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Digital Modelling of the Excitation and Short-Circuit Transient Characteristics of the Short-Circuit Generators

Thesis for the Degree of Master of Science

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ABB

Title

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Abstract

High Power Laboratory in Ludvika has facilities for short-circuit testing of high voltage equipment like circuit breakers, disconnectors, surge arresters, transformers, switchgear cubicles, etc.; simulating the test conditions as in real power transmission network. In order to provide such an extremely high short-circuit current up to 100kA, two specially designed turbo-generators are being used with a total capacity of 4000MVA. Each of generators during the short-circuit test is excited by a separate driven exciter to provide the excitation current. “Flying excitation” method which is used to provide the right value of test current and voltage is described more in detail in Chapter 2.

The excitation system has to be properly set in order to satisfy requirements of short-circuit testing. Therefore correct value of excitation time and an exciter voltage has to be chosen in advance to fulfil the criteria of short-circuit testing. The no-load characteristics of generators have been measured and an analysis of obtained data was made to get the needed excitation time characteristics.

The study of collected data from previous single-phase short-circuit tests showed that it is best to use the same excitation times for the operating sequences open (O), open-close-open (O-CO) and close-open (CO) in order to provide the correct short-circuit current at interruption for a given connection of generator winding, and frequency. For operating sequence close (C) is also recommended to use the same excitation time determined in the study for whole range of short-circuit current at the generator side within the same generator winding connection, frequency and use of the generators.

The final program for calculation of excitation parameters has been developed to visualise the particular excitation time characteristics obtained from the no-load measurements as well as easily and accurately determine the right values of parameters for excitation of the generator, such as exciter voltage and generator output rms voltage, for a certain short-circuit test. Recommended excitation times can be also easily found in the program by various combinations of the input parameters like generator, frequency, winding connection and operating sequence.

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Contents

CHAPTER 1

Introduction

When lightning strikes a power transmission line, high overvoltages are generated that might cause flashovers between the phases. This can lead to short-circuit. Short-circuit might also occur when the line falls to the ground due to heavy storms or severe ice-conditions. No matter what causes short-circuit it always results in a flow of huge currents of several kA in the electrical network. The short-circuit currents impose high electromagnetical stresses on the network equipment. Therefore the high voltage equipment should be designed to withstand that high short-circuit currents without causing any damages to themselves. Hence, extensive tests are performed in the high power laboratory to verify short-circuit withstand capability before certifying.

These high short-circuit currents are simulated on the electrical transmission and distribution equipment in the high power laboratory in Ludvika. Here, short-circuit currents up to 100kA can be achieved with help of two specially designed high-power short-circuit generators. Together they can deliver power up to 4000MVA. Each of generators is driven by an electric motor supplying the mechanical and no-load losses of the generator. During the short-circuit tests, the driving motor is disconnected electrically from the network supply and the mechanical energy stored in the rotating mass supplies the short-circuit current for the short duration of the test. The excitation current for and of the generators is supplied by a separate driven exciter consisting of a motor-generator set equipped with large fly-wheel. “Flying excitation” method which is used to provide the right value of test current and voltage is described more in detail in Chapter 2. The excitation system is a complex system and need to be properly set in order to satisfy the requirements of short-circuit testing. Therefore correct value of excitation time and an exciter voltage has to be chosen in advance to fulfil the criteria of short-circuit testing.

The aim of this thesis is firstly to measure the no-load characteristics of the high power short-circuit generators that are used for short-circuit testing of high voltage equipment, mostly circuit breakers, in order to determine more accurate characteristics of excitation time and its values, such as exciter voltage and generator output rms voltage.

Secondly to make a study based on collected data from previous single-phase short-circuit tests of high voltage equipment to study transient characteristics and to see if it is possible to generalize excitation times for the operating sequences open (O), open-close-open (O-CO), close-open (CO) and close (C) for a chosen generator winding connection, frequency and short-circuit current on the generator side.

Finally results of above two are used as the main input parameters into a new program, developed with use of the software Microsoft Visual Basic 5, in order to provide a user friendly interface, such as easier and comfortable handling and good visual approach, and to substitute very old graphs of excitation time characteristics drawn on millimeter paper that are used nowadays for obtaining the values for excitation, such as exciter voltage and generator output rms voltage. These old characteristics for setting the values of excitation were obtained from previous tests and also do not cover wide range of excitation times and so by the new digital tool it will be more efficient and accurate to adjust values for excitation since it has been taken from real no-load measurements on generators.

This thesis is structured in six Chapters.

In Chapter 2 an overview of the High Power Laboratory in Ludvika is presented and its test facilities and equipment are described.

In Chapter 3 the no-load measurements of generators and its analyses using Matlab are discussed.

In Chapter 4 the data are collected from previous short-circuit tests to study the transient characteristics and carefully analysed to see the dependency on excitation time.

In Chapter 5 the results from previous two Chapters are programmed by Microsoft Visual Basic 5.

In Chapter 6 all of the results are summarized.

CHAPTER 2

Test Facility and Equipment

2.1 High Power Laboratory

The high power laboratory of ABB in Ludvika, Sweden, has facilities for short-circuit testing of electrical transmission and distribution equipment like circuit breakers, disconnectors, surge arresters, transformers, switchgear cubicles; simulating the test conditions as in real network. Other equipment such as thyristor modules used in HVDC systems can be also tested in the laboratory. The laboratory is engaged primarily in the testing and certification of high voltage equipment. Therefore, two specially designed high-power short-circuit generators are installed, which can achieve very high currents up to 100kA with total generating capacity of 4000MVA. The generator voltage can be stepped up to 145kV three phase, and 250kV single phase with help of low impedance transformers. Testing of some high voltage equipment requires very high short-circuit capacity of the order of 30-50GVA. It becomes economically unavailable to add additional generators in the test laboratory to achieve such high capacity. Therefore synthetic test methods have been developed and standardizes for realizing such tests.

The high power laboratory has a test facility of direct and synthetic testing. The main parameters of each testing facility are described as follows.

Direct testing:

max. short-circuit power	4000MVA
max. test voltage - 3 φ	145 kV
max. test voltage - 1 φ	250kV
frequency	$16^2/_3$ - 60 Hz
max. test current	100kA rms
duration	3s a63kA 1s at 100kA

Synthetic testing:

single-phase tests	525 kV, 80kA
three-phase tests	245kV, 63kA
main capacitor banks	3.2MJ
two circuits	± 660kV d.c
4-parameter TRV, a.c. recovery voltage	
short circuit making test	
capacitive current switching tests	

The premises of the high power laboratory consist of the following equipment, which are used for the short-circuit testing and are described later in this chapter in more detail.

- short-circuit generators
- exciters
- transformers
- capacitor banks
- resistors
- reactors

There are 9 test cells for high power testing and two of them are connected to the synthetic test circuit, where test with the voltages over 1000kV can be performed. All the test cells are built to endure explosions and the tests are recorded by the several video cameras.

Digital control systems transmit signals through optical-fibre cables from the control room. These signals control precisely the operation of various equipment in the test circuits. To ensure a trouble-free collection of a large number of data, advanced data collecting system is used. It has a digital transient recorder with optic-fibre isolated digitizers between the control room and the test cells. A powerful computer system conditions the test signals and carries out analyses of the data. Therefore it is easy to determine whether or not the test object has satisfied the requirements according to IEC standards in just a few seconds after the test.

The ABB High Power Laboratory was accredited in 1994 by the Swedish Board for Technical Accreditation (SWEDAC) and is a member of Scandinavians Association for Testing of Electrical Power Equipment (SATS), an independent non-profit organization, and a member of the STL (Short-circuit Testing Liaison). In accordance with the requirements of these institutions, type-tests carried out on high voltage products have to satisfy the standards. The organization and facilities at the Ludvika high power laboratory have been evaluated by an independent committee, and ISO 9001 approval has been granted.

2.2 Generators

The laboratory has two short-circuit test generators. The larger synchronous generator (G1) has a nominal rating of short circuit power of 2500 MVA and a smaller one (G2) with a short-circuit rating of 1300MVA. The machine data are given below in table 2.1. Both machines are of the turbo type, which is particularly suited as a short-circuit test generator, since it enables a considerable amount of energy to be store in the high-speed rotor. The machines have been specially designed due to demand on high short-circuit withstand strength.

Table 2.1 Short-circuit test generators. G1 - the larger unit

		G1	G2
Rated short circuit power[1], MVA		2 500	1 300
Rated voltage, kV		7.5/13/15/(26)[2]	4.33/7.5/8.67/15
Nominal rating[3], MVA		180	130
Frequency, Hz		50/60	50
Speed, r.p.m.		1 500	1 500
Number of windings per phase		2	2
No-load excitation current at rated voltage, kA		2.88	1.3
S.c. excitation current at rated s.c. power, kA		22.5	8.25
Time constant of field windings at no-load, s		4.6	7.0
No-load power, KW	without excitation	710	390
	with excitation to rated voltage	2 240	1 300
Rotor diameter, mm		1 700	1 550
Driving-motor output, MW		3.0	1.0

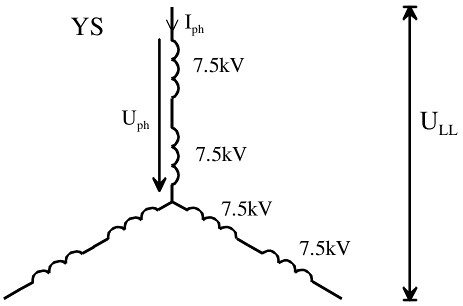
[1] Symetrical breaking power after a short-circuit time of 0.2 s

[2] When connected to 26kV, it is only used for tests at 25 and 16 $^2/_3$ Hz

[3] Continuous load carrying capacity for the conventional design of the machine type

2.2.1 Winding connections of Generator 1 (G1)

Maximum voltage across each generator winding of G1 is 7.5kV with the maximum permissible value of current 50kA, which can flow through one winding. Summary of all parameters is shown in figure 2.1 for each generator winding connection.

