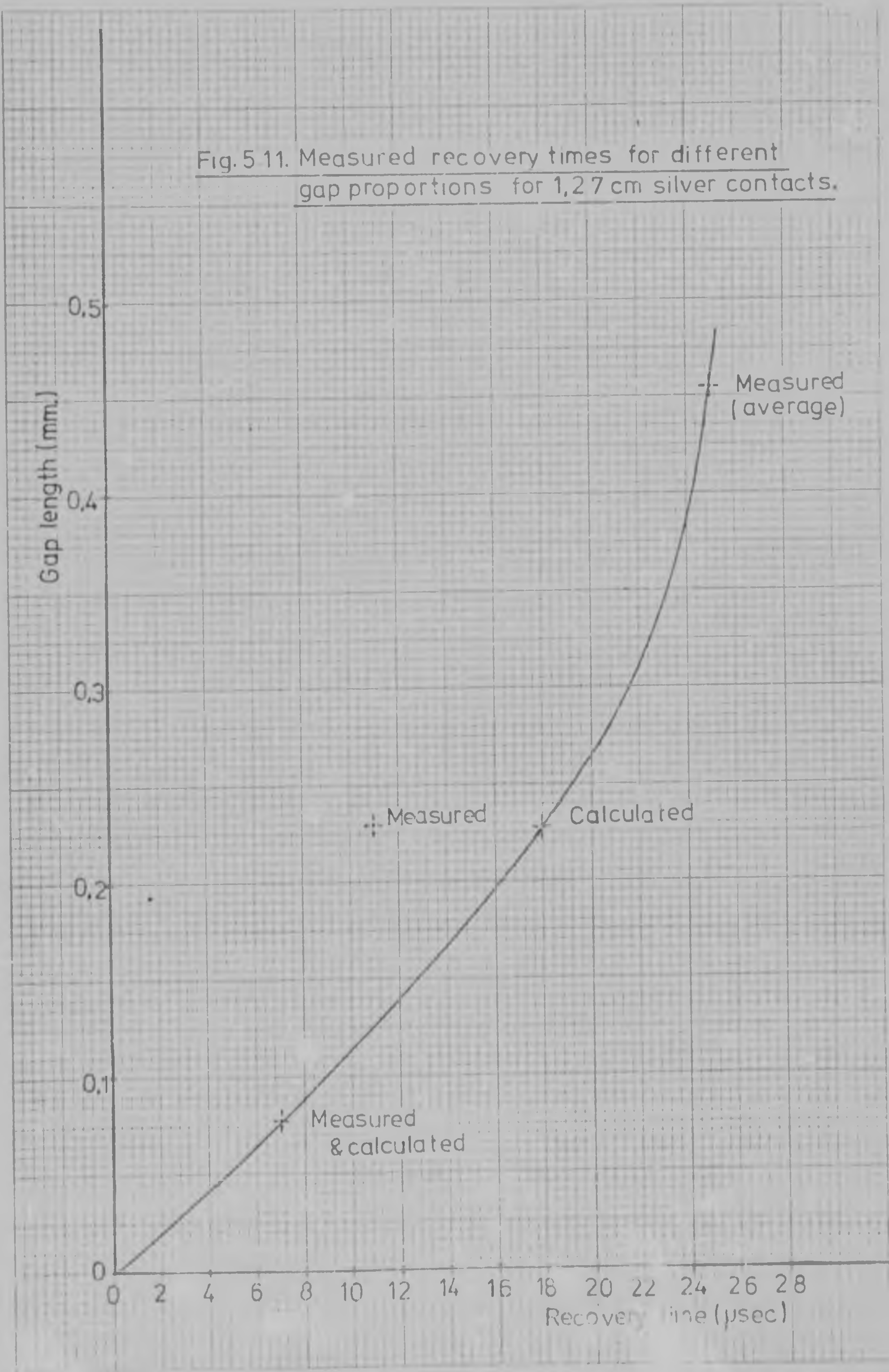


Fig. 5.11. Measured recovery times for different gap proportions for 1,27 cm silver contacts.

GEC's vacuum contactors contain antimony and bismuth, and both these have greater relative atomic masses than silver. Bismuth has a much lower melting point and will therefore contribute the majority of the vapour arc. It's relative atomic mass is 208,98 as compared with silver 107,87. Therefore it is expected that the rise times of the dielectric recovery for the contactor will be shorter than those experienced with silver contacts. But, as shall be seen, these times are much shorter than the rise times of the recovery voltages across the contacts, so do not really enter into the calculations or theory.

Figure 5.12 is a graph of the opening speed of the contactor. This is from tests done by the author on the 6,6 kV GEC contactor

The circuit used to determine the recovery voltage across the contacts is shown in figure 5.13, and the calculations are based on an example by J.C. Jaeger [49].

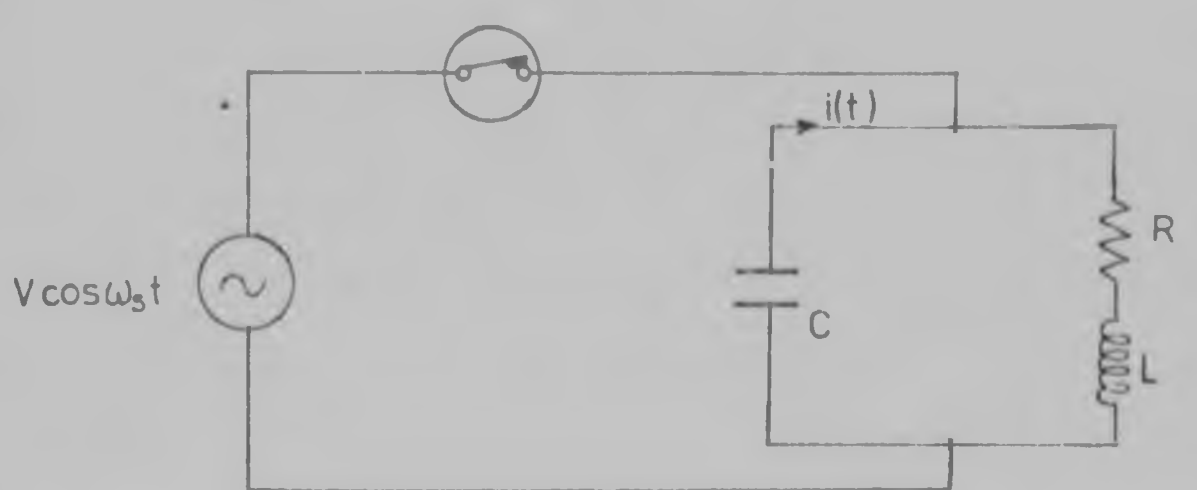


Fig.5.13 Circuit used to determine recovery voltage.

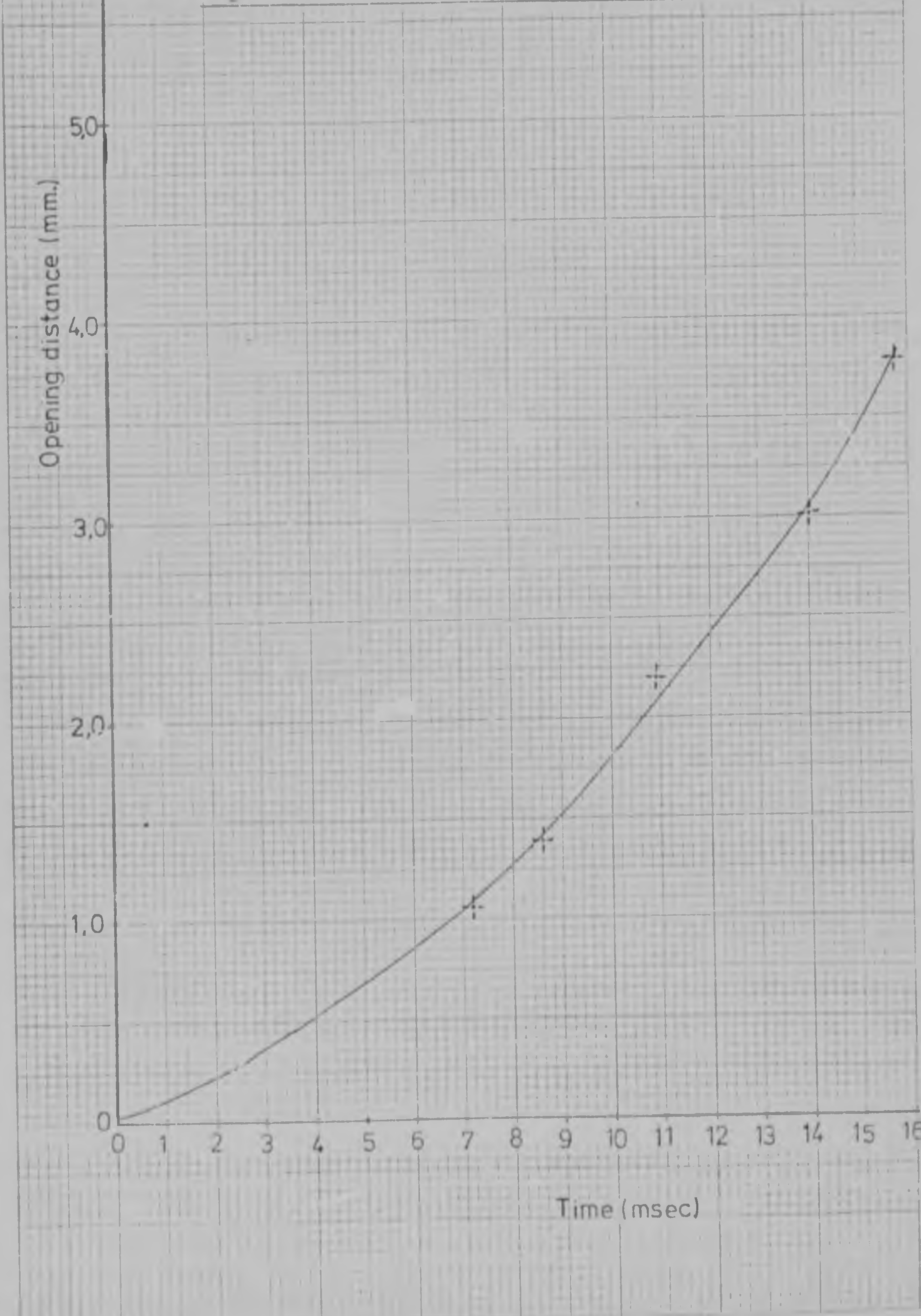


Fig.5.12. Opening speed of 6,6 kV GEC vacuum contactor.

5.4.3 CALCULATIONS

In figure 5.13, the supply feeds a parallel combination of capacitance C (cable) and inductive resistance L,R (standstill reactance of the motor), when at t = 0 the switch is opened. This is taken as the actual moment that arc extinction occurs. For these calculations, to simplify matters. it is assumed that arc extinction occurs at or near current zero and that the load is of low power factor, so that at t = 0, the supply voltage is at a maximum and the current is zero.

The mesh equation for the circuit is

$$0 = i(t)R + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)dt$$

$$0 = i(t)R + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)dt$$

Assum... d that the capacitor is charged to V volts. The initial charge on the capacitor will be $q_o = VC$.

Taking Laplace transforms the equation becomes,

$$0 = i(s)R + sLi(s) - Li(0^+) + \frac{i(s)}{sC} + \frac{q_o}{sC}$$

$$-\frac{VC}{sC} = \left(R + sL + \frac{1}{sC}\right) i(s)$$

$$\text{i.e. } -\frac{V}{s} = \frac{1}{sC}\left(sRC + s^2 LC + 1\right) i(s)$$

$$\text{i.e. } -\frac{V}{s} = \frac{LC}{sC}\left(s^2 + s\frac{R}{L} + \frac{1}{LC}\right) i(s)$$

$$\text{i.e. } i(s) = -\frac{V}{L}\frac{1}{\left(s^2 + s\frac{R}{L} + \frac{1}{LC}\right)}$$

$$= -\frac{V}{L}\frac{1}{\left(s + \frac{R}{2L}\right)^2 - \left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

let $\frac{R}{2L} = \alpha$, $\frac{1}{\sqrt{LC}} = \omega_o$ and $\omega_o^2 - \alpha^2 = \omega^2$

then $i(s) = \frac{V}{L} \frac{1}{(s+\alpha)^2 + (\omega_o^2 - \alpha^2)}$

now taking inverse Laplace transforms,

$$i(t) = -\frac{V}{\omega L} e^{-\alpha t} \sin \omega t$$

The voltage across the capacitor is

$$v_{cap} = \frac{1}{C} \int i(t)dt$$

$$v_{cap} = -\frac{V}{\omega LC} \int e^{-\alpha t} \sin \omega t \; dt$$

$$= -\frac{V}{\omega LC} e^{-\alpha t} \frac{(-\alpha \sin \omega t - \omega \cos \omega t)}{(-\alpha)^2 + \omega^2} + \text{const.}$$

at $t = 0$, $v_{cap} = V$

$$\therefore V = -\frac{Ve^o}{\omega LC} \frac{(0 - \omega . 1)}{\alpha^2 + \omega^2} + \text{const}$$

$$\alpha^2 + \omega^2 = \alpha^2 + \omega_o^2 - \alpha^2 = \omega_o^2 = \frac{1}{LC}$$

$$\therefore V = -\frac{V}{\omega LC} \left(-\frac{\omega}{1/LC} \right) + \text{const.}$$

i.e. V = V + const.

$\therefore$ const. = 0

$$\therefore v_{cap} = \frac{V}{\omega} e^{-\alpha t} (\alpha \sin \omega t + \omega \cos \omega t) \qquad \ldots (1)$$

The voltage across the switch is therefore

$$V \cos \omega_s t - v_{cap}$$

$$\text{i.e.} = V \left[\cos \omega_s t - \frac{1e}{\omega}^{-\alpha t} (\alpha \sin \omega t + \omega \cos \omega t) \right]$$

As is known, in equation (1), if R is neglected and t is very small (1) reduces to $V\cos\omega_{\cdot}$.

$$\text{were } \omega = 2\pi f = \sqrt{\frac{1}{LC}}$$

The 225 kW motor chosen, has a standstill inductance of 99 mH. per phase and a resistance of 1,55 ohms per phase.

The capacitance of the 6,6 kV P.I.L.C. 16mm.^{2} cable is of the order of 0,22 µF/km.

Thus for 18m. of cable

$c = 0{,}003\,96$ µF, $R = 1{,}55$ ohms., $L = 99$ mH, $V = 8\,084$ V.

$\alpha = 7{,}83$, $\omega_o = 50\,505$, $\omega = 50\,505$.

voltage across the contacts is given by:-

$$8\,084 \left[\cos 100\pi t - \frac{1}{50\,505} e^{-7{,}83t} (7{,}83 \sin 50\,505t + 50\,505 \cos 50\,505t) \right]$$

For 90m. cable

$c = 0{,}019\,8$ µF, $R = 1{,}55$ ohms, $L = 99$ mH, $V = 8\,084$V.

$\alpha = 7{,}83$, $\omega_o = 22\,587$, $\omega = 22\,587$

voltage across the contacts is given by :-

$$8\,084 \left[\cos 100\pi t - \frac{1}{22\,587} e^{-7{,}83t} (7{,}83 \sin 22\,587t + 22\,587 \cos 22\,587\,t) \right]$$

4.4.4 RESULTS

To plot the dielectric strength profile, the relative graphs of dielectric strength vs. gap, opening speed and dielectric recovery are combined using a known lapse of time from contacts part to arc extinction.

Figure 5.14 shows the results for a time from contacts part to arc extinction, of 1,0 msec. As can be seen the recovery voltage with 90m. of cable intersects the dielectric strength relatively higher then with 18m. of cable. The difference is approx. 400 volts, which allowing for reflection due to mismatch of surge impedance, would result in 0,15 p.u. difference in the average magnitudes of voltage peaks.

Only the first strike is calculated, and this only for the single phase simplified equivalent diagram. Computer studies for restriking in a three phase circuit are very complex and in fact being currently attempted by the GE company in the U.S.A.[24].

Figure 5.15 shows the results for a time from contacts part to arc extinction of 2,2 msec. From this it can be seen that the probability of a restrike is greater with shorter cables, but if a restrike occurs with longer cables, it is likely to be of greater magnitude.