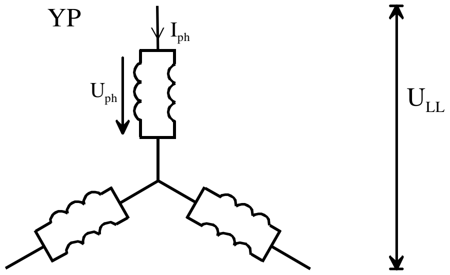


YS (131)

$U_{LL} = \sqrt{3}U_{ph} = 15\sqrt{3}kV = 26kV^{*}$
$U_{ph} = 15kV$
$I_{ph} = 50kA$ (current through windings)
$S = 3U_{ph}I_{ph} = 3 \cdot 15kV \cdot 50kA = 2250MVA$
Used only for lower frequency tests:

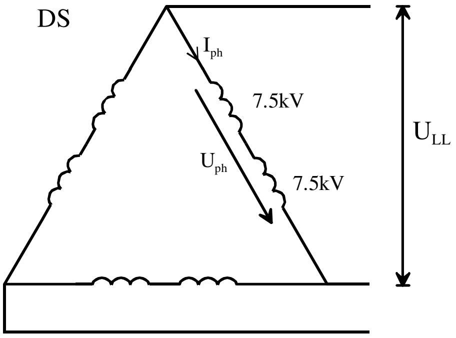
- 16 $^{2}/_{3}$ Hz
- 25 Hz

*used only up to 15kV



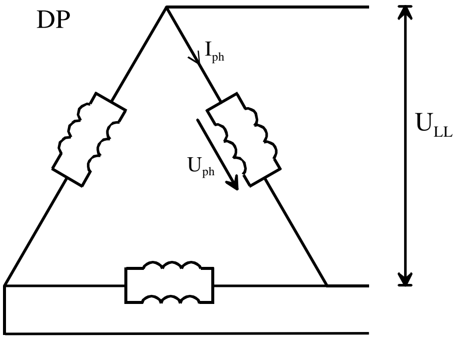
YP (133)

$U_{LL} = 7.5\sqrt{3}kV = 13kV$
$U_{ph} = 7.5kV$
$I_{ph} = 100kA$
$S = 3 \cdot 7.5kV \cdot 100kA = 2250MVA$



DS (132)

$U_{LL} = 2 \cdot 7.5kV = 15kV$
$U_{ph} = 15kV$
$I_{ph} = 50kA$
$S = 3 \cdot 15kV \cdot 50kA = 2250MVA$



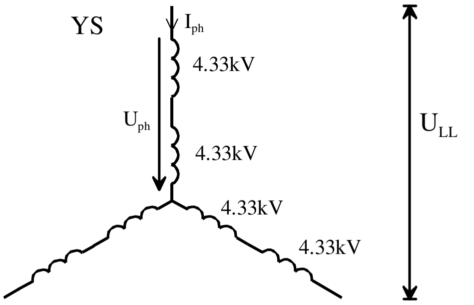
DP (134)

$U_{LL} = 7.5kV$
$U_{ph} = 7.5kV$
$I_{ph} = 100kA$
$S = 3 \cdot 7.5kV \cdot 100kA = 2250MVA$

Figure 2.1 Generator 1 – parameters of winding connections for YS, YP, DS, DP

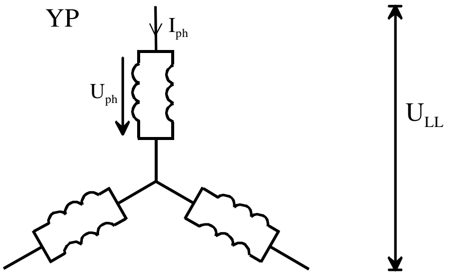
2.2.2 Winding connections of Generator 2 (G2)

Maximum voltage across each generator winding of G2 is 4.33kV with the maximum permissible value of current 45kA, which can flow through one winding. Summary of all parameters is shown in figure 2.2 for each generator winding connection.



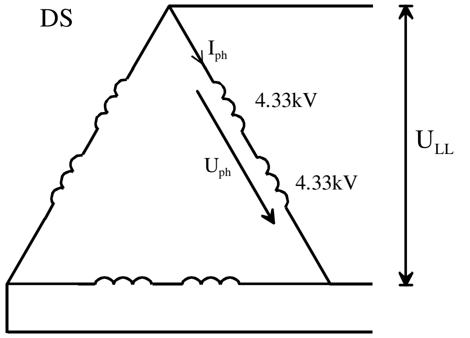
YS (231)

$U_{LL} = \sqrt{3}U_{ph} = 8.66\sqrt{3}kV = 15kV$
$U_{ph} = 8.66kV$
$I_{ph} = 45kA$ (current through windings)
$S = 3U_{ph}I_{ph} = 3 \cdot 8.66kV \cdot 45kA = 1170MVA$



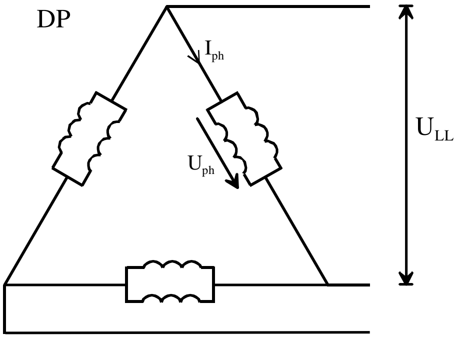
YP (233)

$U_{LL} = 4.33\sqrt{3}kV = 7.5kV$
$U_{ph} = 4.33kV$
$I_{ph} = 90kA$
$S = 3 \cdot 4.33kV \cdot 90kA = 1170MVA$



DS (232)

$U_{LL} = 2 \cdot 4.33kV = 8.66kV$
$U_{ph} = 8.66kV$
$I_{ph} = 45kA$
$S = 3 \cdot 8.66kV \cdot 45kA = 1170MVA$



DP (234)

$U_{LL} = 4.33kV$
$U_{ph} =4.33kV$
$I_{ph} = 90kA$
$S = 3 \cdot 4.33kV \cdot 90kA = 1170MVA$

Figure 2.2 Generator 2 – parameters of winding connections for YS, YP, DS, DP

2.3 Exciters

Both high power generators have their own separately driven exciter set. Their design enables to supply a considerable super-excitation during the test. The exciter set consists of a driving motor, fly-wheel and a dc generator. The second one has a compensating winding and because of the high currents, which are to be commutated it is designed with a laminated stator and a special rotor winding. The data for the two exciters are given in table 2.2.

Table 2.2 Exciters

		Set 1	Set 2
Rated voltage, V		1 050	1 000
Rated short-circuit current for 0.2s, kA		27	9.75
Speed, r.p.m.		428	428
Max. permissible peak current at short-circuit, kA		60	15
No-load excitation current at rated voltage, A		46	30
Continuous output, kW		6 500	3 000
No-load power, kW	without excitation	100	85
	with excitation to rated voltage	155	130
Retardation at s.c. with rated s.c. current for 0.2s, %		9	10
Starting time, min		5.6	1.2
Retardation time, min		8	3
Stopping time without retardation, min		38	44
Driving-motor output, kW		3 000	1 000

A balanced beam-relay, which senses the ratio between the voltage and the field current of the exciter, is used as a protection for any flashovers on the commutator. The relay must have a certain dead zone to prevent it from tripping during the short-circuit tests. Despite of this, it is quite capable of tripping reliably, when a flashover occurs on the commutator. An earth fault in the main winding of the exciter is detected by the rotor protection of the generator. A separate earth-fault protection, designed using the same principle as above, is employed for the field windings of the exciter. In the events of more severe faults, the exciters are decelerated automatically.

2.4 Excitation

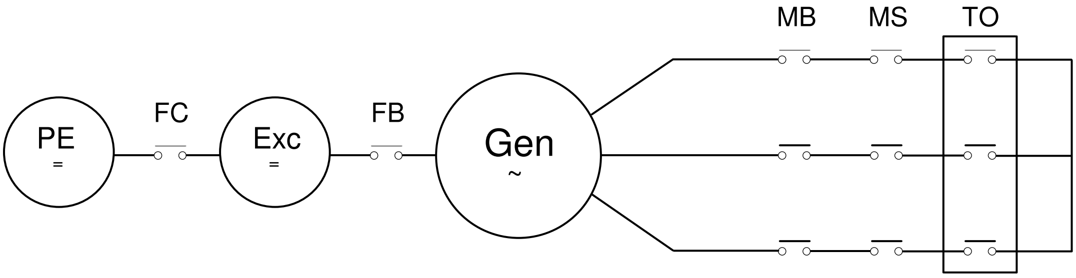
Excitation of the high power generators can be obtained by two different methods, in order to get the right values of the short circuit current for the testing. First, the super-excitation will be described and then the “flying excitation”, which is the system that is actually being used within ABB High Power Laboratory in Ludvika. This is a very unique method how to maintain a short-circuit current for the testing and thus it will be described more in detail later on.

Super-excitation

A super excitation is required if the current is to be maintained constant while the short circuit last, since otherwise the generator will be de-magnetised due to influence of the armature reactance, thus causing the short-circuit current to decrease. This great super-excitation can be obtained with the help of a powerful exciter and can be applied to the generator field by short-circuiting a series resistor in the field circuit at the same time instant, as the generator is short-circuited.

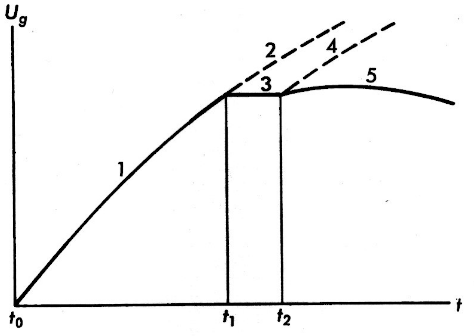
Flying excitation

This system of flying excitation implies that the generator is short-circuited while the generator field is still rising shortly after it has been connected in. This principle is shown in figure 2.3 along with the characteristic of generator voltage during the time instant.



PE – primary exciter
Exc – main exciter
Gen – high power generator
TO – test object

FC – exciter field circuit-breaker (“Fältkontaktor”)
FB – generator field circuit-breaker (“Fältbrytare”)
MB – main circuit-breaker (“Säkerhetsbrytare”)
MS – main switch (“Snabbslutare”)



1 Generator voltage during the excitation time
2 Generator voltage without short circuit
3 Main flux and the short-circuit current during the period of short circuit
4 Generator voltage after the short circuit without de-magnetizing
5 Generator voltage after the short circuit with de-magnetizing

Figure 2.3 Principle of flying excitation

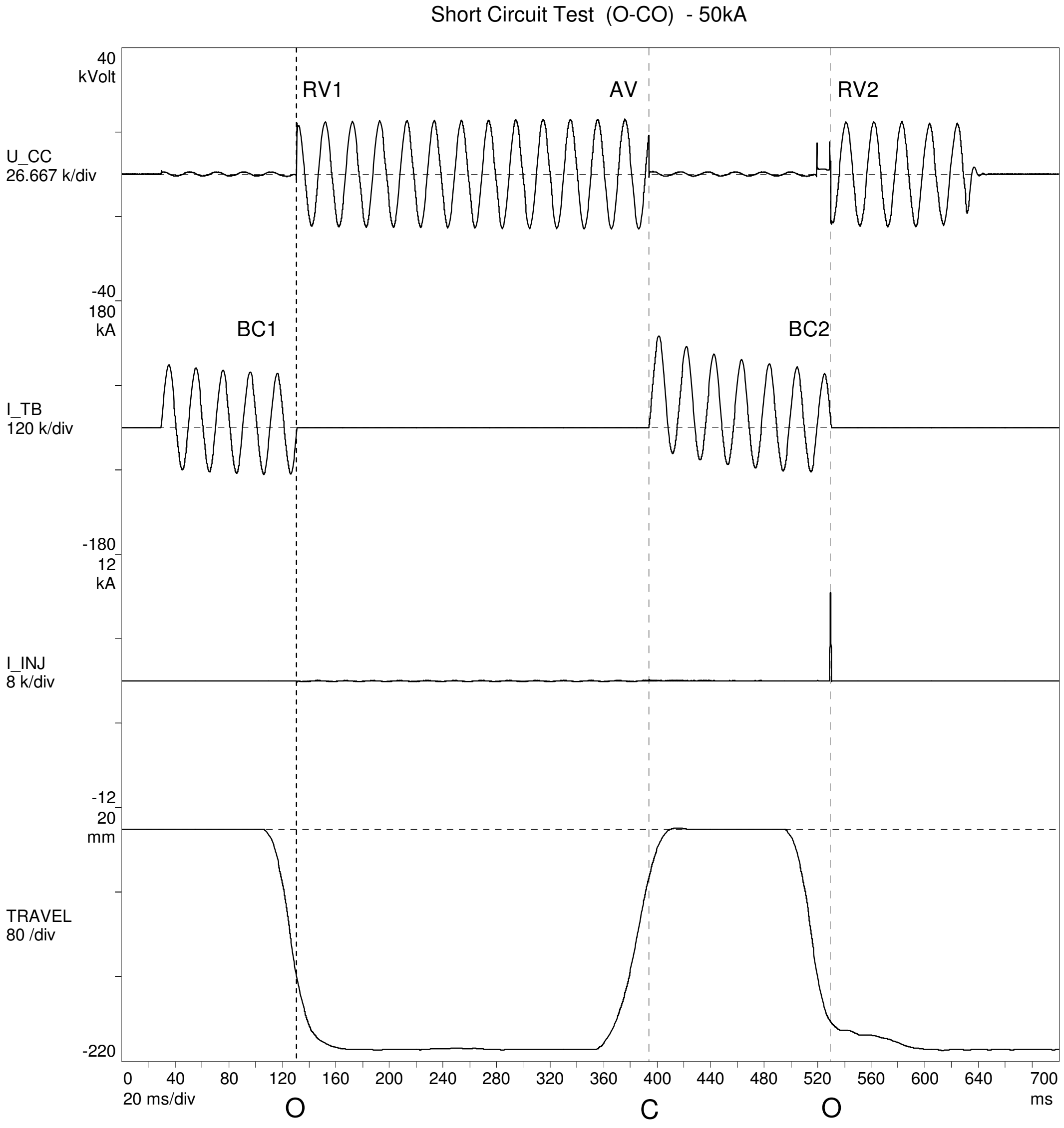
Initially (before t_0), the main exciter is excited to a certain voltage determined in advance, but it is disconnected from the generator field. At the instant t_0 the generator field switch is switched on, and the generator voltage then starts to rise, following an exponentional curve. The steepness of this increase depends on the setting of the exciter voltage. At the instant t_1 the generator voltage is assumed to have reached the value at which the test is to be performed, and the short circuit is initiated. The time t_0 – t_1 is normally about 0.5 – 1s. After an interval of about 0.1 – 0.2s, the short circuit is interrupted (t_2). During the period of the short circuit, the excitation thus strives to increase the main field of the generator at the same time as the armature reaction strives to reduce it. When the system is properly set, these forces counterbalance one another and so the main field will be maintained constant throughout the duration of the short circuit test. In this way, the short-circuit current will also be constant, and so the recovery voltage immediately after the interruption will be the same as the voltage applied before the short circuit. After the instant t_2, the generator voltage would once again strive to attain its no-load value, unless special measures were taken, and would thus reach excessively high values. Just before this instant, however, the exciter field is interrupted and reversed, which means that the generator voltage rises only slightly after which it rapidly decays. The parameters of interest here are the exciter voltage and the excitation time ($t_0 – t_1$). The higher the exciter voltage, the steeper the voltage-rise curve of the generator will be and the shorter the excitation time required for a certain generator voltage to be obtained. The setting to be selected is determined by the magnitude of the power, which is to be taken out of the generator, which means, the magnitude of the armature reaction needs to be compensated for. By knowing the machine data, a suitable setting can easily be determined in advance.

The main difference between these two methods, super-excitation versus flying excitation, is that with the series resistor in the field (super-excitation) it is possible for the generator to be excited to the desired voltage already before the test. But on the other hand, when using the flying excitation method, it is possible to avoid the losses occurring both in the generator and the series resistor.

In practice, the conditions are complicated slightly by the presence of the damping circuit of the generator. The transients in these cannot be fully compensated for by taking any measures in the field circuit, which means that the short-circuit current cannot be maintained at a fully constant value during the period of a short-circuit current, instead it will decrease during the first part of this period. If a large super-exciter is used, a certain amount of compensation can be obtained if the current is forced to increase during the latter part of the short circuit so that it reaches the initial value once again shortly before the interruption. Such a form of compensation can be achieved for the case in question without any difficulties, since the exciters are very powerfully dimensioned. This compensation is facilitated also by the fact that the generators lack any damping windings and that special measures have been taken to prevent the occurrence of eddy currents in the rotor surface.

Another reason for the dissimilarity between the conditions at making and interruption is the retardation of the machine during the short circuit. The same recovery voltage and applied voltage can only be attained by means of over-compensation, and this will cause the current to rise slightly. Over-compensation is also required during the first short-circuit period for a high-speed reclosing test to enable more or less the same condition to be obtained during the second short-circuit period. This will occur namely on a less steep part of the voltage-rise curve. It is naturally impossible to obtain fully comparable conditions during making and interruption, but by adopting suitable setting it is possible to reduce such differences to a low level and they can always be maintained within the tolerance limits stipulated in the circuit breaker standards.

An example of this is shown in figure 2.4, which is an oscillogram of an open-close-open (O-CO) operating sequence on SF_6 circuit breaker.



U_CC – voltage on tested breaker
I_TB – short-circuit current on tested breaker
I_INJ – injection current of high frequency
TRAVEL – contact travel

O – instant of contact separation
C – instant of contact closure

RV1 – recovery voltage after first opening
AV – applied voltage
RV2 – recovery voltage after second opening

BC1 – breaking current at 1st opening
BC2 – breaking current at 2nd opening

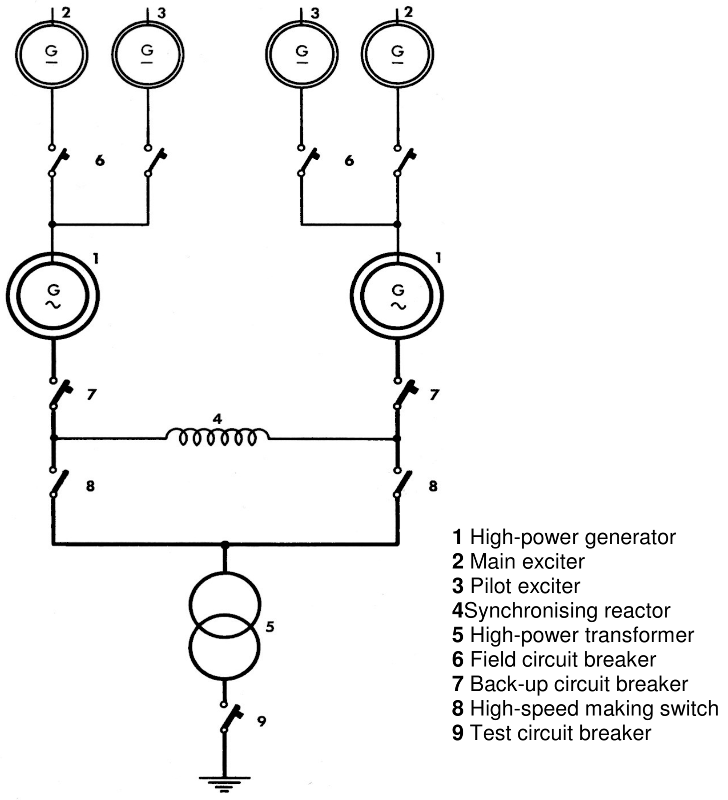
Figure 2.4 Oscilogram of the O-CO operation on SF_6 circuit breaker.