Comparing the theory with actual measured results switching a 200 kW stalled motor with 18 and 90m. of cable between the contactor and the motor, it was found that there was a difference of 0,52 p.u. with the two lengths of cables in the max. voltage swing. In practice, there is coupling between the

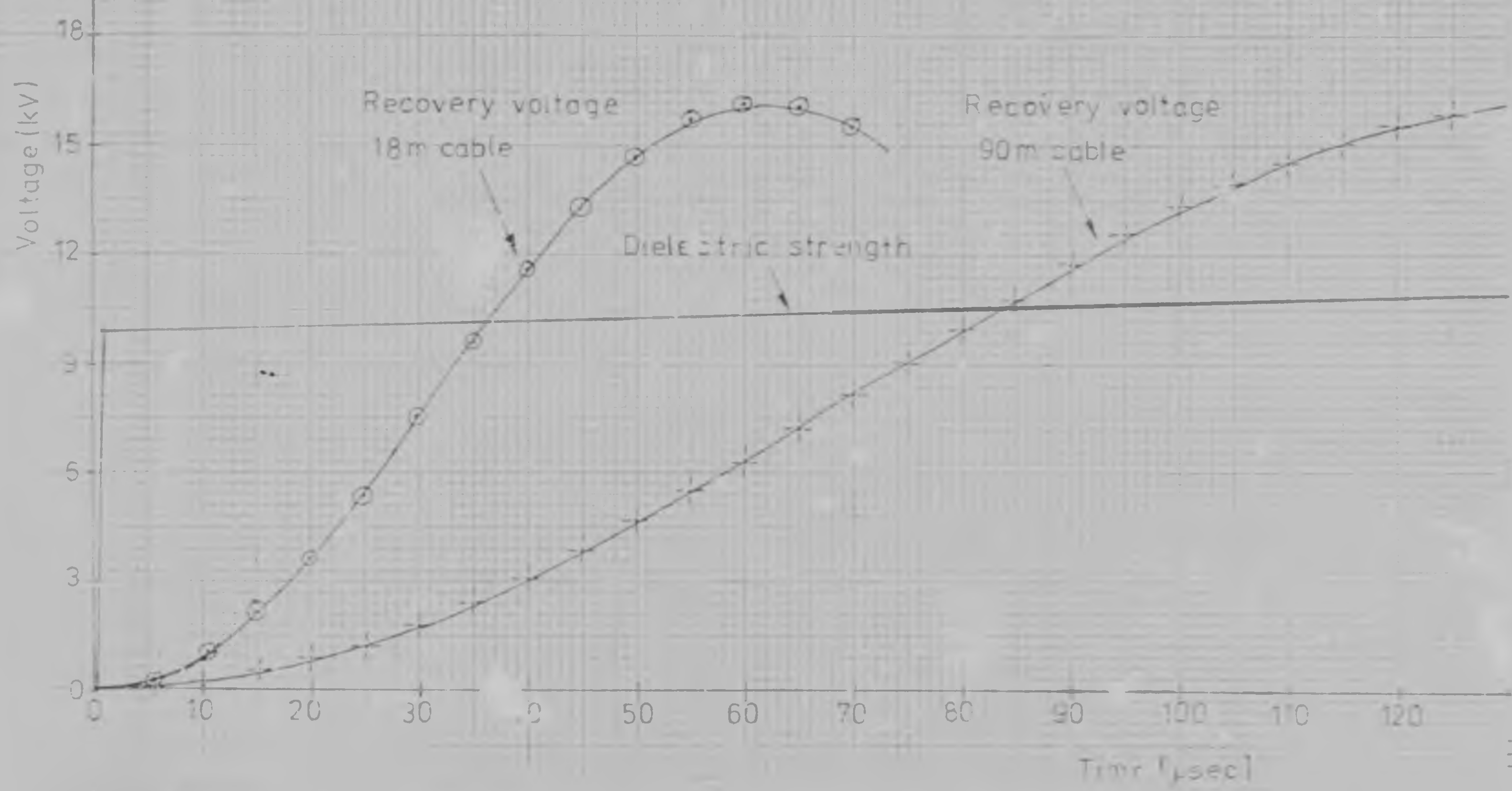


Fig.5.14. GEC 6,6kV Vacuum contactor switching a stalled 22.5 kW motor.

Arc extinction occurring 1 msec after contacts part.

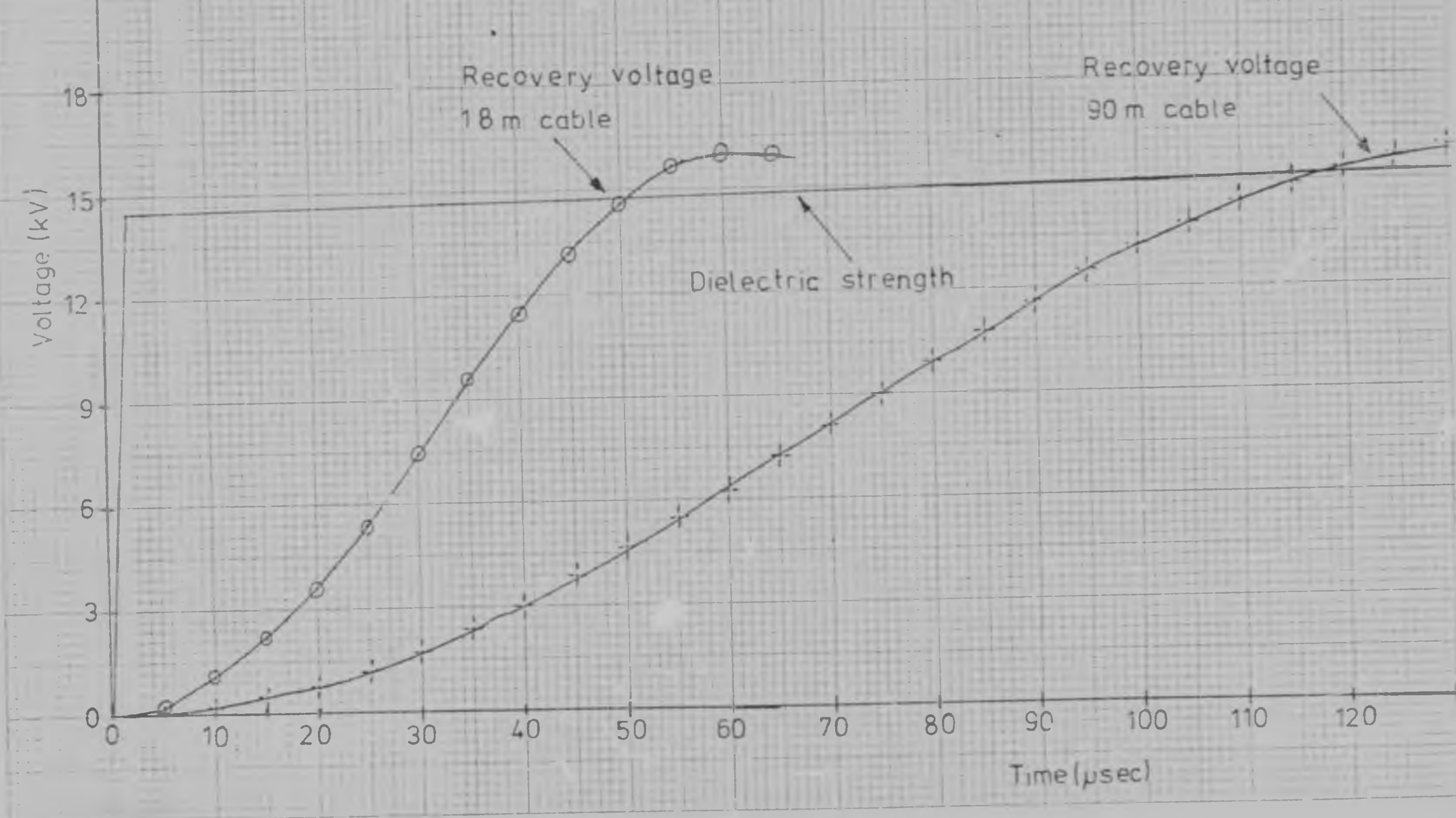


Fig. 5.15. GEC 6,6 kV Vacuum contactor, switching a stalled 225 kW motor.
Arc extinction occurring 2,2 msec after contacts part.

phases and recovery voltages will exceed 2 p.u. across the contacts. Pflanz[50] has calculated that the max. peak voltage that can occur theoretically is 7 p.u. In practice however this is limited by the dielectric strength of the switch.

As regards the probability, from the actual measurements it was found that with 18m. of cable the probability of not restriking was 33% i.e. as there is 3,3 msec. between current zeros, the time after contacts part to arc extinction would be 2,2 msec. In the calculated results, it can be seen that after 2,2 msec. the dielectric strength is just beginning to exceed the recovery voltage, confirming that a probability of 33% for not restriking is correct.

5.5 TRANSFORMER SWITCHING

5.5.1 ARC FURNACE TRANSFORMER SWITCHING

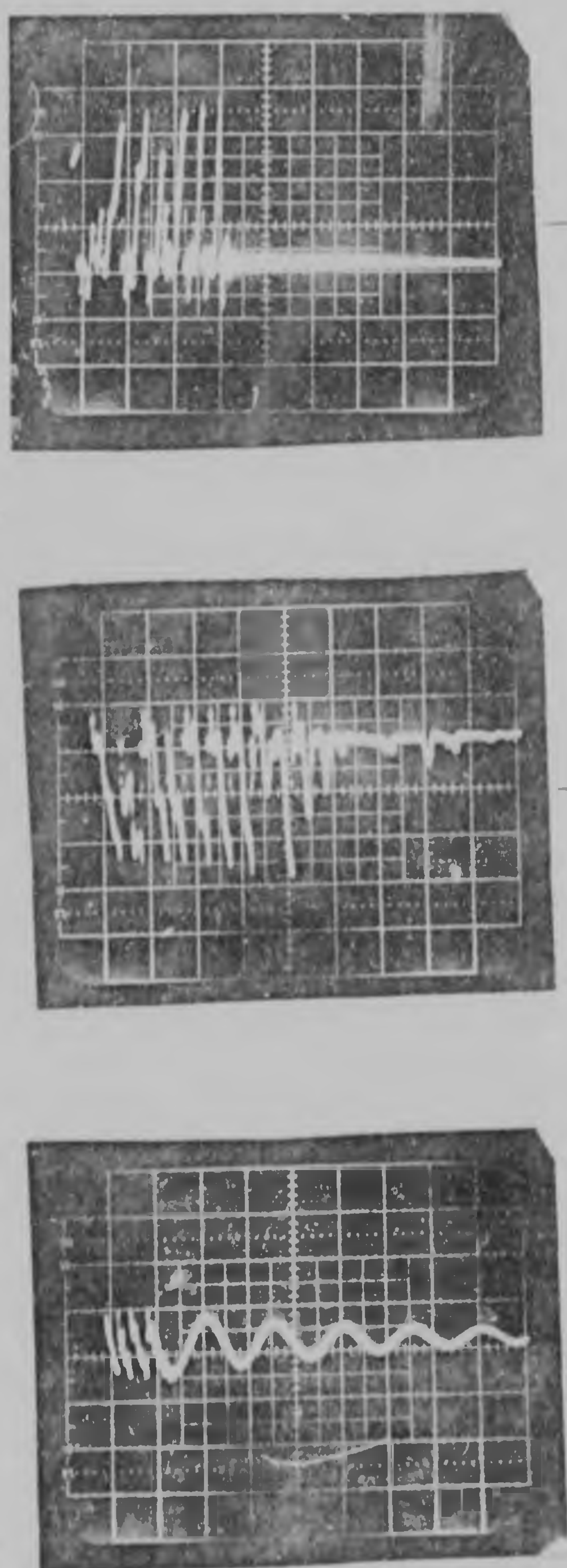
On site measurements were conducted on a 6,6 kV GEC vacuum contactor switching a 2 000 kVA arc furnace transformer. The circuit diagram is the same as that shown in figure 4.14 and a typical switch-off transients are shown in figure 5.16.

Approx. 30 switch-offs were monitored, mostly on the red phase, and the greatest magnitude recorded was 3,5 p.u.

5.5.2 VACUUM CONTACTOR SWITCHING A 250 kVA TRANSFORMER

The test circuit was as for figure 3.25 and has already been partly described in 3.10. Six circuit configurations were investigated and they are listed below.

A. Power factor correction capacitors connected to the supply, RC surge suppression disconnected, short cable



Red phase
5 kV/div.
50 µsec./div.

Red phase
5 kV./div.
50 µsec/div.

Red phase
5 kV/div.
100 µsec./div.

Fig. 5.16. Switch-off with a 2 000 kVA transformer

(18m.) between transformer and contactor and no supply cable i.e. the supply was connected to the contactor by short, direct, single core cables. Twelve switch-off operations were performed and for each operation measurements were made of maximum overvoltage, maximum voltage swing, number of restrikes and duration of transient. Graphs of the results were shown in figure 3.27 and a typical switch-off restrike transient was shown in figure 3.26.

B. No power factor correction capacitance, no RC surge suppressor, short load cable and no supply cable. Ten switch-off operations were recorded and graphs of the results are shown in figure 5.17. A typical switch-off is shown in figure 5.18.

C. No power factor correction capacitance, long load cable, short supply cable, RC surge suppressor disconnected. Ten switch-off operations were recorded and graphs of the results are shown in figure 5.19. A typical switch-off is shown in figure 5.20.

D. As for C but with power factor correction capacitance connected to the supply. Ten switch-off operations were recorded and graphs of the results is shown in figure 5.21. A typical switch-off is shown in figure 5.22.

E. Power factor correction capacitance connected, short load cable, long supply cable, no RC suppressor. Measurements were made for 11 switch-off operations and graphs of the results are shown in figure 5.23. A typical switch-off is shown in figure 5.24.

F. No power factor correction capacitance short load cable, long supply cable, no RC suppressor. Measurements were made for ten switch-off operations and graphs of the results are shown in figure 5.25. A typical switch-off is shown in figure 5.26.