Parallel running of the generators

The two generator sets can be run in parallel. This brings out certain problems, both due to the excitation system selected and due to the fact that the machines are not identical from the electrical or mechanical points of view.

When using flying excitation, the generators are excited for a very brief interval in conjunction with a test (total time in order of 1s). This time does not suffice, however, for synchronisation due to their large masses. It is impossible to excite the machines to their full voltage before the test, and synchronise them in this manner. The reasons for this are that the generators are not designed to run for longer duration at a full voltage and that the ordinary exciters cannot be employed, since this would prevent their use for super-excitation during the tests.

A special system shown in figure 2.5 has therefore been adopted for the synchronisation and excitation. Prior to a short-circuit test the generators are excited by the pilot exciters 3, which enables them to be excited up to a few kV. The generators have been connected in parallel on the AC side across a synchronising reactor 4 with a rating of 2 ohms per phase, and the back-up circuit breakers 7 are closed. The power transmitted in this case is sufficient to synchronise the generators and maintain them in synchronism within a few electrical degrees. The pilot exciters are disconnected just before a test is to being performed. The main exciters 2 are then switched in and flying excitation is applied. The machines do not have time to drop out of synchronism during the short time they are without voltage during the reconnection. Since the machines have slightly different excitation curves, equalising currents cannot be prevented from being generated during the excitation.



1 High-power generator
2 Main exciter
3 Pilot exciter
4Synchronising reactor
5 High-power transformer
6 Field circuit breaker
7 Back-up circuit breaker
8 High-speed making switch
9 Test circuit breaker

Figure 2.5 Circuit diagram for parallel running of generators

By selecting a relatively high ohmic reactor, it is possible to limit these currents to a reasonable value. The settings in the field circuits must be such that the generators will attain the same voltage and more or less the same voltage derivative at the instant when the short circuit is initiated by the high speed making switch 8 or the test circuit breaker 9.

For practical reasons, however, the same excitation time is generally used for both machines, and so it is necessary to waive slightly requirements for identical voltage derivatives. This does not have any significant influence. The larger machine has to be always correctly set. The synchronising system employed has been made partly automatic and is sufficiently rapid to enable tests to be performed at intervals of three minutes. When making high speed reclosing tests, the main exciters are connected up throughout the test and supply synchronising power also between the two short circuit periods.

During the short circuit itself the machines try to fall out of synchronism. This is due to the fact that the ratio between the short circuit power and the flywheel capacity is not the same for both machines. When the machines are directly connected in parallel to the test cell (without transformer), no synchronising power can then flow between them during the short circuit. This condition can be improved when transformers are connected and the generators are connected in parallel to their primary side. The voltage drop across the transformer reactance will then permit a certain amount of synchronising power between the machines. In the case of two-phase short circuits, even better conditions will be obtained, since a certain synchronising power across the phase that is not short-circuited will always be available. In practice, however, the position is not so important, since the machines with their large masses will not have time to drop very much out of synchronism during the brief period of short circuit. A slight drop in the power must nevertheless be anticipated. Calculations have shown that the drop in power will be 10-15% when the generators are connected direct to a test cell and the full power is taken out for a period of 0.2s. When the short circuit time is 0.1s, the drop in power will be less than 1%. If the generators are connected across transformers, the maximum drop will be 2 to 3%. To conclude this experience, if the short circuit is limited to 0.1 to 0.2 s, there are no significant difficulties.

2.5 Transformers

The laboratory has two transformer banks, each consisting of six single-phase units. The transformer data are given in table 2.3. Transformer bank 1 is being used together with the larger short-circuit test generator, but from a mechanical point of view, this transformer bank can handle most of the generator connection cases. Transformer bank 2 includes older transformers, which were used previously together with the smaller generator in the old laboratory. The single-phase units have been selected for use, partly because for the transport weight and because the laboratory resources can then be better utilised for single-phase tests.

Table 2.3 Transformers

	Bank 1	Bank 2	
Type	TTTY 10500	EO 89	EO 94
Number of single phase units	6	3	3
Nominal rating for 0.2s, MVA	66.7	33.3	33.3
Short-circuit impedance, per unit	4.5	10	5
No-load losses at rated voltage, kW, per unit	165	170	130
Magnetising power at rated voltage, kVA, per unit	1 130	2 850	1 600
Number of high-voltage windings per transformer unit	3	4	4
Winding voltage, kV	24/√3	22/√3	33/√3
Basic insulation level, kV	625	450	325
Max. voltage, three-phase, kV	144	220	
Max. voltage, single-phase, mid-point of the transformers earthed, kV	250	380	
Primary voltage, kV	15	8	
Short-circuit power, MVA	9 000	3 000	

2.6 Capacitor Banks

The laboratory has one of the world's largest capacitor banks with discharge energy of 4MJ. Two capacitor banks are situated in the laboratory at the premises for the synthetic testing of the voltage circuit. The building in which the voltage circuit stands has a floor area measuring 30 m by 60 m and a height of up to 30 m. The capacitor banks are used to store the energy for recovery voltages during short-circuit breaking tests and high frequency currents during inrush current tests. Each bank consists of 12-level stack of capacitors connected in series. The heavier of the two banks weight approximately 40t.

2.7 Reactors

Each generator is provided with a set of current-limiting reactors. The reactors are designed as concrete units without any iron core and are dimensioned for the highest current to which they are usually exposed. Reactor set for the larger generator consists of 4 units per phase. Similarly, another reactor set consists of 5 units per phase for the smaller generator.

2.8 Resistors

A set of resistors for adjusting the desired power factor is also provided for each generator. The resistor sets are designed to increase the power factor from the inherent value of the plant (approximately 0.05) to the maximum value (0.15) allowed in the circuit breaker standards. The resistors, which are built of cast-iron grids, may be adjusted in most cases in steps of 10 to 20 percent. Full short-circuit strength cannot be obtained for all connections, but they must always be connected in series with a large reactance that the power factor cannot exceed the value 0.15

2.9 Actual testing procedure

Setting the right values for the short-circuit tests as excitation time and the excitation voltage is nowadays done by long time experience from the previous short-circuit testing and there is not any mathematical model or a tool that could easily predict the exact values for different test setting that would be much more accurate and keep the short-circuit current constant during the short-circuit tests as well.

The five basic short-circuit test duties that the IEC recommends for testing the high voltage equipment simulating the various fault conditions are as follows[7].

- 10% short-circuit current (Test Duty T10)
- 30% short-circuit current (Test Duty T30)
- 60% short-circuit current (Test Duty T60)
- 100% short-circuit current, symmetrical wave shape (Test Duty T100s)
- 100% short-circuit current, asymmetrical wave shape (Test Duty T100a)

Other short-circuit tests are also used for short-circuit testing of high voltage equipment.

- 75% short-circuit current (L75)
- 90% short-circuit current (L90)
- short time withstand and peak current (STC)

All the test duties mentioned above are carried out with the rated operating sequence. Regarding to circuit breakers the IEC recommends the following two operating sequences.

- O- t - CO - t’ - CO

where t = 3min for circuit breakers not intended for rapid autoreclosing
t = 0.3 sec for circuit breakers intended for rapid autoreclosing
t’ =3min

- CO - t’’ -CO

where t’’ = 15 sec for circuit breakers intended for rapid autoreclosing

C - represents a closing operation
O - represents an opening operation
t - represents a terminal fault

Terminal faults are the faults occurring in the immediate vicinity of the breaker involving high currents.

The next figure 2.6 shows and explain how the sequence control works when short-circuit is applied.

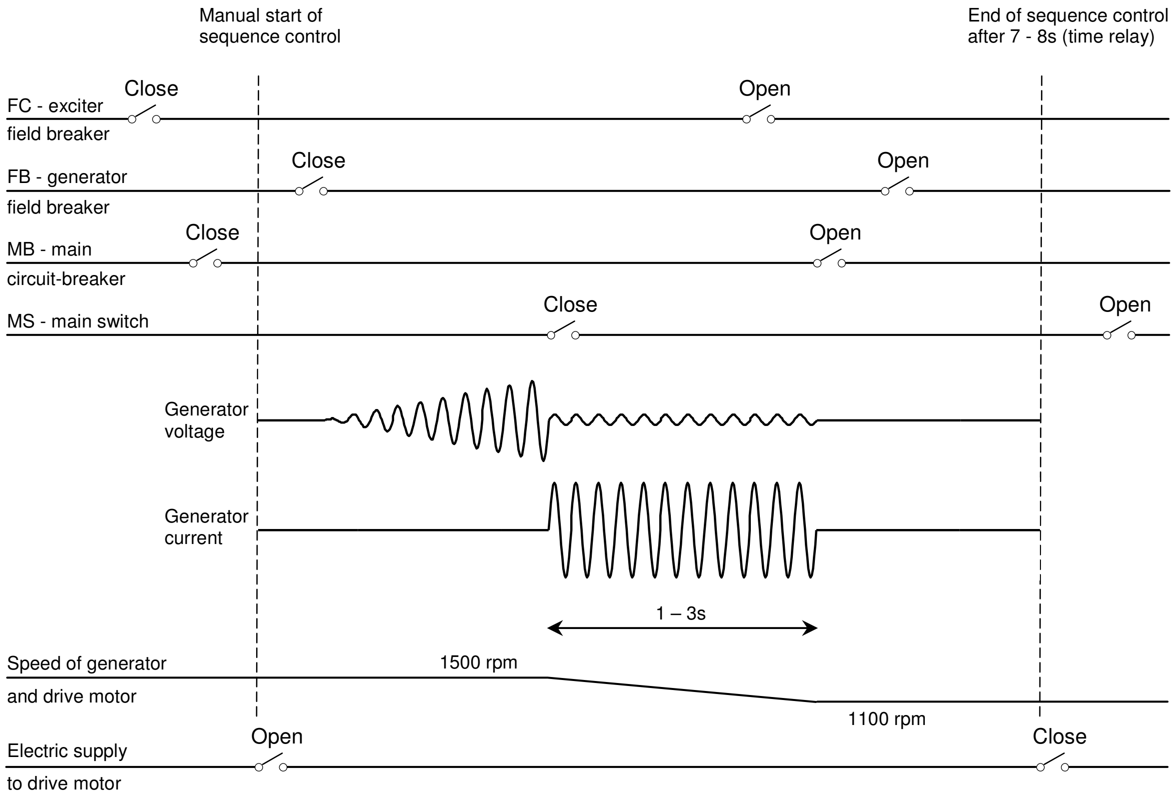


Figure2.6 Principle of the sequence control

- The exciter field circuit-breaker (FC) and main circuit-breaker (MB) is set manually to the “CLOSE” position 5-10s before the start of sequence control

- The electric supply to drive motor is disconnected and then the sequence control starts as can be seen on the figure above

- The generator field circuit-breaker (FB) closes to its ”CLOSE” position about 0.2 s after the start of sequence control and to the position “OPEN” after 2-3 periods and after that the current stops flowing

- The main switch (MS) closes to its ”CLOSE” position 1.5 - 3s after the generator field circuit-breaker (FB) closes (this time is called excitation time)

- The main switch (MS) opens to its “OPEN” position about 5s (by time relay) after the main circuit-breaker (MB) breaks the circuit at current zero

- The exciter field circuit-breaker (FC) opens to its “OPEN” position 2-3 periods before the current goes to zero

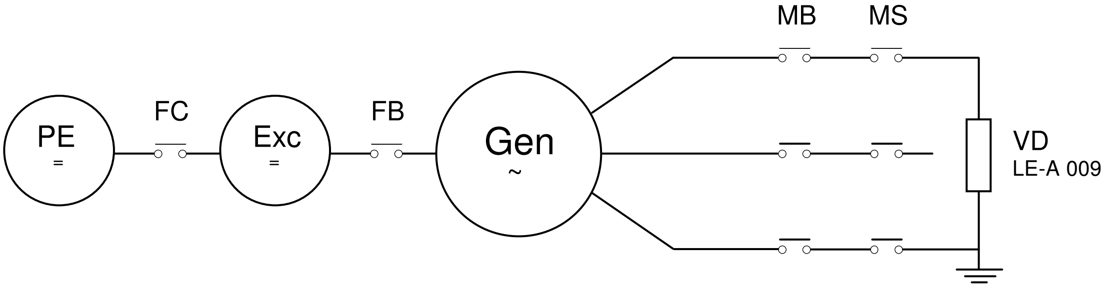
- The generator decelerates its speed as most when providing STC (short-time current withstand) test with 63kAeff and 3s duration, and also when arcing test with 50kAeff under 1s is applied. The rotor speed can drop down to 1100rpm, but in this case there is no requirement to reach 1500rpm directly after the test within a certain time. In other words, it needs some time to return to its previous speed. In other cases the speed does not drop down so significantly

CHAPTER 3

No-load Measurements

3.1 No-load test circuit

Figure 3.1 shows the no-load test circuit for measurements of the no-load characteristics of the generators. Measurements have been performed on both generators, generator G1 and generator G2, with various winding connections and frequencies of 50 and 60Hz.



PE – primary exciter
Exc – main exciter
Gen – high power generator
VD – voltage divider, type LE-A 009

FC – exciter field circuit-breaker (“Fältkontaktor”)
FB – generator field circuit-breaker (“Fältbrytare”)
MB – main circuit-breaker (“Säkerhetsbrytare”)
MS – main switch (“Snabbslutare”)

Figure 3.1 Test circuit of the generator no-load characteristics

The principle of performing the no-load measurements is the same as explained in Chapter 2.4 for the method of flying excitation. First, the exciter voltage is set and the main exciter is excited by the primary exciter to this voltage, but still disconnected from the generator field. The main circuit-breaker (MB) is set manually to the close position 5-10s before the start of the test. When the test is being performed, the main switch (MS) is switched on and after 5 periods the generator field breaker is switched on, and then the generator voltage starts to rise up. This voltage is measured by the voltage divider LE-A 009 between two phases. At the instant the rated voltage is reached, the main circuit breaker (MB) opens and the generator voltage drops to zero. Usually 2 periods before the main circuit breaker is switched off, the exciter field breaker (FC) is disconnected. Generator field breaker (FB) is disconnected the last, about 3 periods after the main circuit breaker is opened. This principle is maintained for every measurement.

For a low excitation voltage, it takes very long time for the generator to excite and therefore the main circuit breaker is disconnected after a certain time even if the voltage does not reach its rated value. The relay, which protects the generator, trips the main circuit breaker (MB), and this time is set to approximately 20s. On the other hand, such a long excitation time is not needed for short-circuit testing.

According to winding connections of generator 1 in Chapter 2, only 3 main winding connections are being used for short-circuit testing of frequency 50 and 60Hz. These connections are DS, YP and DP, and so 6 main tests have been done on the generator G1. The no-load tests have been performed on each winding connection depending on frequency of the generator. Winding connections DS and YS of the generator G2 are the most in use, and therefore only these two winding connections have been measured. Altogether 8 no-load measurements have been performed and recorded in the computer for the later analyses.

Each test for particular winding connection consists of various measurements depending on the value of the exciter voltage. In most 28 measurements are performed on each connection because the value of the exciter voltage is set from 70V to 610V with the step of 20V. Certain exciter voltage is set before the test for each measurement and the no-load generator output voltage up to its rated value has been recorded and transmitted with opto-electronic links and finally saved into the computer by using TeamPro software [3].

Each measurement is saved and written down on a special sheet, called oscilogram tables, provided from the laboratory under a reference number, so it is easy to handle and to look up for the data later on. Also the exciter voltage, time duration of the voltage and the generator voltage until it reaches its rated respectively highest value is written down on the oscilogram tables. Afterwards, all recorded data from the measurements are taken out and saved under an ASCII text file, which are the input data to be analyzed using Matlab.

All of the no-load tests have been performed in the laboratory while the main circuits have not been in use for the short-circuit testing of the high voltage equipment by the test engineers. Therefore, all of the measurements had to be carefully planned in advance and when the main circuits were needed for running the short-circuit tests by the test engineers, the no-load measurements on the generators had to be postponed for later on. That is why all of the no-load measurements on both generators with a different winding connections and frequency could not have been performed at once, but in a period of one month, respectively during the time the main circuits were available to use.

3.2 Obtaining data from the no-load measurements

After the no-load measurements on each generator depending on the winding connections and frequency have been performed and recorded in the computer, the recorded data are taken out and saved under an ASCII text file. The data, points with the particular sampling frequency are saved from the instant the generator field circuit breaker is switched on until the last period of the no-load characteristic. These files are the input data to be analyzed using Matlab. Table 3.1 shows the cases of the sampling time used during the each test and its corresponding values of the exciter voltage for each winding connection.

Table 3.1 Sampling time for every generator winding connection

Generator	G1							G2			
f [Hz]	50Hz				60Hz			50Hz			
Winding connection	DS (15KV)		YP (13kV)	DP (7.5kV)	DS (15KV)	YP (13kV)	DP (7.5kV)	DS (8.66kV)		YS (15KV)	
Sampling time [µs]	100	50	50	50	50	50	50	160	40	100	40
Measure-ments with exciter voltage [V]	70-130V	150-530V	70-610V	70-510V	70-430V	70-530V	70-510V	70-110V	130-610V	70-150V	170-610V

As it is observed from above table 3.1, some measurements are not measured with the exciter voltage up to 610V. This is due to very short excitation time which is lower than 1s and therefore the generator voltage rises up very fast. This gives warnings of earthing failures on the generators, which is not recommended and therefore the higher values of exciter voltages are not set and the no-load measurements are finished for the particular connection.

3.3 Analysis of data from the no-load measurements

Obtained data files in ASCII text format from the no-load measurements of every connection are analyzed using Matlab to calculate the rms voltage and to obtain the excitation time characteristics as a function of the calculated rms voltage and the exciter voltage for a certain time instant, which is called excitation time. The example of the calculation and processing the excitation time characteristics can be found in the Appendix A, which is a Matlab Code using the obtained data files with the same sampling time as well as with the different sampling time.