	Switch OFF
Max. Overvoltage recorded (p.u. pk) Average overvoltage (p.u. pk) Standard deviation	2,0 1,15 0,30
Max. Voltage swing recorded (p.u. pk-pk) Average voltage swing (p.u. pk-pk) Standard deviation	2,00 0,94 0,44
Max. number of strikes recorded Average number of strikes Standard deviation	6 2,5 1,55
Max. duration of transient recorded (ms) Average duration of transient (ms) Standard deviation	4,06 2,95 0,81

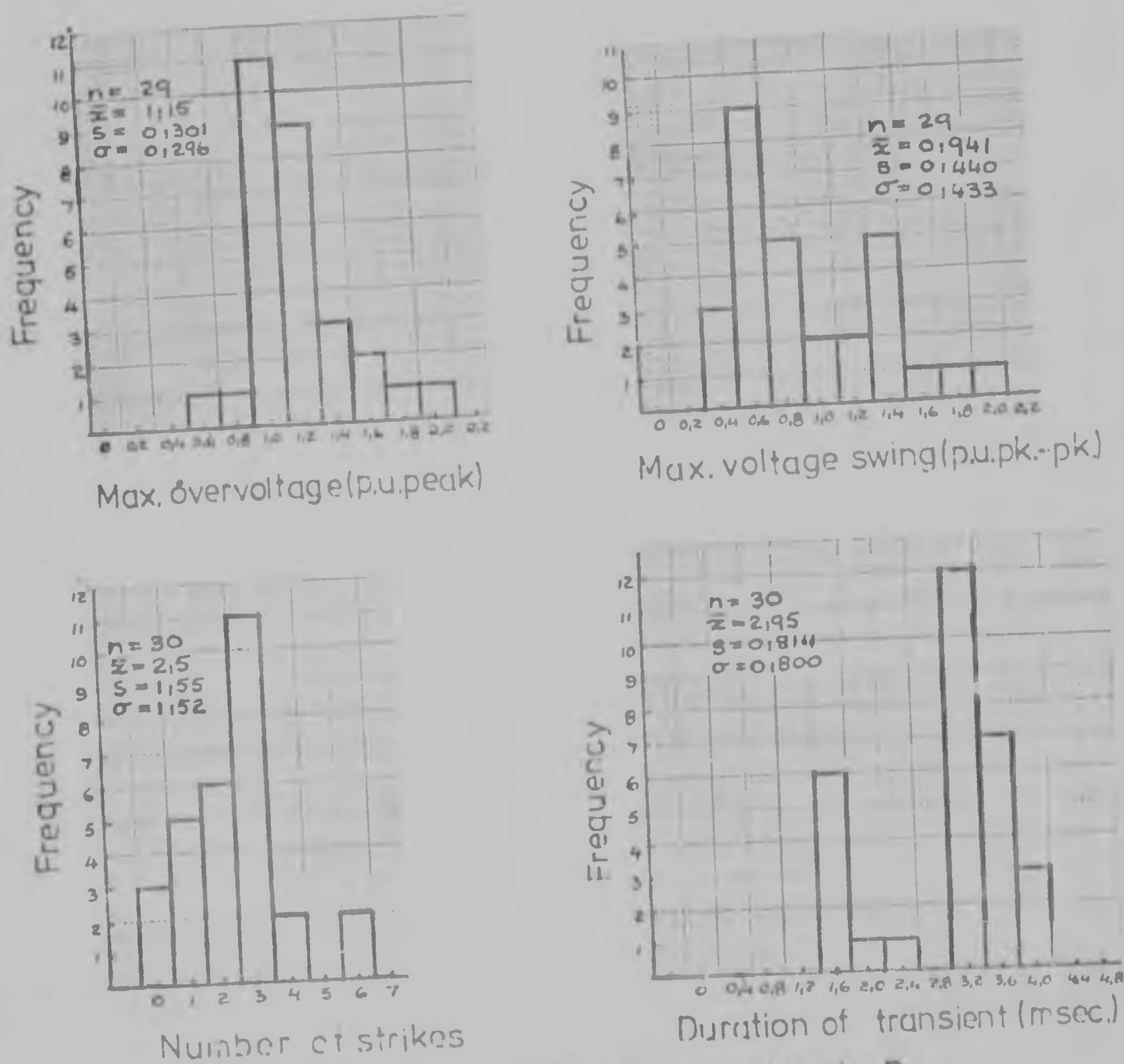


Fig 5.17. Results of transformer switch-off tests B

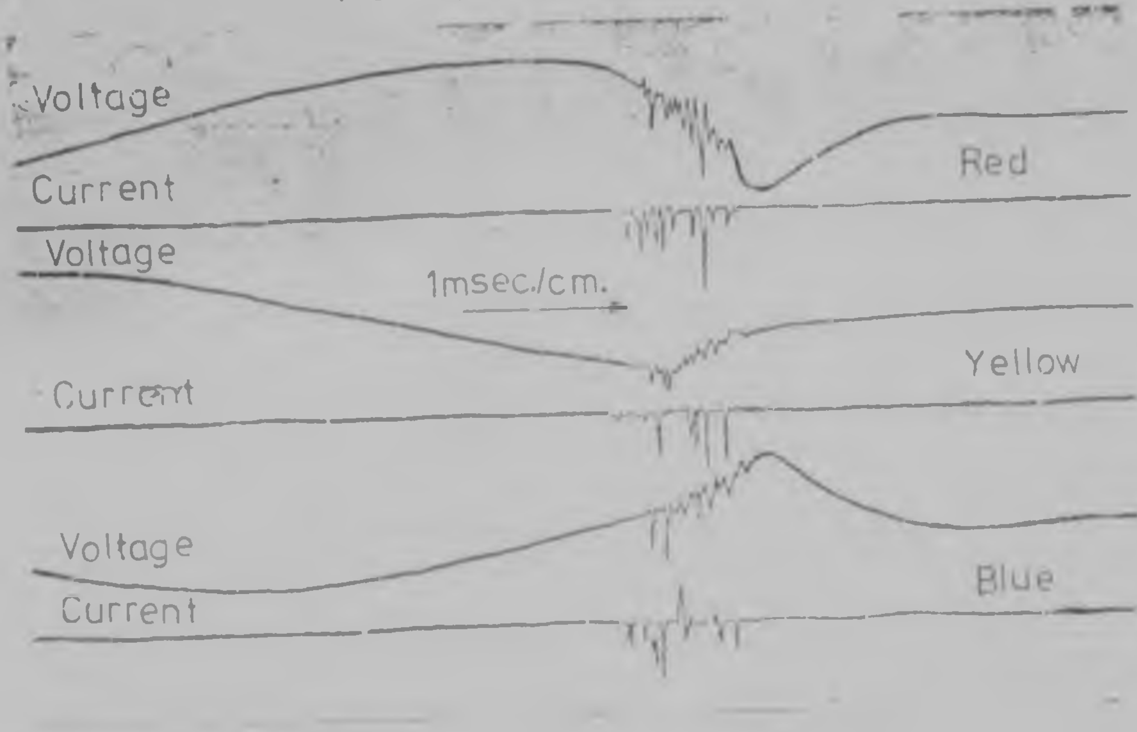
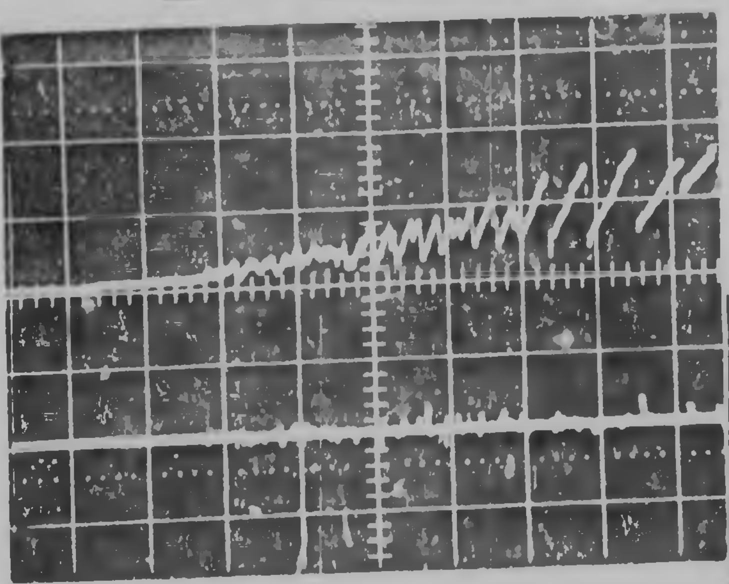
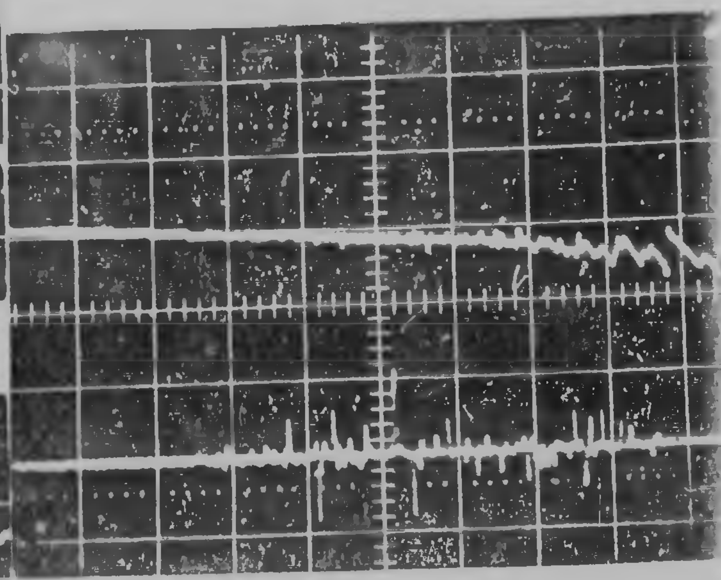


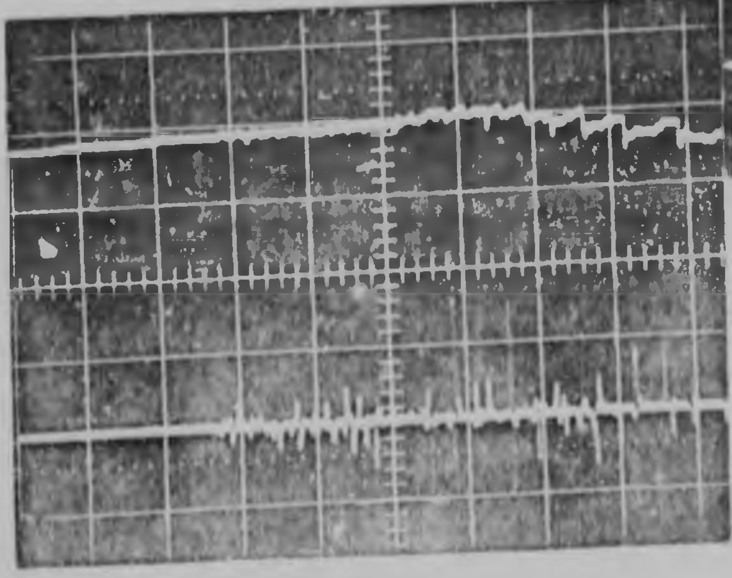
Fig.5.18. Transformer switch-off transients B.



Red phase



Blue phase



Yellow phase

Voltage: 1p.u./div. (Top trace)
Current: 50 A. /div.(Bottom trace)
Time: 200 μsec./div.

	Switch OFF
Max. overvoltage recorded (p.u. pk) Average overvoltage (p.u. pk) Standard deviation	1,2 0,93 0,22
Max. voltage swing recorded (p.u. pk-pk) Average voltage swing (p.u. pk-pk) Standard deviation	1,00 0,48 0,29
Max. number of strikes recorded Average number of strikes Standard deviation	2 0,53 0,68
Max. duration of transient recorded (ms) Average duration of transient (ms) Standard deviation	10,9 7,48 1,41

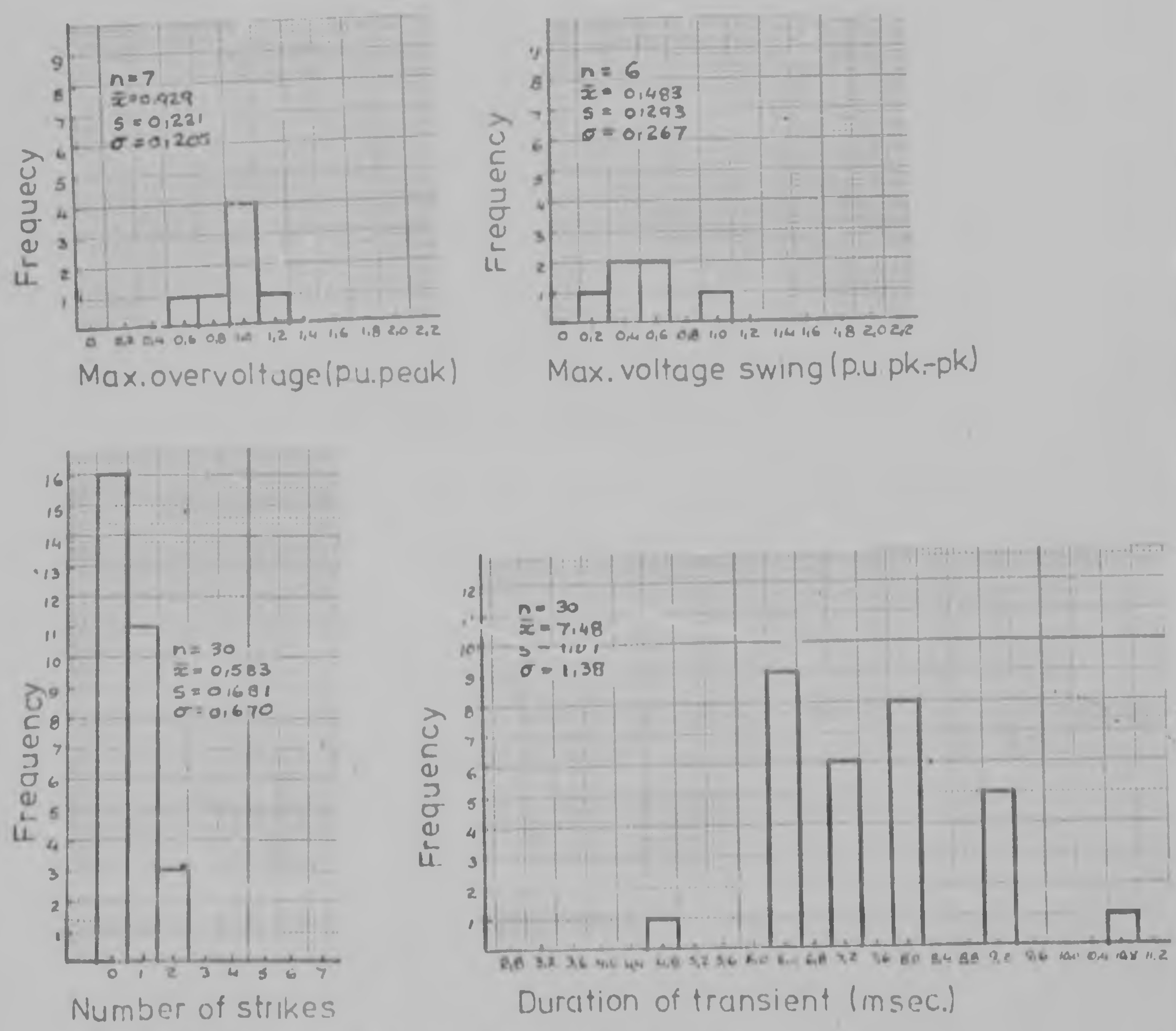


Fig. 5.19. Results of transformer switch-off tests. C.

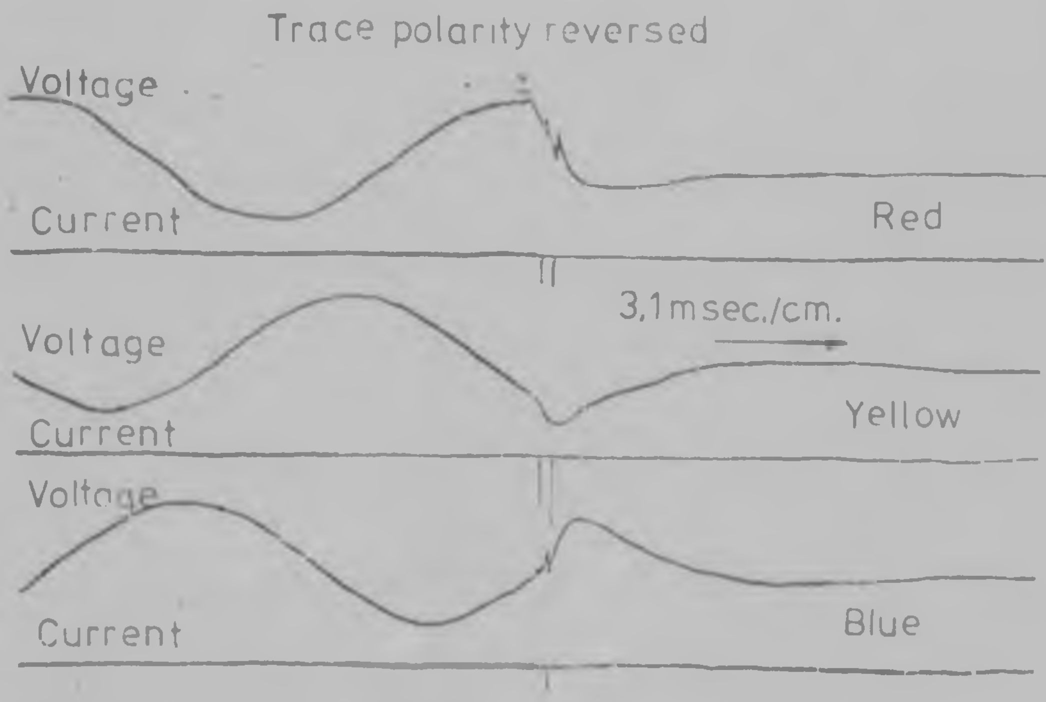
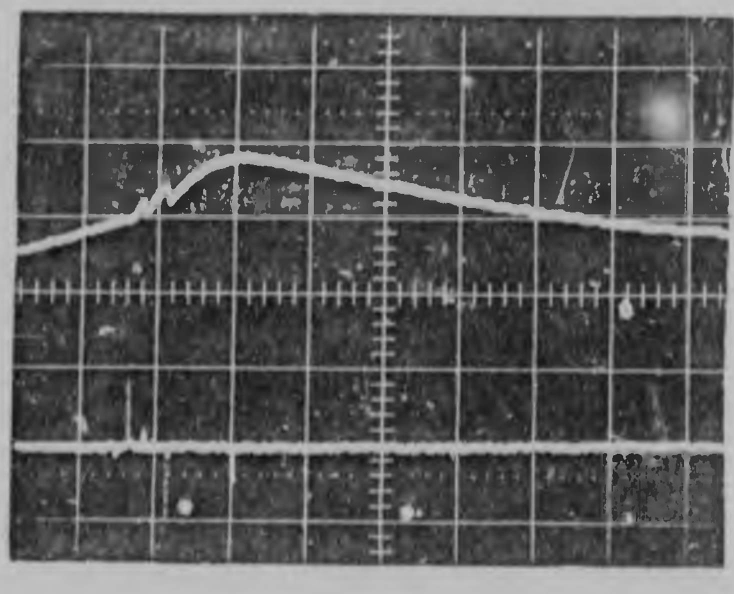


Fig.5.20. Transformer switch-off transients C.