3.3.1 No-load characteristics

The no-load characteristics are obtained from the Matlab using the recorded data of the no-load measurements for every setting of the exciter voltage, winding connection and frequency. Time duration, which is the excitation time, is set up to 6s, and only data up to this time are analyzed for all measurements. This excitation time is enough for obtaining the excitation time characteristics. Figure 3.2 shows the no-load measurements for three different exciter voltages for a certain time instant. As it is seen the higher the exciter voltage is set the shorter time is needed to excite the generator up to its rated value. This is an example of the no-load characteristics on the generator G1 connected in YP with frequency 50Hz. The next figure 3.3 shows the no-load characteristics for different exciter voltages in a closer detail for a certain time instant. Here, can be observed more clearly that with higher exciter voltage the generator voltage rises faster at the same time instant.

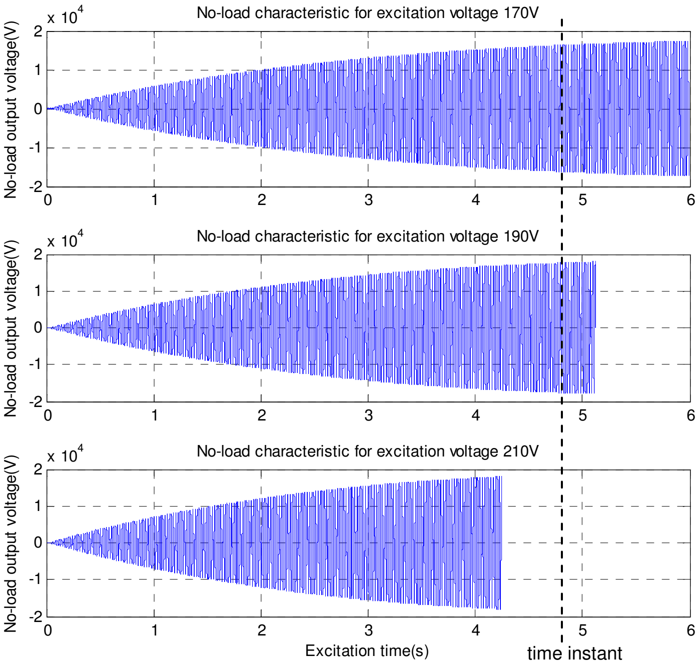


Figure 3.2 No-load measurements with the exciter voltages of 170V, 190V and 210V

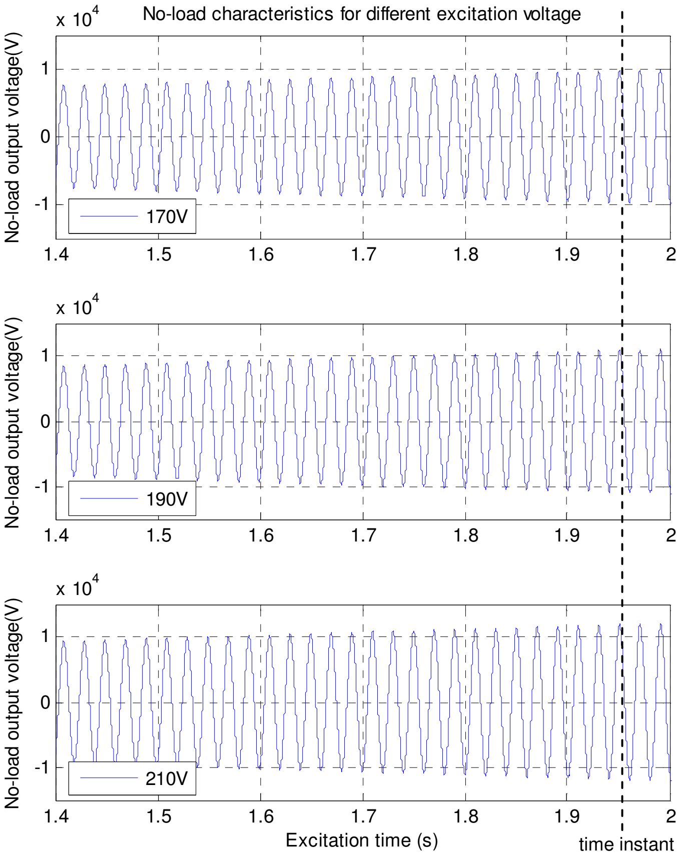


Figure 3.3 No-load measurements with the exciter voltages of 170V, 190V and 210V

3.3.2 RMS Calculation

The IEC power-quality measurement standard IEC 61000-4-30 [5] prescribes a very precise method for obtaining the voltage magnitude as a function of time. The first step in this procedure is to obtain the rms voltage over a window with a length exactly equal to one cycle of the power-frequency. The standard does not prescribe a method to obtain the window length, but it does state an accuracy requirement [6].

According to [6], the calculation of this "one-cycle rms voltage" is repeated every half cycle; in other words: the window is shifted one half cycle in time. This results in a discrete function with a time step equal to one half cycle of the power-system frequency. The one-cycle rms voltage calculated every half-cycle is obtained by

$$U_{rms}(n) = \sqrt{\frac{1}{N} \sum_{k=1+n\frac{N}{2}}^{(\frac{n}{2}+1)N} u(k)^2} \tag{3.1}$$

where N is number of samples per cycle, $u(k)$ is the sampled voltage waveform and k = 1, 2, 3, etc. The first value is obtained over the samples (1,N), the next over the samples ($\frac{1}{2}$N +1, 1$\frac{1}{2}$N) , etc [5].

The one-cycle rms voltage calculated every sample is obtained by

$$U_{rms}(n) = \sqrt{\frac{1}{N} \sum_{k=n-N+1}^{n} u(k)^2} \tag{3.2}$$

where N is number of samples per cycle, $u(k)$ is the sampled voltage waveform and k = 1; 2; 3, etc.

According to [6], in some cases it may be more appropriate to use a half-cycle window to calculate the rms voltage. The half-cycle rms voltage calculated every sample is obtained by

$$U_{rms\frac{1}{2}}(n) = \sqrt{\frac{1}{N} \sum_{k=n-N+1}^{n} u(k)^2} \tag{3.3}$$

where N is number of samples per half-cycle, u(k) is the sampled voltage waveform and k = 1; 2; 3, etc.

Here, the one-cycle rms voltage calculated every sample (3.2) from the measured data on the generators by Matlab, is used. Figure 3.4 shows this rms voltage calculation for exciter voltage of 70V and YP winding connection of G1 with frequency 50Hz. Measured data are analysed and rms voltage is calculated for the time duration of 6s. The characteristic of rms voltage follows exponentional curve due to magnetization.

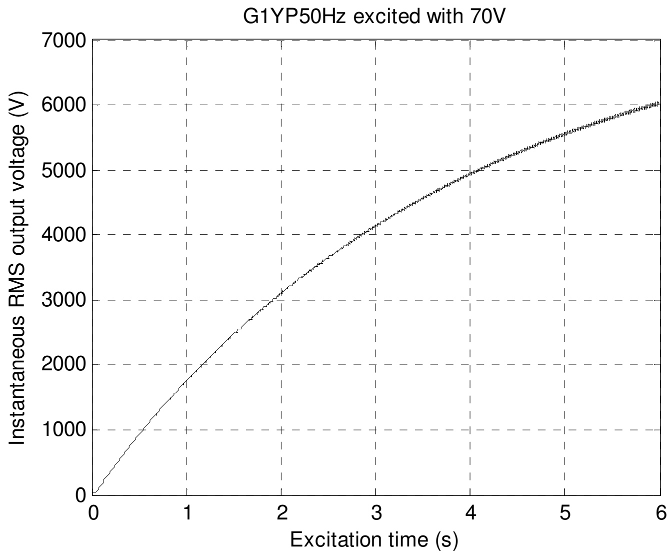


Figure 3.4 One cycle RMS voltage calculated every sample.

Rms voltages are calculated with respect on measured data for every value of the exciter voltage, starting from 70V up to 610V with the voltage step of 20V for particular winding connection. As mentioned previously, higher the exciter voltage is the less time is needed to excite the generator up to its rated voltage. Figure 3.5 shows the one-cycle rms voltage calculated every sample for exciter voltages from 70V to 170V having still values for time duration 6s.

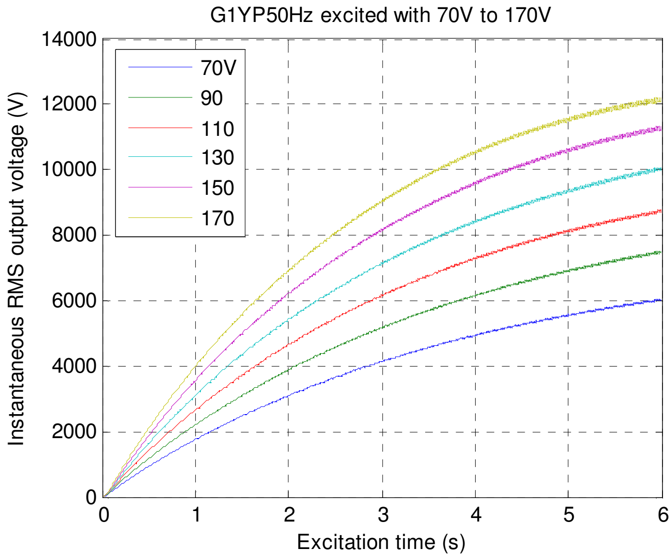


Figure 3.5 RMS voltages for the same time length

Since all data are analysed for time duration 6s, which is called excitation time, and in order to calculate rms voltage also for the higher exciter voltages, Not a Number (NaN) values have to be assigned in Matlab for the missing data up to 6s since it takes less time to excite the generator to the rated values to obtain the result in the same manner. Therefore, figure 3.6 shows this rms voltage as the exciter voltage increases and time length for exciting the generator decreases.

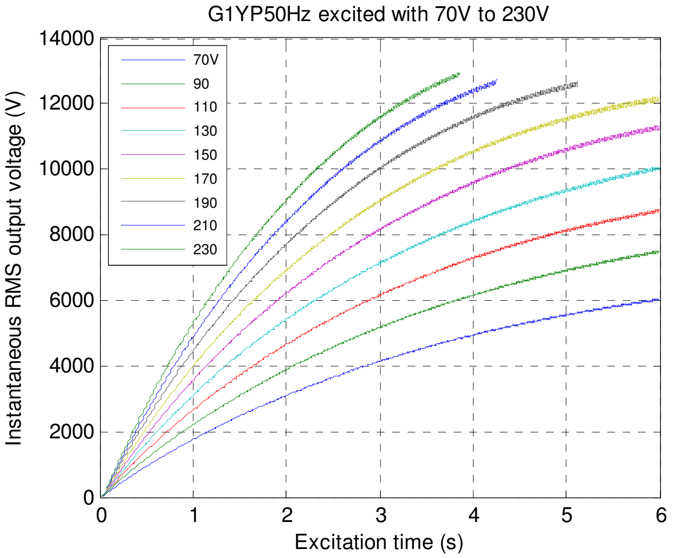
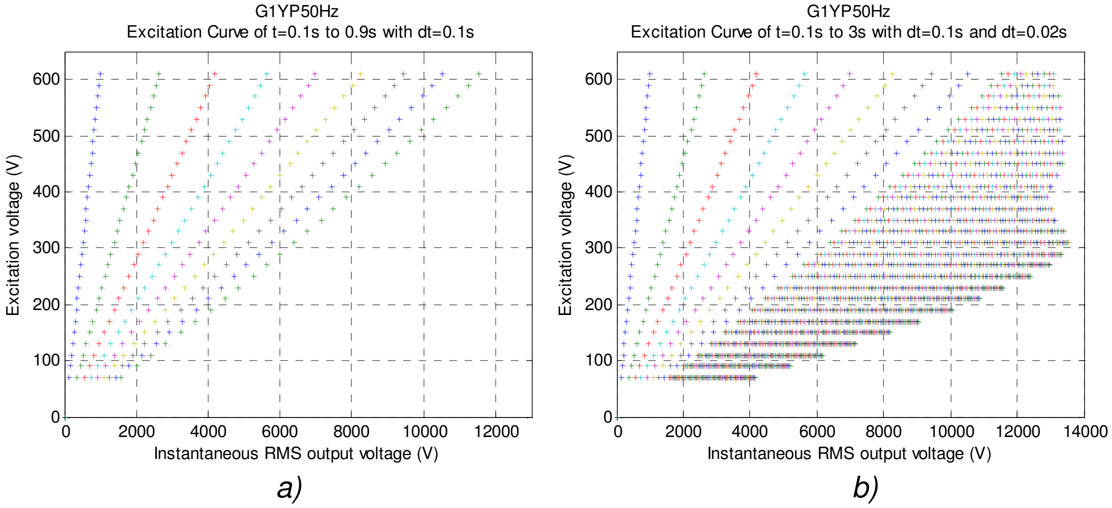


Figure 3.6 RMS voltages for decreasing time length

3.3.3 Evaluation of excitation time characteristics

When all rms voltages are calculated for every exciter voltage for excitation time length of 6s, excitation time characteristics can be obtained from this result as a function of rms voltage on x-axis and excitation voltage on y-axis for every instant of excitation time. These excitation time characteristics are shown in figure 3.7.



a) *b)*

Figure 3.7 Excitation time characteristics before fitting by the exponential equation $ax^2 + bx + c$

Left hand side of figure shows excitation curves evaluated for 0.1s to 0.9s with step dt=0.1s. Similarly, right hand side of figure 3.7 depicts excitation time characteristics with the same range as in a) and is followed by wider range of the excitation time curves with step 0.02s up to the time instant 3s. As it can be seen from figure 3.7b), the longer duration of excitation time is the less steep curve is obtained and lower excitation voltage is needed to excite the generator for the same generator output voltage. Therefore the missing values for higher excitation voltage and longer excitation times are substituted by NaN values to obtain excitation time characteristics also for longer time duration. In the next step of evaluating the right excitation time characteristics by Matlab, the NaN values are excluded from every characteristic, which contains these values and the points of every characteristic are fitted by the exponential equation $ax^2 +bx +c$ to obtain the characteristic for particular excitation time as can be seen in figure 3.8. The parameters of the exponential equation a, b and c are obtained for the range of the excitation times from 0.1s to 4s. This is adequate and accurate range of the excitation time characteristics, which are used for exciting the generator during the short-circuit testing. In most of the time the excitation times are used up to 3s, and therefore it is enough to evaluate and obtain the parameters only till 4s since longer times are never in use for the short-circuit testing of the high voltage equipment.

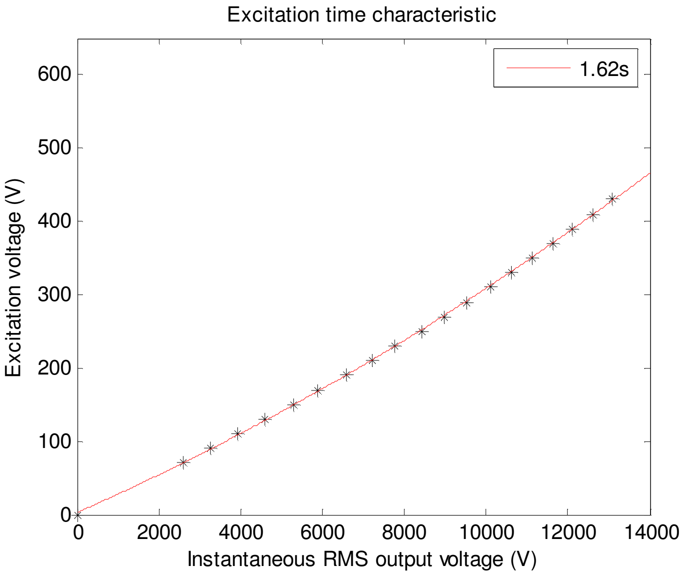


Figure 3.8 Excitation time characteristic for 1.62s after fitting

Next figure 3.9 shows the range of the excitation time characteristics from 0.1s to 4s and some example characteristics are taken out and depicted in figure. This is a nice example where can be clearly seen that the steeper the excitation time curve is chosen, the higher the excitation voltage is required to obtain a certain generator voltage.

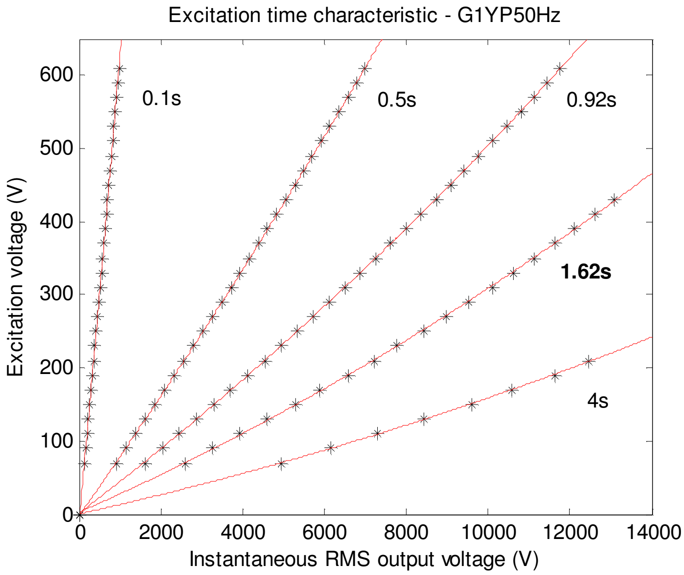


Figure 3.9 Range of excitation time characteristics after fitting of exponential equation $ax^2 + bx + c$ *from 0.1s up to 4s*

3.4 Summary of results

For one winding connection, 125 excitation time characteristics and its relevant parameters a, b, and c are obtained by analysis in Matlab. The same process of calculation rms voltage and obtaining the correct excitation time characteristics with its parameters a, b and c is maintained for all no-load measurements of high power short-circuit generators. Altogether, 8 sets of no-load measurements have been measured, which represents 1000 characteristics to be evaluated. These parameters of each excitation time are stored in the excel file for every generator winding connection that has been measured and are as an important input values for later use by the programme being developed by Visual basic for easy and fast visualisation of any excitation time characteristic within the range of 0.1s to 4s.

CHAPTER 4

Data Collection and Analysis

In this chapter various parameters are studied and collected from the different sources of the previous single-phase short-circuit tests on the high voltage equipment in order to see the behaviour of the excitation times according to the short-circuit current on the generator side within the same operating sequence, winding connection and frequency.

4.1 Collecting data from the previous tests

Every short-circuit test of the transmission and distribution equipment is recorded in the hard disk of the computer by transmission over opto-electronic links, and the main parameters are written down in the Oscilogram tables for every single test. Such a links are excellent carriers of data as they allow trouble-free transmission and also electrically isolate the data collection system from the test circuit, which makes it immune to any disturbances.

Every Oscilogram table has a main reference number, under which is then stored in the folders in archive, so it is very easy to look up for the particular tests in the future. Usually the same reference number is used for the set of the tests required from the standards and also requested from the customer that has to be tested for a certain transmission and distribution equipment like circuit breakers.

The only possibility how to collect the data is to go through these oscilogram tables and to take out those values that are very important for the study and also to look for other parameters from the sequencer as well as certain values from the short-circuit transient characteristics. These characteristics are shown in figures 4.1, 4.2, 4.3 and 4.4 for operating sequences O, O-CO, CO and C.