Voltage: 1p.u/div. (Top trace)
Current: 50A./div.(Bottom trace)
Time: 100μsec./div.

Yellow phase

	Switch OFF
Max. overvoltage recorded (p.u. pk) Average overvoltage (p.u. pk) Standard deviation	1,6 0,92 0,33
Max. voltage swing recorded (p.u. pk-pk) Average voltage swing (p.u. pk-pk) Standard deviation	1,8 0,82 0,48
Max. number of strikes recorded Average number of strikes Standard deviation	6 1,73 1,44
Max. duration of transient recorded (ms) Average duration of transient (ms) Standard deviation	9,38 7,19 1,05

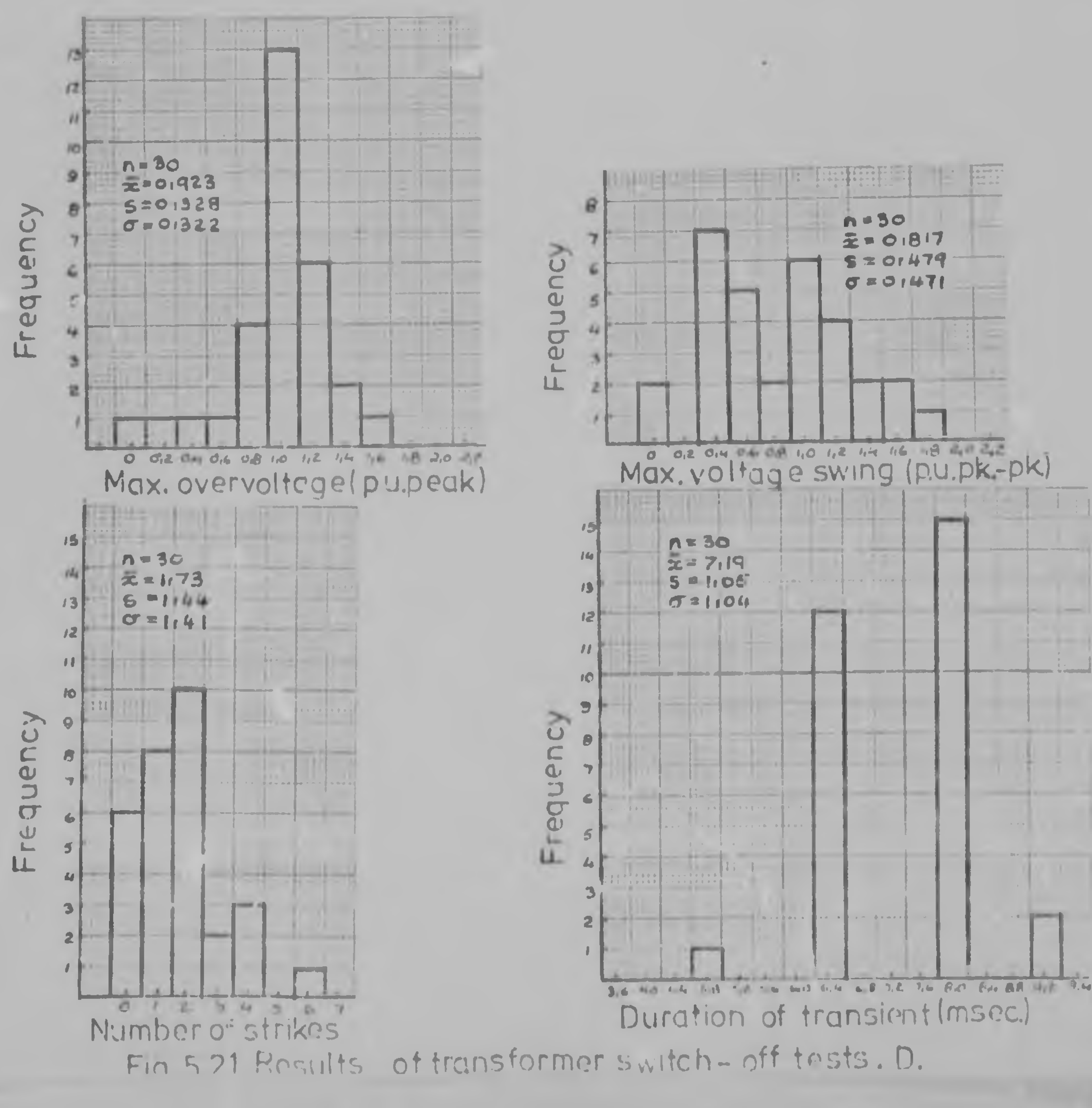


Fig. 5.21 Results of transformer switch-off tests. D.

Trace polarity reversed

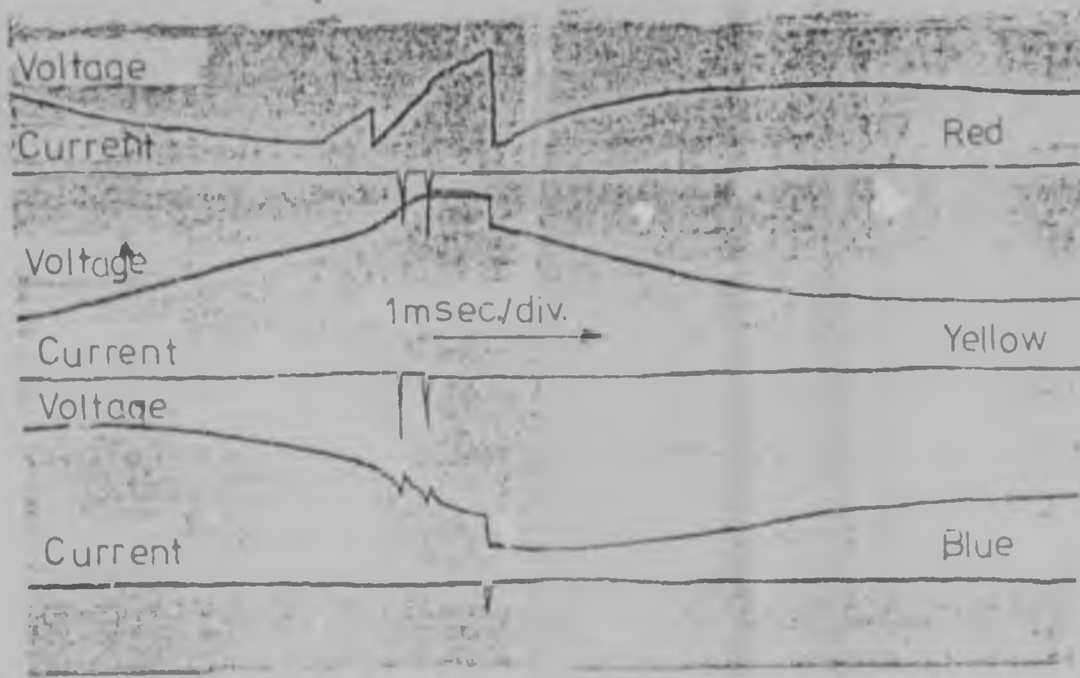
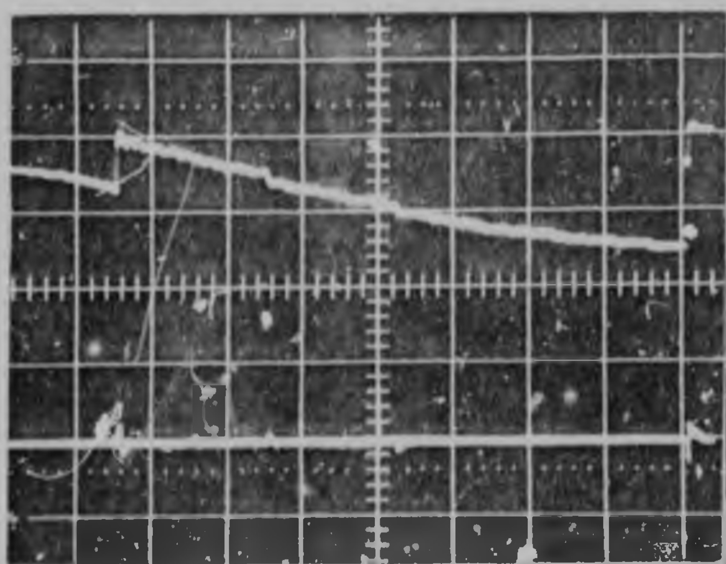
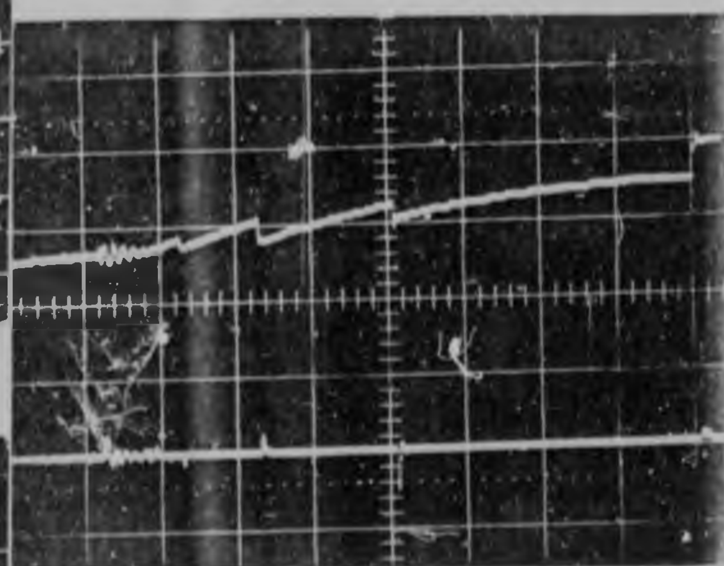


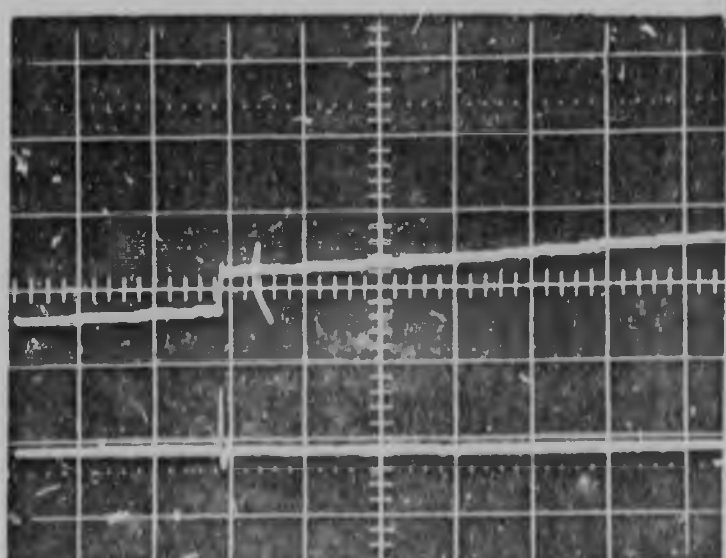
Fig.5.22. Transformer switch-off transients. D.



Red phase



Blue phase



Yellow phase

Voltage: 1p.u./div. (Top trace)

Current: 50 A. /div. (Bottom trace)

Time 200 μsec./div.

	Switch OFF
Max. overvoltage recorded (p.u. pk) Average overvoltage (p.u. pk) Standard deviation	2,3 1,29 0,30
Max. voltage swing recorded (p.u. pk-pk) Average voltage swing (p.u. pk-pk) Standard deviation	2,1 1,10 0,55
Max. number of strikes recorded Average number of strikes Standard deviation	8 4,03 1,85
Max. duration of transient recorded (ms) Average duration of transient (ms) Standard deviation	4,69 3,56 0,75

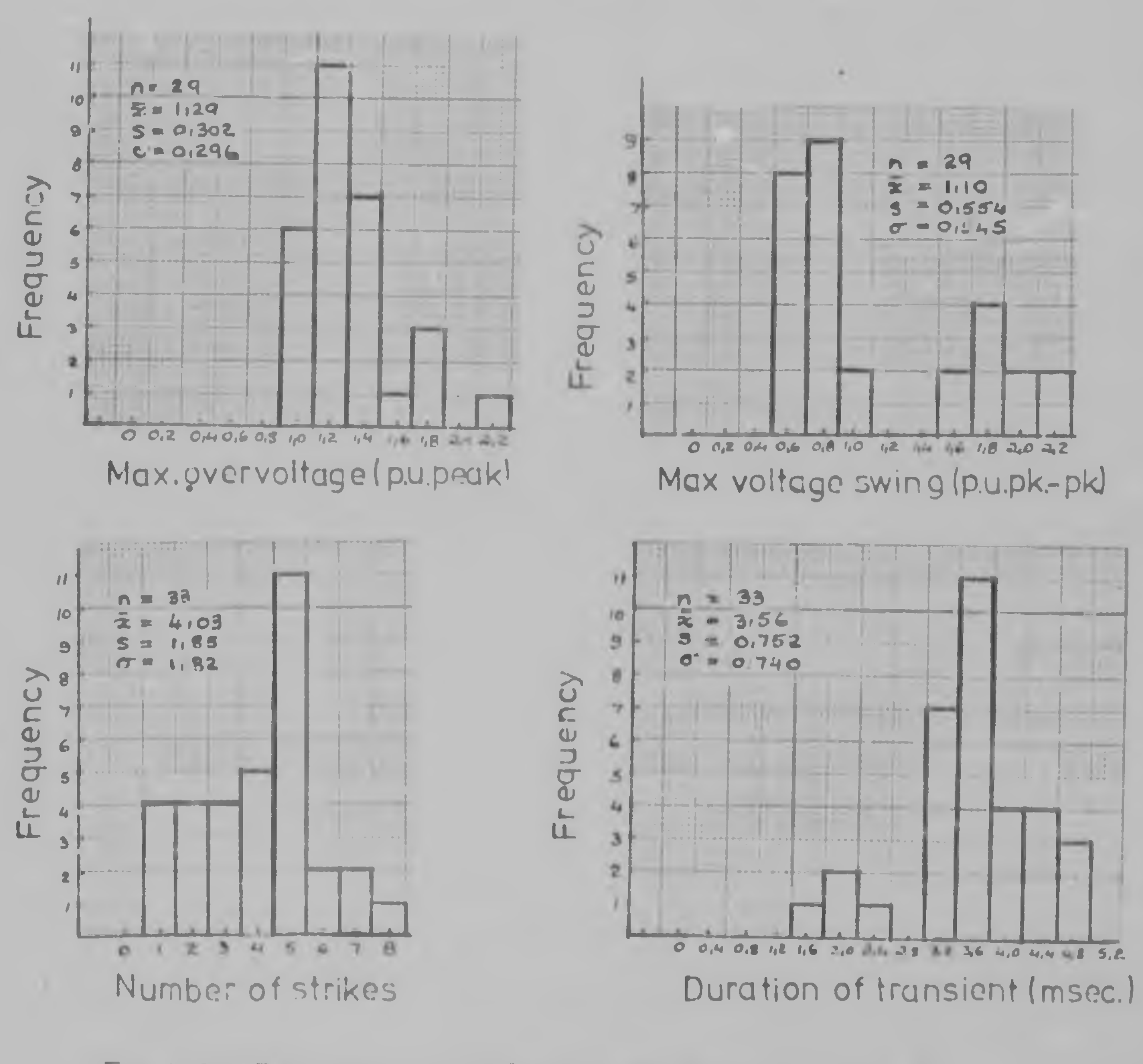


Fig. 5.23. Results of transformer switch-off tests E.

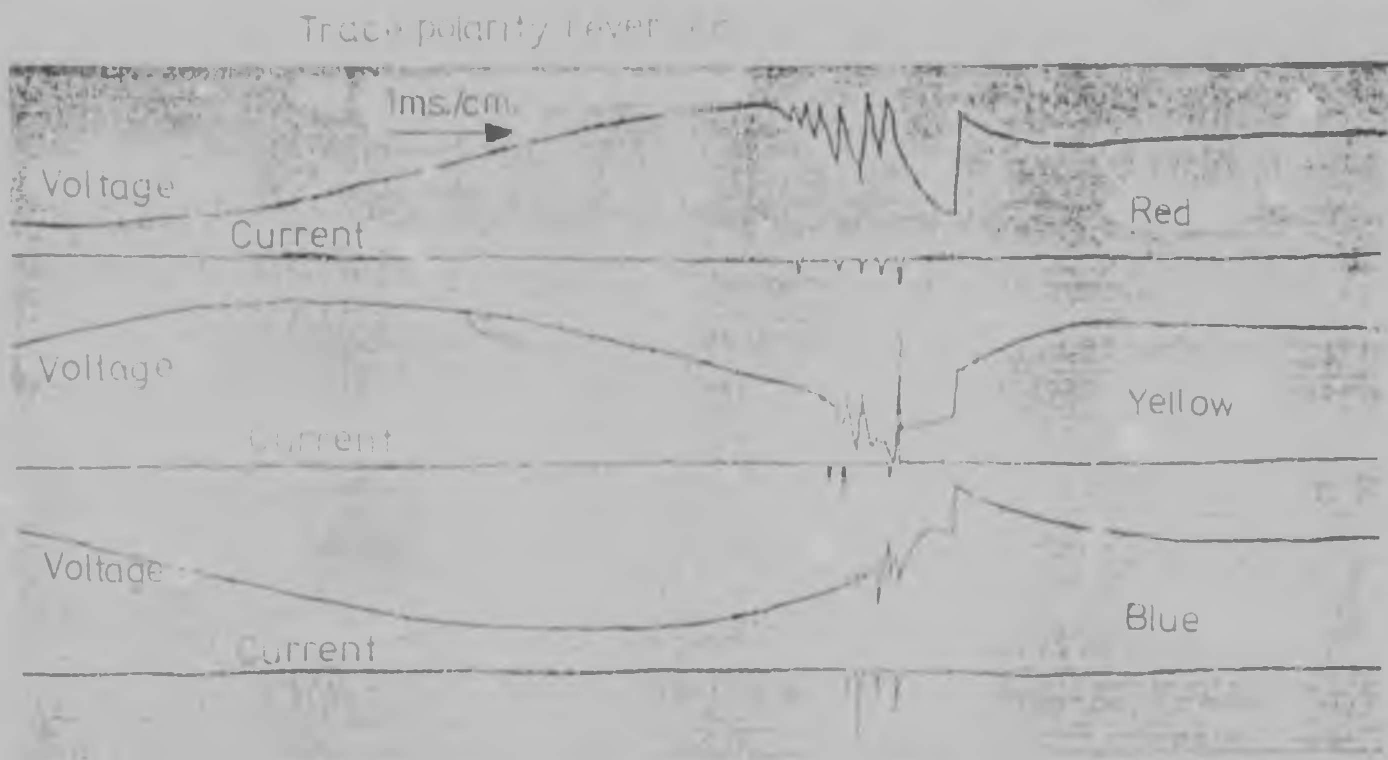
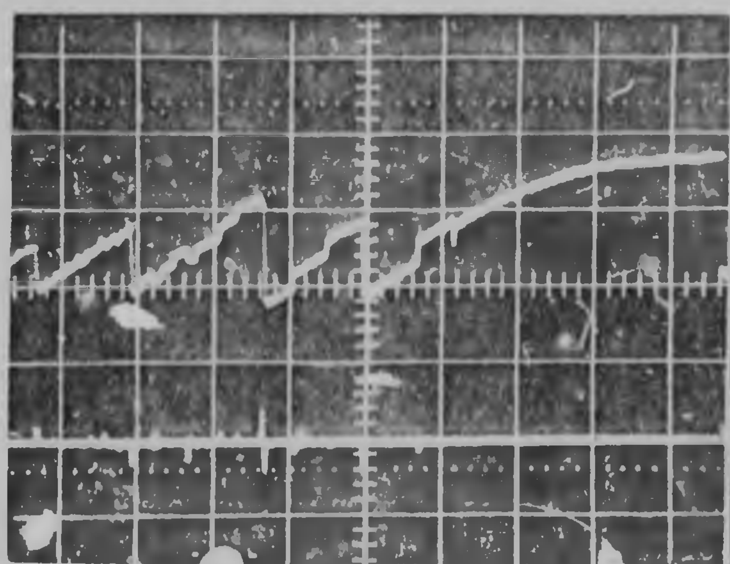
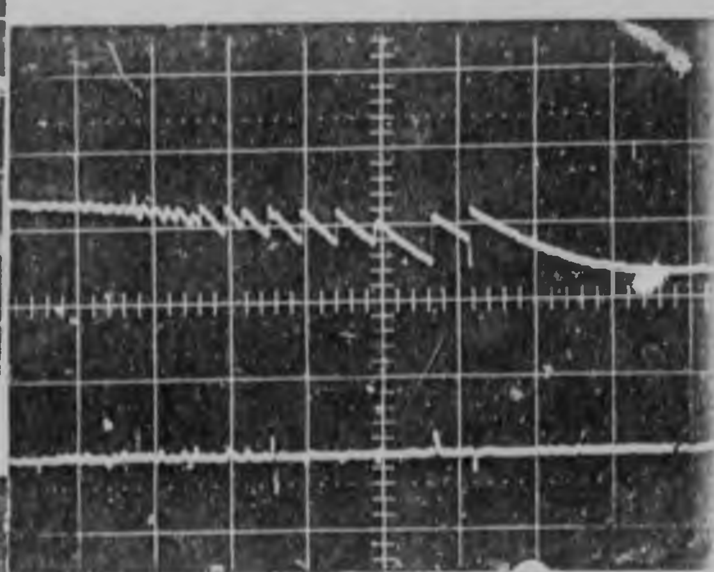


Fig.5.24. Transformer switch-off transients

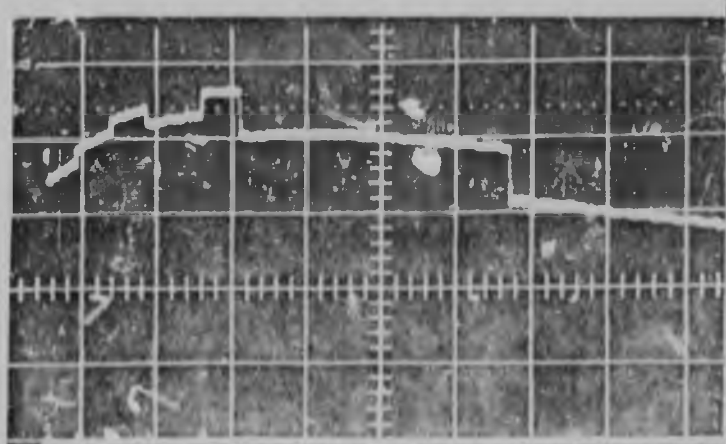


Red phase



Blue phase

Voltage: 1p.u./div.(Top trace)
Current: 50 A/div.(Bottom trac
Time: 200 µsec/div



Yellow phase

	Switch OFF
Max. overvoltage recorded (p.u. pk) Average overvoltage (p.u. pk) Standard deviation	2,3 1,21 0,42
Max. voltage swing recorded (p.u. pk-pk) Average voltage swing (p.u. pk-pk) Standard deviation	1,9 0,95 0,42
Max. number of strikes recc ded Average number of strikes Standard deviation	7 3,89 1,69
Max. duration of transient recorded (ms) Average duration of transient (ms) Standard deviation	6,25 3,87 1,22

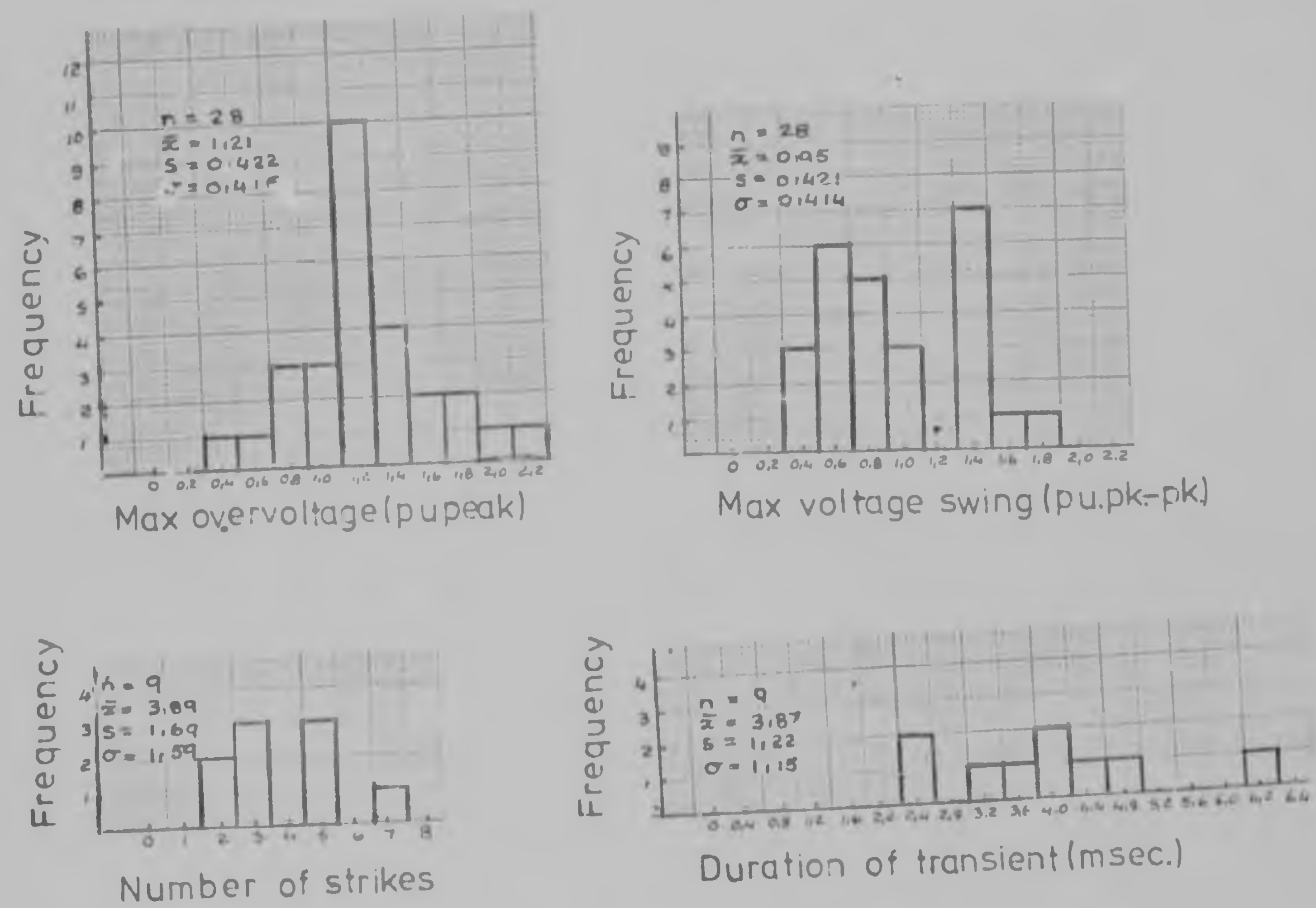


Fig. 5.25. Results of transformer switch-off tests. F

Trace polarity reversed

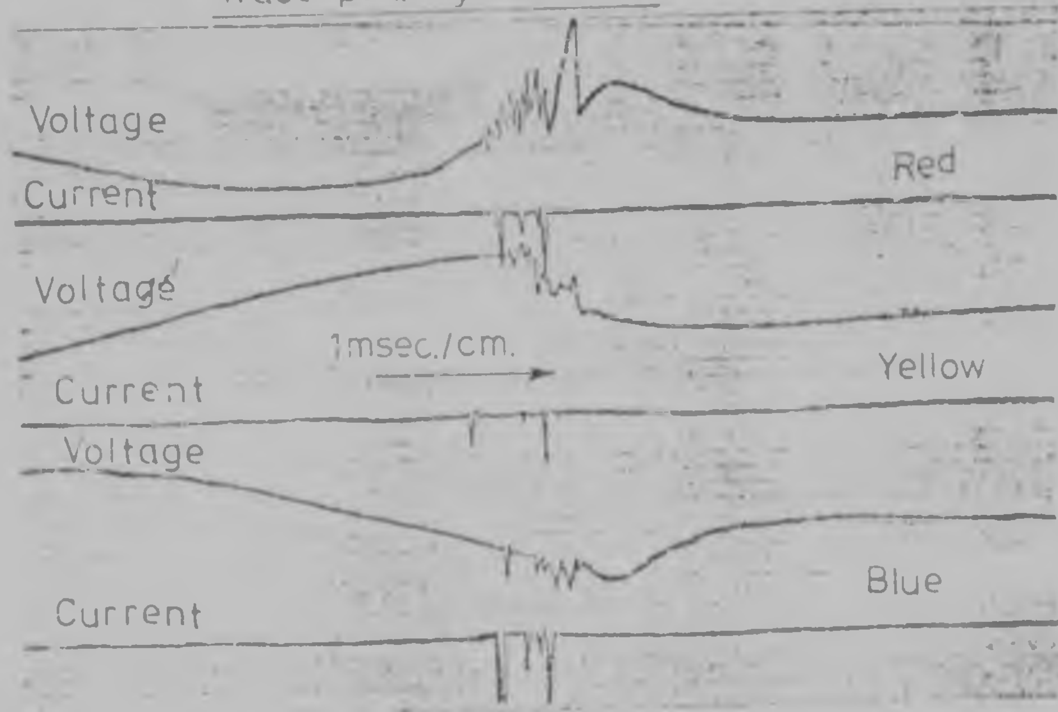
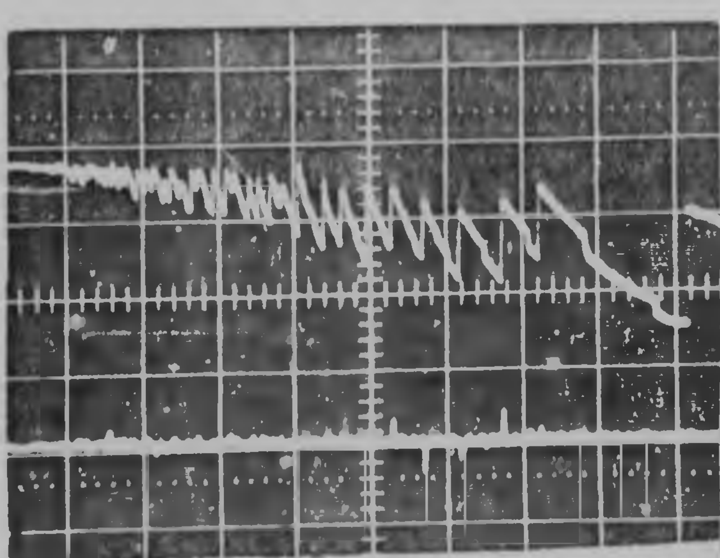
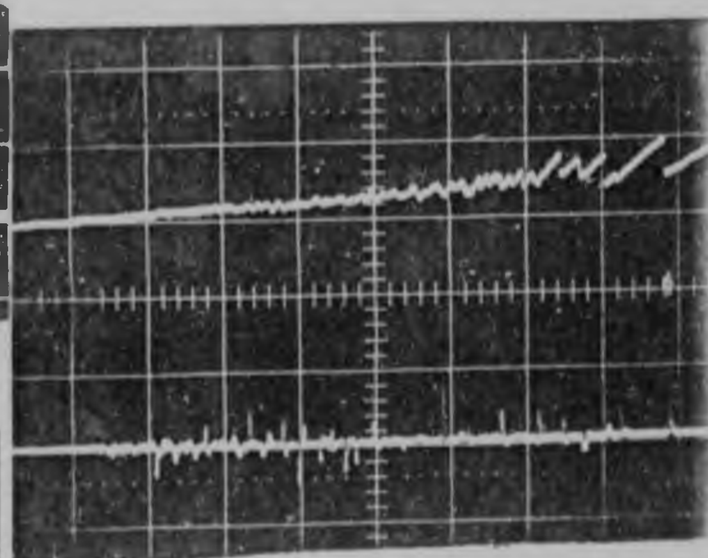


Fig.5.26. Transformer switch-off transients.F.



Red phase

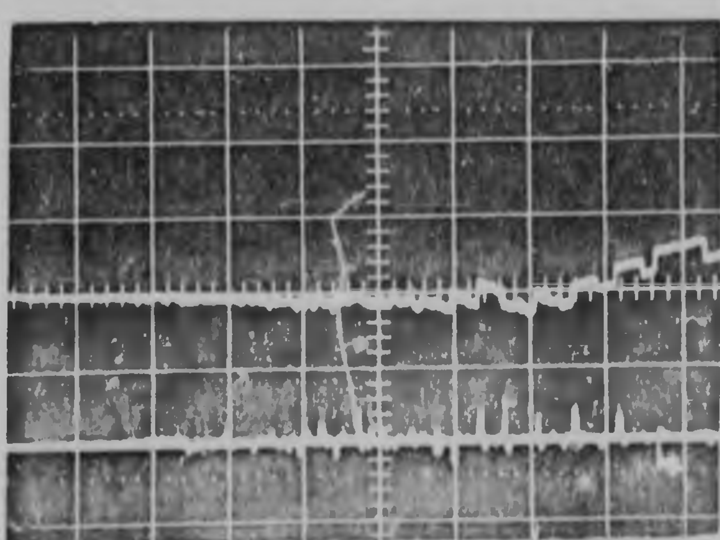


Blue phase

Voltage: 1 p.u./div.(Top trace)

Current: 50 A./div.(Bottom trace

Time: 200 μsec./div.



Yellow phase

5.6 SUMMARY AND DISCUSSION

Restrikes can only occur when there is no back-emf, and when low factor loads are switched e.g. stalled motor switching and low power factor transformer switching. Here, current zeros coincide with supply system peak voltages.

Futbermore, the occurrence of a restrike depends upon the moment in time that contacts part after a current zero. It has been shown in the stalled motor switching tests that there is a probability of 33% of only current chopping occurring. Restrikes occurred everytime with the 250 kVA transformer no-load switching tests, as the no-load current was below that of the current chopping level of the contactor.

The most severe transients, in respect of magnitudes, occurred when doing stalled motor switch-offs with substantial lengths of cable (e.g. 90m.). The max. voltage swing recorded in the tests done with 90m. of cable was 7,5 p.u. with a rise time of 4 μsec. The average max. voltage swing was 2,19 p.u. with a standard deviation of 1,23 p.u. The probability of a max. voltage swing above 7,0 p.u. was estimated, assuming a Gaussian distribution, as being 1 in 2 000 operations. With 18m. of cable there was no probability of achieving a voltage swing above 5,0 p.u.

The results of the stalled motor switching tests also show that whereas the magnitudes of the transients increase with increase in length of cable e.g. 18m. to 90m., the rate of rise decreases. The average max. voltage swing with 18m. of cable was 1,67 p.u. compared with 2,19 p.u. with 90m. of cable. The max. rate of rise recorded, decreased from 16 kV/μsec. to 10 kV/μsec.

Comparison with theory, showed that it was possible to prove that there was a small probability for restriking to be larger with longer cables. The theory that restriking should only occur within 2,2 msec. of contacts opening after a current zero, compared very well with the measured results.

Whilst, the transformer tests did not realize any transients of significance, they did show the effect of capacitance on the supply, and varying lengths of cable. They were also useful in determing the effect of RC suppressors, to be discussed in 6.1.4

Table 5.1 summarises the transformer switching tests, and from comparison of tests A and B, C and D, it can be seen that the overvoltages generated when there was capacitance connected to the supply, are more severe than when this capacitance is absent.

Tests when measuring switch-offs when switching a 2 000 kVA transformer, show that it was possible to have magnitudes of 3,5 p.u. when switching transformers.

In conclusion, restriking when switching motors is rare, as it only occurs when switching stalled motors, or switch-off at start. Whilst it is possible in a worse case to achieve levels of magnitude of swings of 7,5 p.u., the rates of rise are less than those that can occur when prestriking takes place.

Restriking when switching transformers, although more frequent, pose little problem in practice for transformers, because of their known, proven lightning impulse withstand ability.

	SWITCH-OFF					
	A	B	C	D	E	F
Max. overvoltage (p.u. peak) Average overvoltage (p.u. peak) Standard deviation (p.u. peak)	2.00 1.38 0.28	2.00 1.15 0.30	1.20 0.93 0.22	1.60 0.92 0.33	2.30 1.29 [illegible]	2.30 1.21 0.42
Max. voltage swing (p.u. pk-pk) Average voltage swing (p.u. pk-pk) Standard deviation (p.u. pk-pk)	2.20 1.35 0.49	2.00 0.94 0.44	1.00 0.48 0.29	1.80 0.82 0.48	2.10 1.10 0.55	1.90 0.95 0.42
Maximum number of strikes Average number of strikes Standard deviation	8.00 3.89 2.26	6.00 2.50 1.55	2.00 0.53 0.68	6.00 1.73 1.44	8.00 4.03 1.85	7.00 3.89 1.69
Maximum duration of transients (ms) Average duration of transients (ms) Standard deviation (ms)	4.69 3.12 0.69	4.06 2.95 0.81	10.9 7.48 1.41	9.38 7.19 1.05	4.69 3.56 0.75	6.25 3.87 1.22

A - With p.f. correction cap.; short load cable; no supply cable.

B - Without p.f. correction cap.; short load cable; no supply cable.

C - Without p.f. correction cap.; long load cable; short supply cable.

D - With p.f. correction cap.; long load cable; short supply cable.

E - With p.f. correction cap.; short load cable; long supply cable.

F - Without p.f. correction cap.; short load cable; long supply cable.

Table 5.1. Summary of transients measured under various circuit conditions.

CHAPTER 6

SURGE SUPPRESSORS

6.1 TYPES OF SURGE SUPPRESSORS

6.1.1 VOLTAGE LIMITING DEVICES

One of the most common surge suppressors is a surge diverter consisting of spark-gaps and non-linear resistors. These are designed to be connected between line and earth on all phases of the system, so that they discharge harmlessly to earth any surges travelling along the line towards them.

The function of the spark-gaps is to prevent the passage of current to earth during normal operation. In the event of an excessive overvoltage, however, the spark-gaps spark over and allow the current to pass through the non-linear resistors to earth, thus discharging the surge and preventing any further rise of voltage on the system. The non-linear resistors are made of a special material, the resistance of which decreases very rapidly as the current through it increases. It follows, therefore, that such non-linear resistors can carry very large currents without the voltage drop across them rising to an excessive value. The residual voltage across the diverter therefore remains low, thus limiting the voltage on the line to a low value. As soon as the surge has been discharged, the voltage across the diverter tends to fall and the current therefore decreases. The resistance of the resistors then begins to increase, and the follow-current due to the system voltage is thus reduced. Within one half cycle of the system frequency the follow-current falls to a negligible amount and can thus be interrupted by the spark-gaps. The diverter then resumes it's normal non-conducting condition and is ready for further operation.

The only function of these arresters is to limit the voltage across their terminals to a certain value. They will do whatever they must to accomplish this, including committing suicide[51].

Voltage limiting devices, or arresters as they are sometimes called, began with simple spark gaps but designs quickly progressed to multi-gap units with added resistance[52]. As power systems grew, this approach proved inadequate and the aluminium cell arrester was introduced. This was the first arrester to utilise a non-linear resistance material. It's high field maintenance requirements initiated the development of the lead-oxide film arrester in 1920.

In the 1930s, arresters using series gaps and silicon-carbide non-linear resistors were introduced and operated as described in the first part of this section. In the 1960s and early 1970s most improvements in station class arresters focused on the arrester gap units where arc resistance development and spark-over control were enhanced. Recently,[52] the development of zinc-oxide-based non-linear resistors was announced. These arresters are noted for an absence of series gaps, simple construction and superior performance characteristics. They enter into conduction at a specific voltage level, hold that level with no change for the duration of the overvoltage surge, and cease conduction at approx. the same voltage at which conduction started. The arrester only conducts that current required to reduce the surge voltage to the arrester protective level and therefore dissipates only the minimum energy possible commensurate with the protection provided.

One producer of surge equipment combines VDRs (voltage dependent resistors) with station type arrestors[53]. The function of the non-linear resistor is to limit switching surges, whilst the station type arrester deals with any major overvoltages from whatever source which might otherwise damage the non-linear resistors. The non-linear resistors, because of their construction, can be selected to have a break down relatively close to the operating voltage.

Most of the above types of voltage limiting devices were attached to the circuit of figure 3.20 when switching on the induction motor. None had any effect on the prestrike transients. The reason for this is that the average voltage swing in a prestrike is of the order of 1,2 p.u. and is thus well below any of the arrester protection levels. If this form of switching surge is a problem, other means of protection must be used.

6.1.2 SURGE CAPACITORS

These are discussed theoretically by Pretorius[30] and he shows that they can drastically alter the characteristics of the surges. With the increased load capacitance, the magnitude of the inrush current increases due to the lower surge impedance, whilst the frequency of both current and voltage transients will decrease considerably. The number of prestrikes during a closure are correspondingly reduced and final closure of the switch may even be achieved before the first current zero occurs.

The role of the surge capacitor is two-fold as far as current chopping is concerned (with or without restriking), in that it decreases the peak value of the chopping surge and also eliminates the severity of restrike wavefronts. Apart from being sloped by the addition of the surge capacitor (due to the lower frequency), the peak value of the resultant surge voltage can also be limited to acceptable voltage levels. In addition, the number of restrikes following a current chop may also be reduced considerably, due to the sloping effect, and multiple restriking may even be eliminated in some cases.

Surge capacitors differ from power factor correction capacitors in that they have very low inductance.

They are normally positioned across the load connections, (usually a motor).

6.1.3 SURGE REACTORS

Another way of sloping the steep fronted wave which may occur, is to employ a reactor which is connected in series with the switch [54].

The surge suppression reactor is constructed with a saturable core and a few turns of conductor wound on the core. Figure 6.1 shows a schematic drawing of the reactor designed for use with a vacuum contactor.

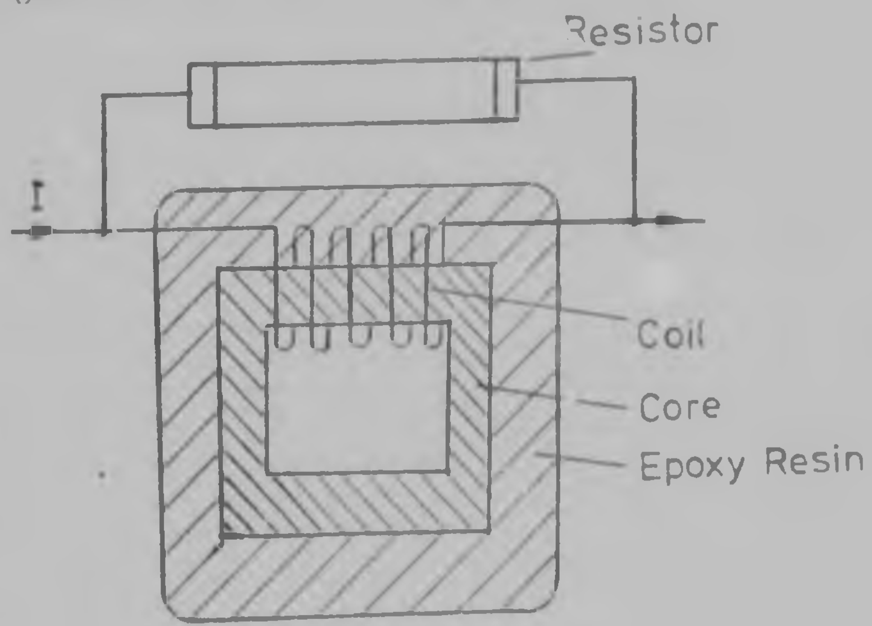


Fig. 6.1. Schematic drawing of interior construction of the reactor.

The reactor can be connected directly to the terminals of the contactor owing to the molded contruction with no bare parts accept the current terminals. The voltage drop for high load current is negligibly low because the core is saturated in this condition. The withstand instantaneous current is co-ordinated with that of the contactor.

The core of the reactor is made of ferrite so as to have fairly high frequency characteristics, because the switching surge has frequency components of the order of 1 MHz. Because of the low loss of the ferrite core, the reactor is shunted by a resistor of the order of the surge impedance of the cable (± 40 ohms).

The insertion of the reactor is effective in reducing the steepness of the wave front of the surges. The theoretical estimation of the effect is complicated due to the non-linearity and frequency characteristics of the core. However Murai et al[54] report the effect when examined experimentally. A voltage surge with a front of 0,2 µsec was applied to the cable through the reactor. Since the surge impedance of a motor or transformer is much higher than that of a cable, the far end of the cable was left open in the test. The wave front was found to reduce to between 1 and 2 µsec depending on cable length as shown in figure 6.2.

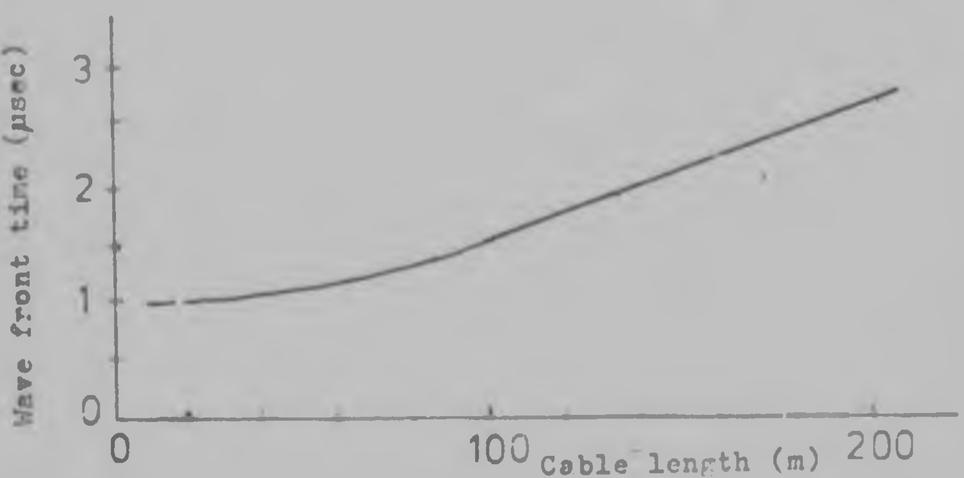


Fig. 6.2. Wave front time as a function of cable length (with reactor)

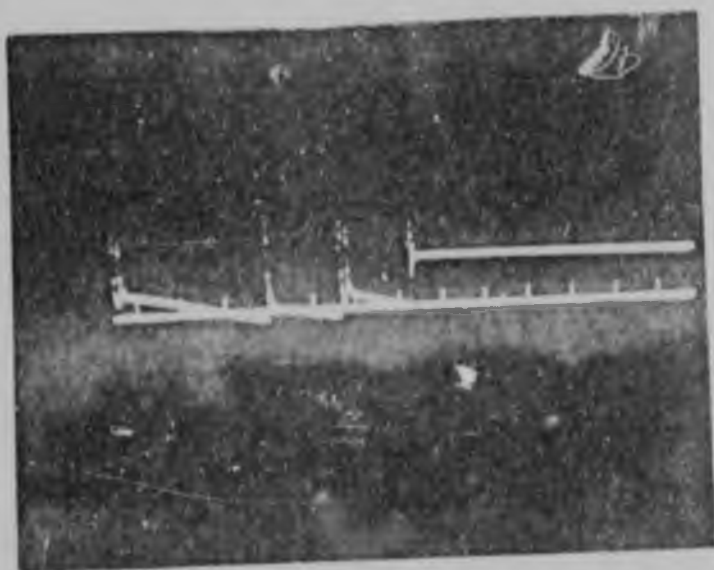
Because of the non-linearity of the core and the loss in the core and parallel resistor, the reactor effectively damps the high frequency current which is produced by the striking of the switch. The high frequency current is damped to within one cycle even if the di/dt at the first current zero is very high. The restriking voltages always rise from zero and the rate of rise of the recovery voltage is suppressed to a low value in comparison with the case without the reactor.

6.1.4 RC SUPPRESSORS

RC suppressors consist of a capacitor in series with a damping resistor. They are connected between each phase and earth and can be positioned at either end of the load cable. They are the most successful means of totally eliminating prestriking and restriking and several tests using these devices were carried out by the author.

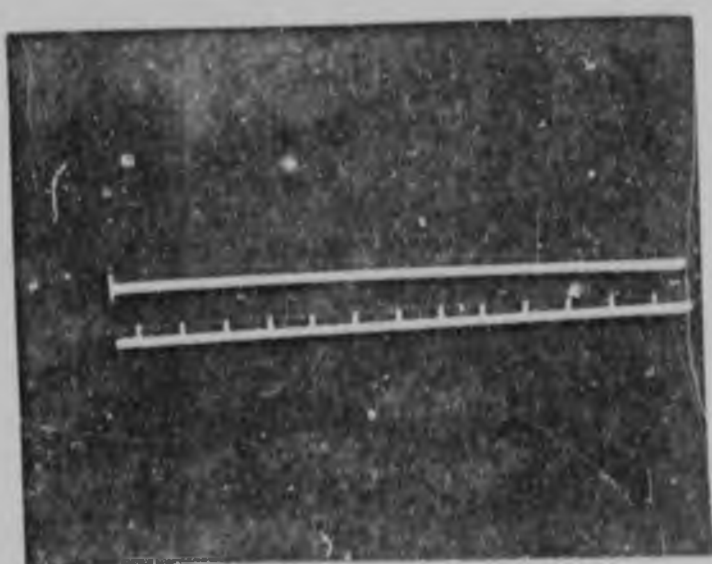
In the simulated circuit of figure 4,2 an RC series combination of R = 100 Ω and [illegible] F, was connected across the load. A typical switch-on [illegible] is shown in figure 6.3. As can be seen the number of prestrikes has been reduced due mainly to the slower recovery voltage across the contacts. Figure 6,4 shows the result of reducing the resistance to 50 ohm. Here, the prestrike transient has been eliminated altogether. The prestrikes in figure 6.3 were caused by the interruption of high frequency currents. When this occurred, the voltage to which the capacitor had been charged was not sufficient to prevent the recovery voltage across the contacts, from producing further breakdowns. In figure 6,4, however, the lower resistor allowed a larger initial current and the capacitor by retaining it's charge prevented any further prestrikes from occurring.

Switch-on transients were monitored using the circuit of figure 3.4 and included an RC suppressor of R = 75 ohms and C = 0,1 µF at the transformer terminals. The equivalent circuit is shown in figure 6.5. A record of the switch-on is shown in figure 6.6 and in it is shown the current recorded. This is oscillatory and has a half period of approx. 70 µsec. Analysing the circuit of 6.5, yields an R-L-C series circuit with 18m of cable



1 p.u./div.
100 μsec./div.
C = 0,25 μF
R = 100 Ω

Fig.6.3: Switch-on using a simulated circuit and a RC suppressor



1 p.u./div.
100 μsec./div.
C = 0,25 μF
R = 50 Ω

Fig. 6.4. Switch-on using a simulated circuit and an RC suppressor

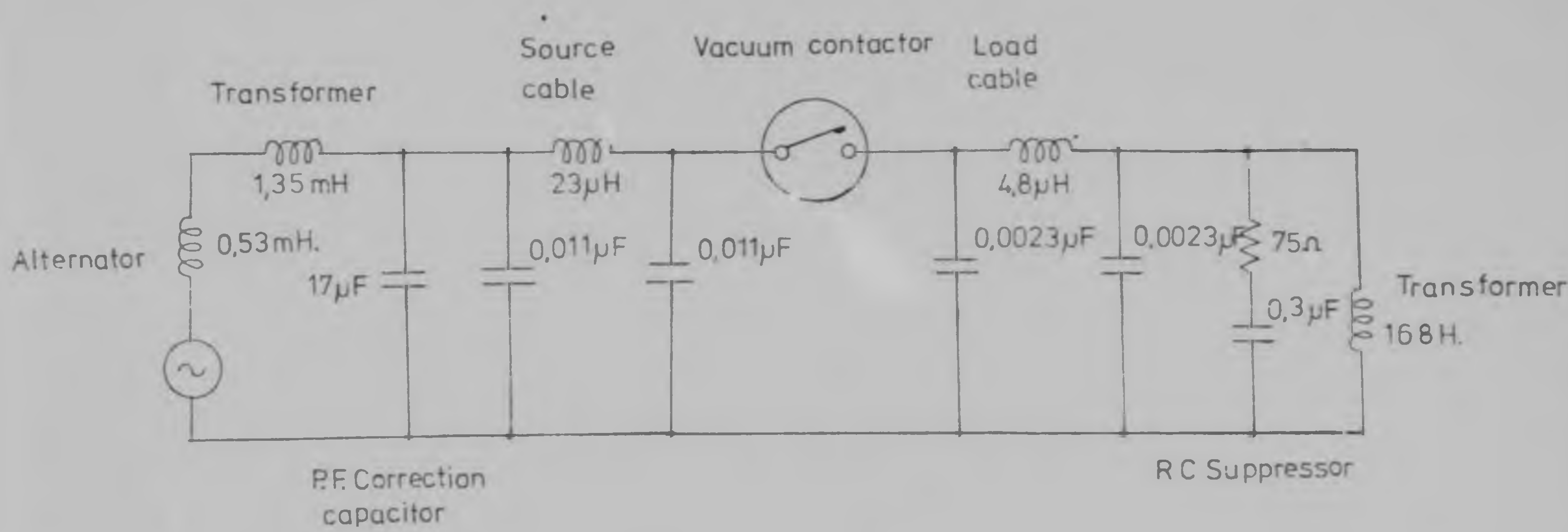


Fig. 6.5. Equivalent circuit of tests on transformer using RC suppressor.

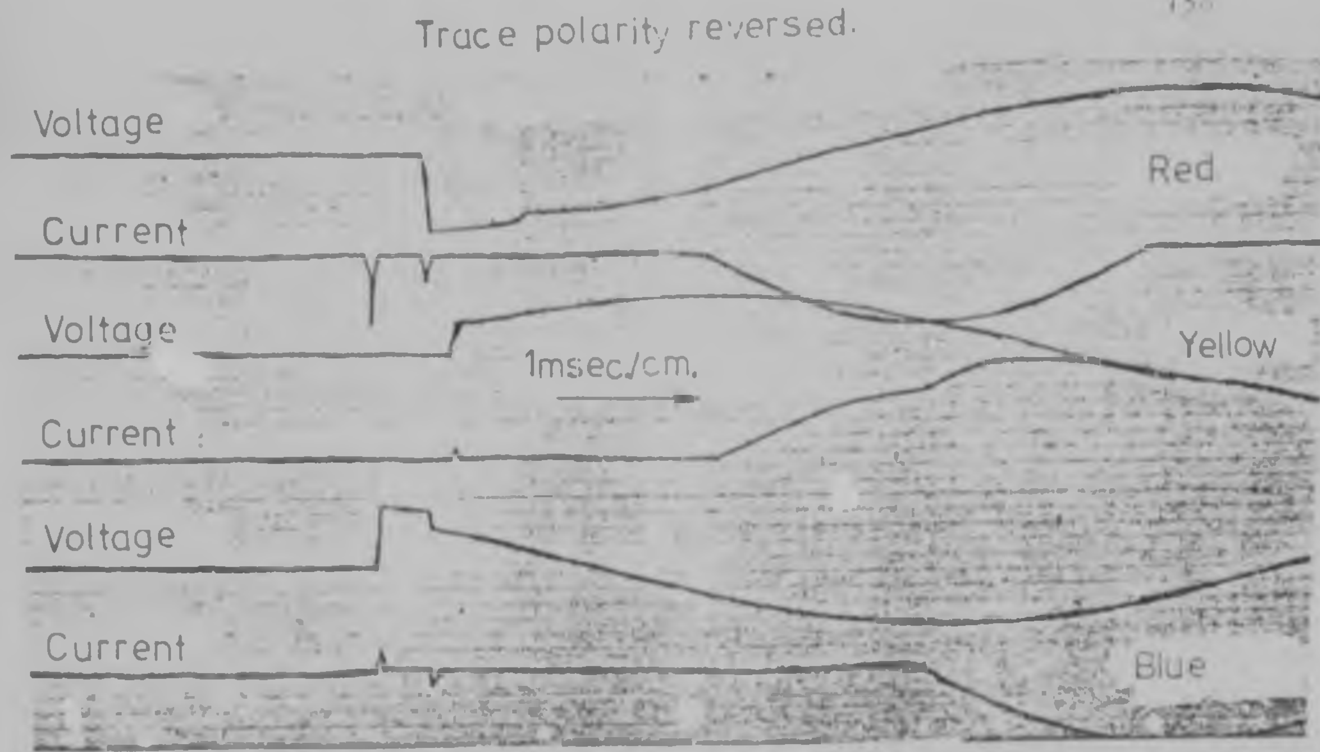
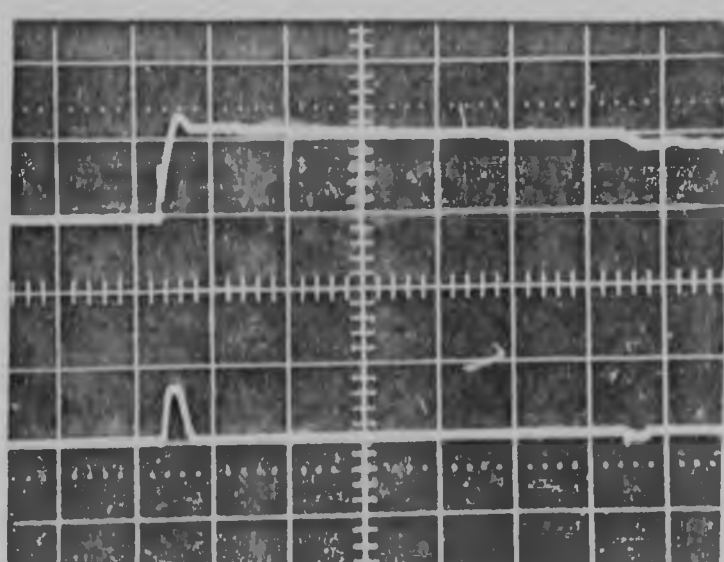


Fig.6,5 Transformer switch-on with RC suppressor

C = 0,3 μF

R = 75 Ω



Voltage: 1 p.u./div.

Current: 50 A./div.

Time 200 μsec./div.

of L = 1,88 mH, R = 75 ohms and C = 0,3 µF. The transient response of this circuit, assuming a dc source, is

$$i = \frac{E}{\omega_o L} e^{-\xi\omega_n t} \sin \omega_o t \quad \text{if } (\xi<1 \text{ or } R<R_d)$$

where $\omega_o = \omega_n\sqrt{(1-\xi^2)}$

$\omega_n = 1/(LC)^{\frac{1}{2}}$

$\xi = \dfrac{\text{actual circuit resistance } R}{\text{resistance } R_d \text{ for critical damping}}$ = damping factor

$R_d = 2(L/C)^{\frac{1}{2}}$

Evaluating ω_o for the circuit, the half period of the current is calculated to be 74,6 µsec. which is very good calaboration indeed. The contactor then interrupted this oscillatory current at the current zero. At this point the capacitor will be charged up to the source voltage and the resultant recovery voltage across the contacts till contacts touch is not sufficient to cause any further prestrikes.

Figure 6,7 shows a switch-on using the circuit of figure 3.20 and an RC suppressor of R = 150 ohm and C = 0,3 µF connected at the terminals of the motor. As can be seen , the initial prestrike occured in the red phase which resulted in the other two phases also rising in potential until they too experienced a prestrike when the voltage across the contacts exceeded the dielectric strength of the switches. The equivalent circuit is similar to that of figure 6,5 and again the half period of the current flowing at each prestrike would be approx. 75 µsec. This current would be interrupted by the switch at current zero. The blue phase experienced further prestrikes and the results of these can be seen on the red and yellow phases. However, the number of prestrikes has been greatly reduced and the magnitude of the prestrike limited

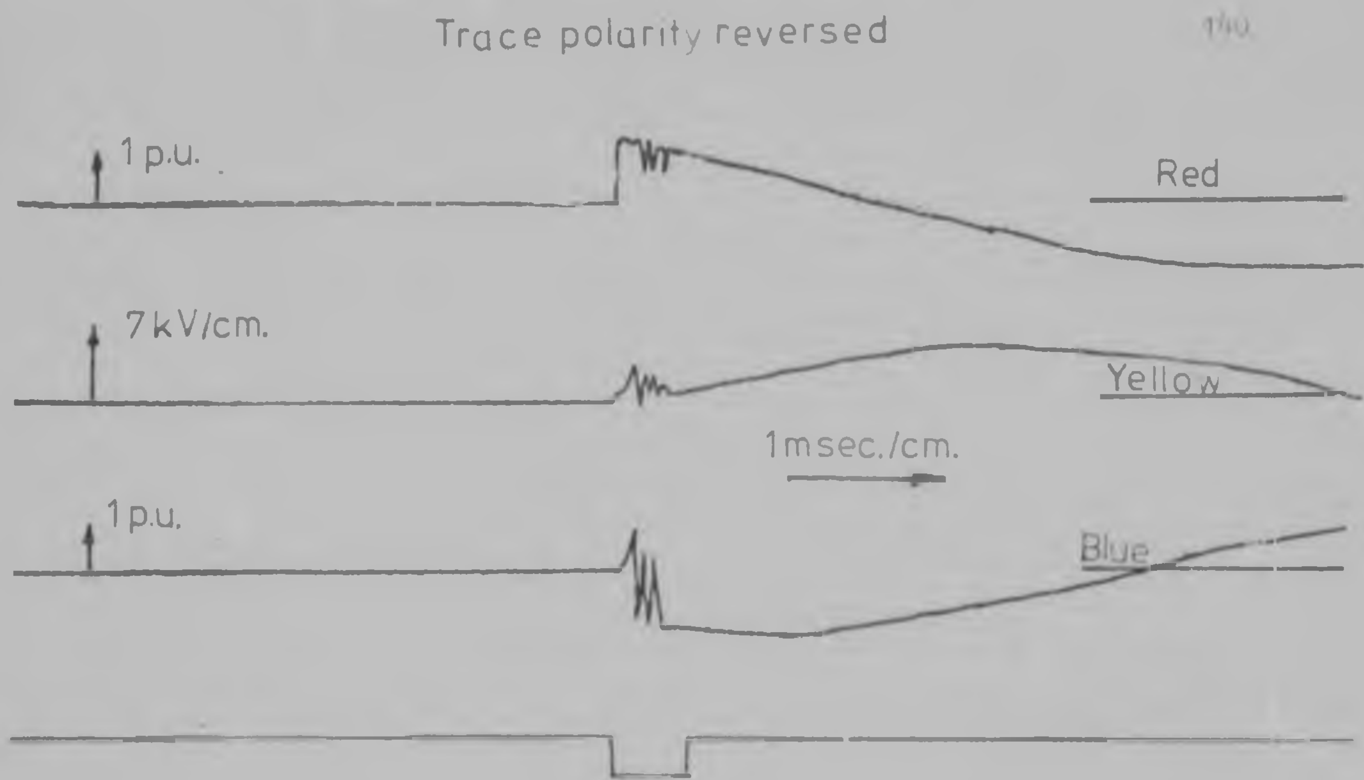
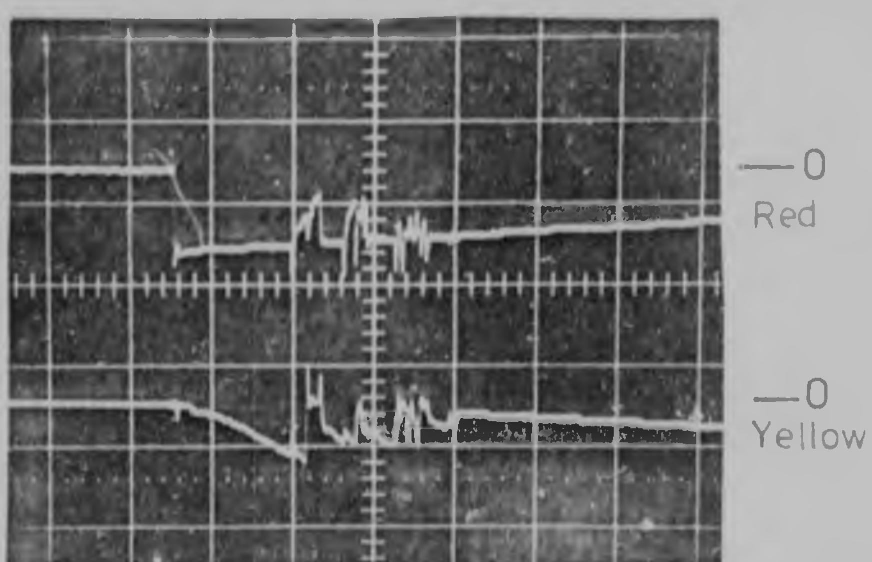


Fig. 6.7. Motor switch-on transient with RC suppressor

C = 0.3 μF

R = 150 Ω



1 p.u./div.

200 μsec./div.

very close to 1 p.u.

Figure 6,8 shows the results of a switch-off using the circuit of figure 3.24 with an RC suppressor of R = 75 ohm and C = 0,3 μF connected at the transformer terminals. The record shows a complete absence of any restriking. This is due to the long recovery times of the circuit once the current has been extinguished in the switches.

Switch-ons and switch-offs were also monitored with the RC suppressor positioned at the contactor side of the load cable. Again there was an absence of any multiple prestriking or restriking. This shows that in some circuits, the RC suppressor is equally effective operating from either position. This is confirmed by Asayama and Sugioka[56]. They used an RC suppressor of C = 0,3 μF and R = 300 ohms at either end when switching a motor. They determined that the suppression rate with the suppressor at the contactor was 83% and that when at the load it was 85%.

In certain special circuit conditions it is recommended to also fit a small capacitor in parallel with the RC combination to remedy possible refracted wavefronts[31].

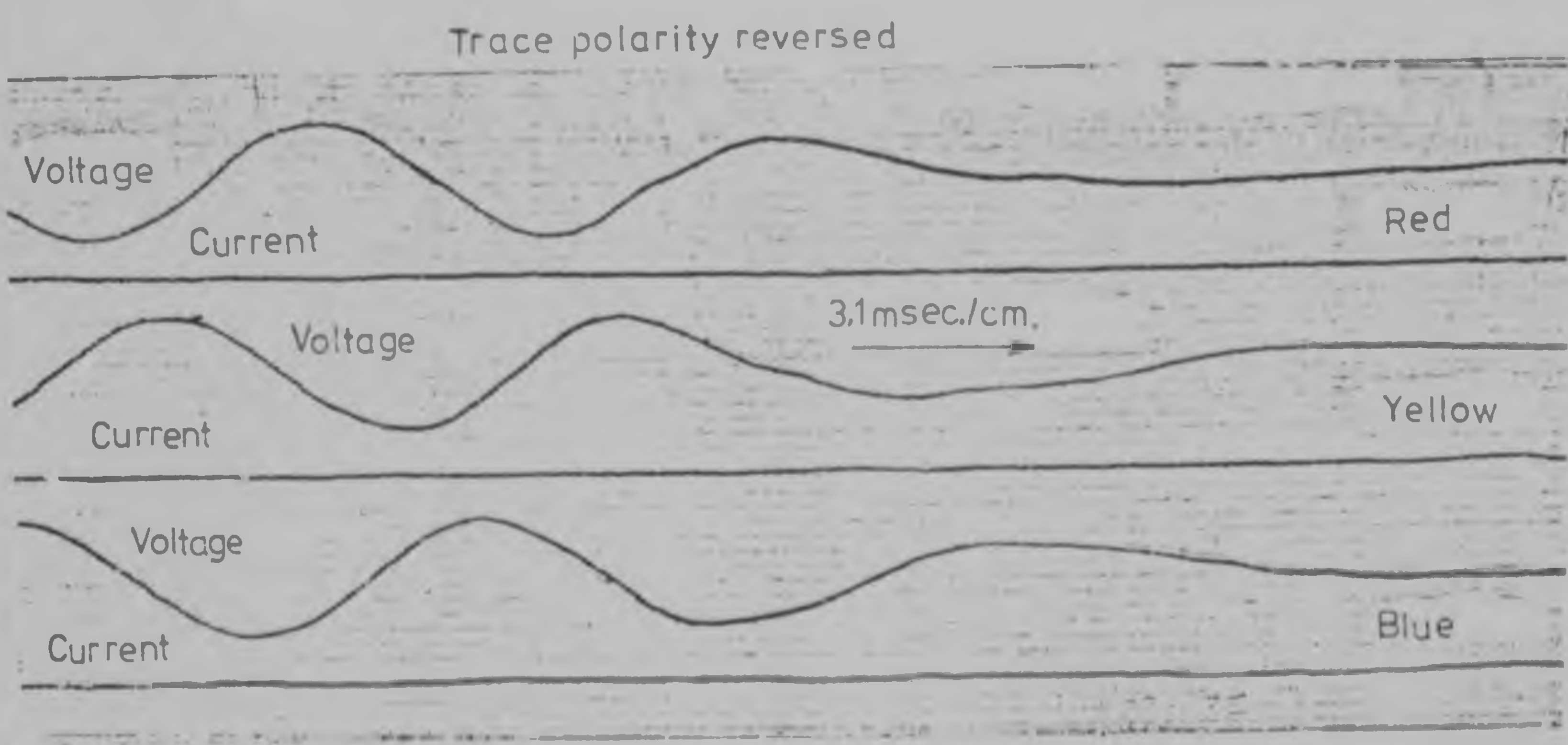
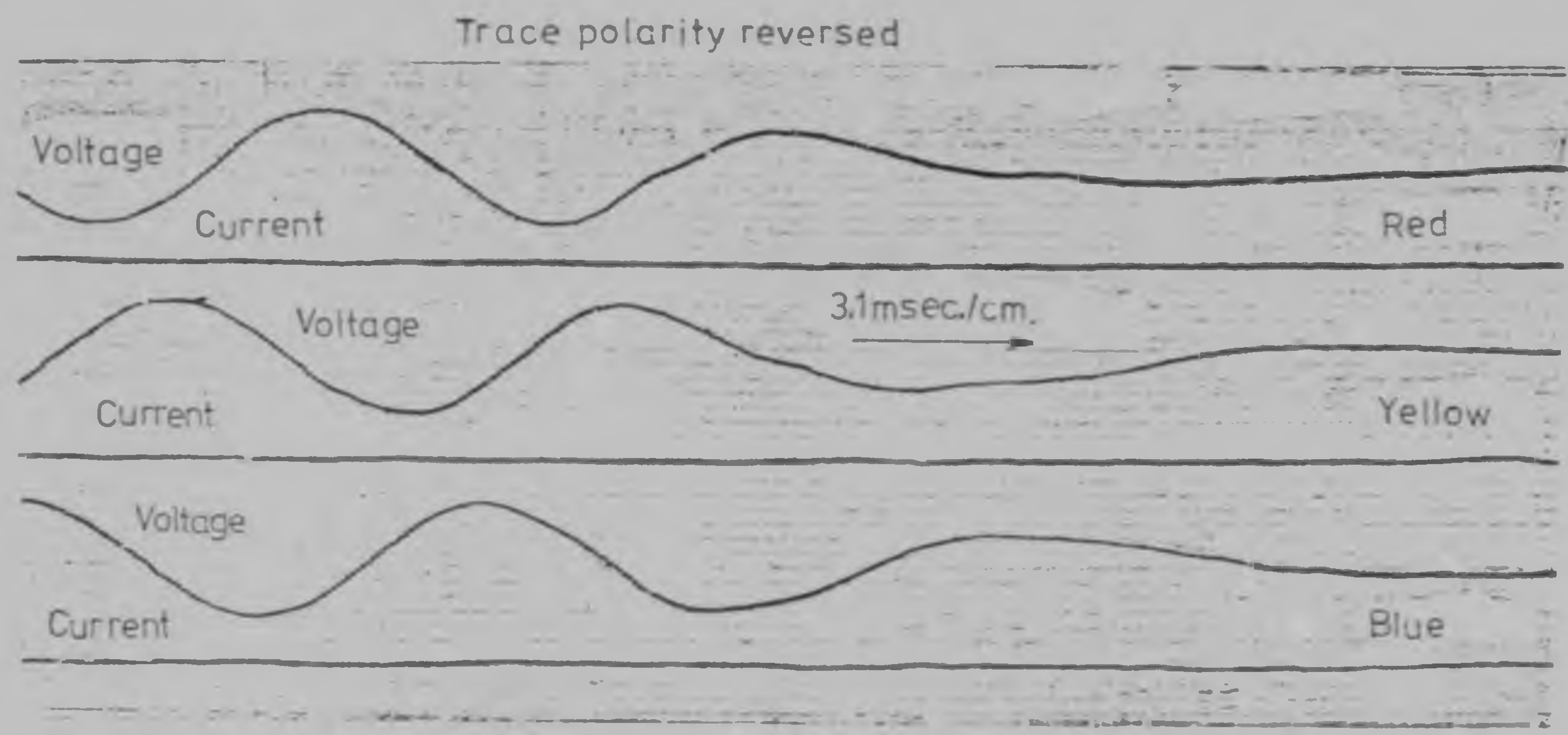


Fig.6,8. Transformer switch-off with RC suppressor.

C = 0,3 μF
R = 75 Ω



$C = 0{,}3\,\mu F$

$R = 75\,\Omega$

Fig.6,8. Transformer switch-off with RC suppressor

6.2 RECOMMENDED APPLICATION OF SUPPRESSORS

6.2.1 VACUUM CONTACTORS SWITCHING MOTORS

A recommendation of the application of suppressors when using vacuum contactors to switch motors has already been published by Speedy and the author[55]. Some of the salient points are reproduced below.

"In the past many statements as to the suppression required when switching motors by means of vacuum contactors have been made. However, few have been sufficiently specific so as to enable the user to make a valid decision in this respect. The main reason for this is that the suppression requirement is linked not only to the characteristics of the particular contactor but equally to the insulation system design of the motor to be switched. Since motor specifications have not laid down the high frequency withstand characteristics of the insulation system, motors having varied capabilities in this direction have been produced around the world. Because of this, satisfactory experience with one make of contactor with motors manufactured to the normal standards adopted in one country, gives no assurance of similar performance with other machines. Line end coils of machines in particular are stressed by the train of sharp fronted transients produced by prestriking on closure and in some cases also by restriking on switch-off. Certain insulation materials that have been used by motor manufacturers and that may still be used by rewind companies because of availability, are not suitable in this respect and have caused problems in the past.

It is important to note that all the transients produced during normal operation i.e. starting and full speed switch-off, are of very modest magnitude. The potentially harmful effects arise from their high rate of rise under certain circuit conditions.

Voltage limiting devices were found to have no modifying effects on such transients because even the closest protection level available with any known form of such suppressor, is above the peak level of these transients. RC suppressors of suitably selected component values, were found to eliminate all restriking on closure and on opening and are considered to be the most suitable suppression equipment to be used where unsuitable systems must be protected."

Should a machine have a known impulse withstand capability, e.g. 35 kV or higher for a 6,6 kV motor, no suppression is required. This approach in machine insulation design has been the normal practice in a number of countries and is certainly the approach now adopted by at least two large local machine manufactures. Ohkawa and Koike[45] recommend an impulse level of 32,7 kV for a 6,6 kV motor. They arrive at this value by multiplying the AIEE's recommended value[56] by 1,3. The AIEE arrived at their value by multiplying the AC dielectric voltage by 1,25.

From 5.3 it is seen that the largest transient recorded was 4,5 p.u. which equals 24,3 kV. The largest recorded rate of rise, see 4.5.2, was 25 kV/µsec. A 35 kV 1,2/50 µsec. impulse withstand capability will thus be above both these maximums and should ensure adequate insulation for all switching and circuit conditions.

Where the insulation system employed in the machine has an unknown or doubtful high frequency withstand level, surge suppression in the form of suitable RC suppressors should be seriously considered.

In the final analysis however, the decision as to whether suppression should be fitted rests with the user, who for critical drives, may wish to use all available means to safeguard such devices, or to protect his drives against any other transient voltages that may be produced on his electrical system.

6.2.2 VACUUM CONTACTORS SWITCHING TRANSFORMERS

Surge suppression is not normally provided for switching transients when switching a transformer, with a known, proven lightning impulse withstand capability. For 6,6 kV transformers, this is normally 75 kV. This represents 14 p.u. with a rise time of 1,2 µsec., and is far greater in magnitude and rate of rise than any transients known to be produced by a vacuum contactor.

However, for transformers with doubtful high frequency withstand capabilities, such as dry type transformers, voltage limiting devices should be seriously considered. Station type arrestors are however usually fitted to these transformers to protect them against lightning surges. If they are fitted, they should ensure adequate protection for switching surges as well.

CHAPTER 7

CONCLUSIONS

The preceding chapters have shown that current chopping is not the problem with vacuum contactors which it was originally considered to be. If anything, the GEC contactor has a much lower current chopping ability than that which the user has been accustomed to and could in fact be raised, to some other advantage perhaps. The Toyo Denki contactor has a relatively higher current chopping ability and results show that this is not generally unacceptable in motor switching circuits. The frequency of the current chopping has been shown to be dependent on the length of cable and is normally between 1 and 10 kHz. The resulting overvoltage is therefore fairly evenly distributed throughout the load.

Prestriking, from a transient point of view, is the most onerous of the phenomena associated with the vacuum contactor. It occurs on every closure, but unlike other switches, instead of perhaps a few at worst, tens of prestrikes can occur. These can have high rates of rise and cause uneven voltage distribution in loads, particularly in line end coils. Load insulation of low impulse withstand capability will be highly stressed on closure of the contactor and the insulation can fail. There are perhaps three remedies to this problem. One is load insulation with proven impulse withstand capability. The second is RC suppression with correct selection of the R and C components, to ensure the elimination of prestriking on closure. The third is faster closing speeds together with increased bottle dielectric, to reduce the number of prestrikes to one or two. All three have problems associated with them. To date there is still no impulse specifications laid down for motors. The chief reason for this is the difficulty of detecting impulse failure on a machine when impulsing. Secondly, although RC suppressors are commercially available, the selection procedures of the individual components has been vague and complicated or not known. There is also not a wide range c [illegible] suppressors available. However, RC suppressors are now quite widely used and with some success.

Thirdly, contactors a[illegible] generally electrically held, and driven by a magnetically attracted armature. High speeds would require large solenoids and power consumption, which is undesirable in a switch which should have a very long mechanical life. Dielectric strength is to some extent dependent on contact material and can be increased at the expense of current chopping level, as is done in the Toyo Denki switch. This alone does not solve the problem completely, but does go someway towards eleviating it.

Restrikes are potentially the surge with the largest magnitudes, and increased dielectric strength can result in larger restrike magnitudes. Opposing this, the larger dielectric strength results in fewer restrikes occuring due to earlier successful interruption. Where stalled motor switching is normal, it is recommended to fit surge arrestors to limit the overvoltages. If RC suppressors have been fitted, these will also deal successfully with restrikes.

In summary, switchin[illegible] transients [illegible]ssociated with the vacuum contactor are now quite well understood and no longer need perturb the user from enjoying the many excellent advantages he obtains from using them.

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