Therefore, to gain all the important data from the previous single-phase short-circuit tests, the research is divided into three main parts

- Oscilogram tables
- Sequencer
- Short-circuit transient characteristics

4.1.1 Oscilogram tables

These are the parameters collected from the oscilogram tables considering single-phase short-circuit tests:

- Reference number
- Oscilogram number of the short-circuit transient characteristics
- Date of test
- Transformer ratio and the reference number of the transformer
- Generator winding connection (DS, YP, DP, YS)
- Type of generator being used (single or parallel connection of the generators)
- Frequency (50 or 60 Hz)
- Type of provided short-circuit test
    - T10
    - T30
    - T60
    - T100a
    - T100s(a) or T100s(b)
    - L75
    - L90
- Type of operating sequence (O, O-CO, CO, C)
- Excitation voltage [V]
- Breaking currents [kA]
- Recovery and applied voltages [kV]

The obtained breaking currents, recovery and applied voltages are re-calculated on the generator side with the corresponding transformer ratio of the transformer. Sometimes values of the breaking currents, recovery and applied voltages are not written in these oscilogram tables, and therefore the missing values are taken out from the short-circuit transient characteristics as explained in chapter 4.1.3 and every value is also double-checked with the obtain ones.

4.1.2 Sequencer

The BE-3200 test sequencer is a switching device with 64 channels used for executing series of pre-programmed operations in synchronization with the generator voltage. It provides precise timing for the operation of devices like switches, breakers and testing objects used for testing in the high power laboratory. The operations are transferred through the optical fibres, which assign the electrical impulses to operate the previously mentioned devices. Windows software provides control in milliseconds, cycles or degrees of phase via an optically-isolated serial port and the timing accuracy can be better than one degree.

Therefore, according to the theory of flying excitation, excitation time can be taken down from the sequences of the TeamSequence control program running on the PC as shown in table 4.1. Excitation time is one of the most important parameters to be collected for the study and later evaluation.

Table 4.1 Excitation time taken from the sequencer

Type of Sequence	**Excitation Time as**	**Labeled in Sequencer**
O, O-CO	Main switch close (MS) – Generator field breaker close (FB)	SS – FBT
CO, C	Test breaker close (TBC) – Generator field breaker close (FB)	TBC – FBT

SS – Snabbslutare (main switch)
FBT – Fältbrytare till (generator field breaker)
TBC – Test breaker close

Most of the time sequences in the sequencer are labeled in Swedish language and therefore table 4.1 shows these abbreviations in the last column.

Once the oscilogram numbers of every short-circuit test are obtained from the oscilogram tables, the same number is also assigned for the sequencer and so the value of excitation time can be easily obtained and taken out.

4.1.3 Short-circuit transient characteristics

Values of short-circuit currents and voltages are checked respectively obtained from the transient characteristics, if these values are missing in the oscilogram tables. Values of parameters to get from the short-circuit transient characteristics depending on operating sequence are as follows

- Breaking short-circuit current (BC), respectively making current (MC)
- Transient short-circuit current (TC)
- Recovery voltage (RV)
- Applied voltage (AV)

In this case transient current means value of the current 4 periods after closing operation, and it is significant for the operating sequences O-CO and CO. This value of transient current has to be maintain in certain margins during the short-circuit testing in order to get the right values of breaking current, which has to fulfill criteria as per IEC Standards. If the breaking current is not in the right margins, different value of excitation time and exciter voltage has to be chosen to get the right result.

All of the parameters mentioned above as well as its occurrence vary depending on the chosen operating sequence. Four operating sequences have been studied and its transient characteristics with regarding parameters are shown in following figures.

In figure 4.1 is shown operating sequence open (O) with parameters of breaking current and recovery voltage. These two values are significant for this operating sequence and therefore are taken out for the later analyses. Following figure 4.2 represents operating sequence open-close-open (O-CO) with parameters of breaking currents after first and second opening and its corresponding recovery voltages as well as transient current and applied voltage. All of the mentioned parameters are carefully checked and its values are registered. From these two figures can be observed that the first opening of the operating sequence O-CO is most of the time based on the operating sequence O, since it uses roughly the same time duration.

Third important operating sequence that is used for short-circuit testing is close-open (CO), and its transient characteristics as well as parameters like applied and recovery voltage, and also transient and breaking current is shown in figure 4.3. Also all these parameters are taken down and summarized later on. Last operating sequence, which has been included in the study, is close (C) sequence, and its transient characteristic with applied voltage and corresponding making current after closing is shown in figure 4.4. In this case, the important value is called making current instead of breaking current as in previous cases, and this is the current of interest to be obtained during this operating sequence of short-circuit testing.

Typical examples of the time duration used within the operating sequences in the high power laboratory for short-circuit testing are as follows

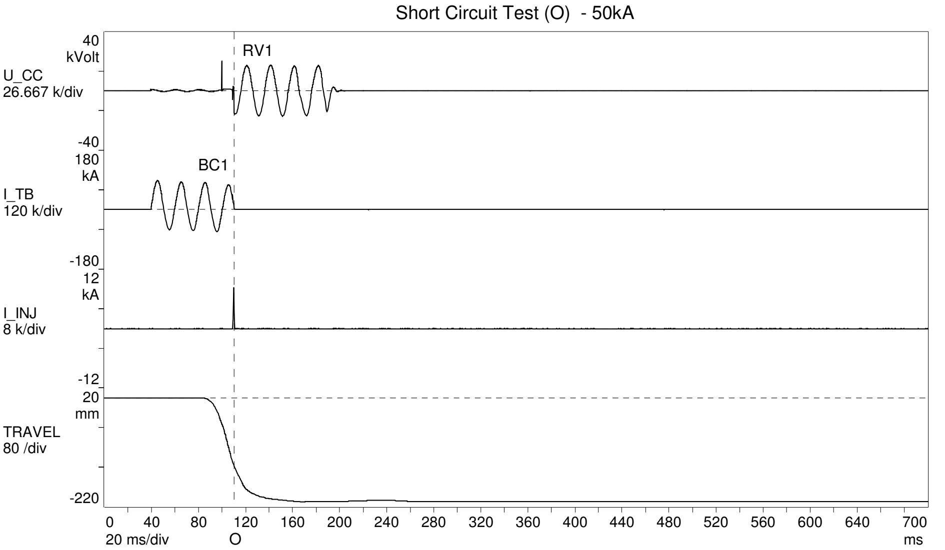
- open (O)	80ms
- open-close-open (O-CO)	560ms
- close-open (CO)	180ms
- close (C)	80ms

In case of operating sequence O-CO and CO, the time between closing and second opening takes approximately 7 to 8 periods. The behaviour of the short-circuit current in this period is mainly influenced by two main factors:

- instant of making
- L/R ratio

Instant of making
If the making takes place at the peak value of the voltage, the short-circuit current will have shape of symmetry, and if the making takes place at zero or close to zero value of the voltage, the short-circuit current will have asymmetrical wave shape.

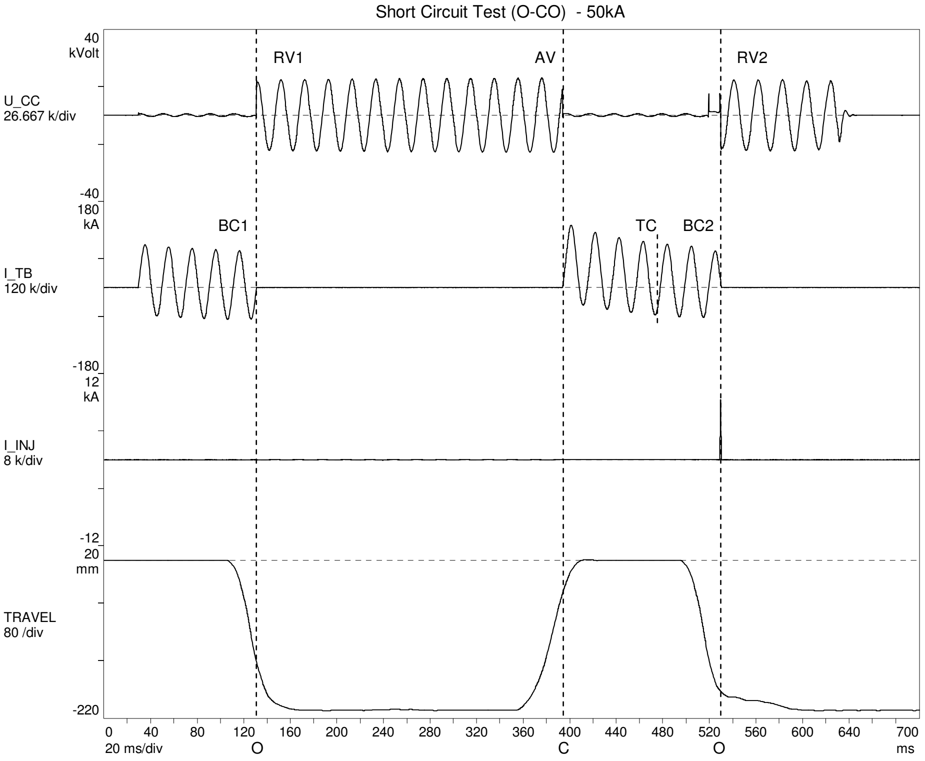
L/R ratio
Shape of the short-circuit current also depends on the values of inductance and reactance in the circuit. Therefore the more inductive circuit it is the longer time is needed for the current to decay. Also the first peak of the current after closing is influenced by the subtransient reactance of the machine.



U_CC – voltage on tested breaker
I_TB – short-circuit current on tested breaker
I_INJ – injection current of high frequency
TRAVEL – contact travel

O – instant of contact separation
RV1 – recovery voltage after opening
BC1 – breaking current at opening

Figure 4.1 Oscilogram of the operating sequence O (open) on SF$_6$ circuit breaker with test current 50kA



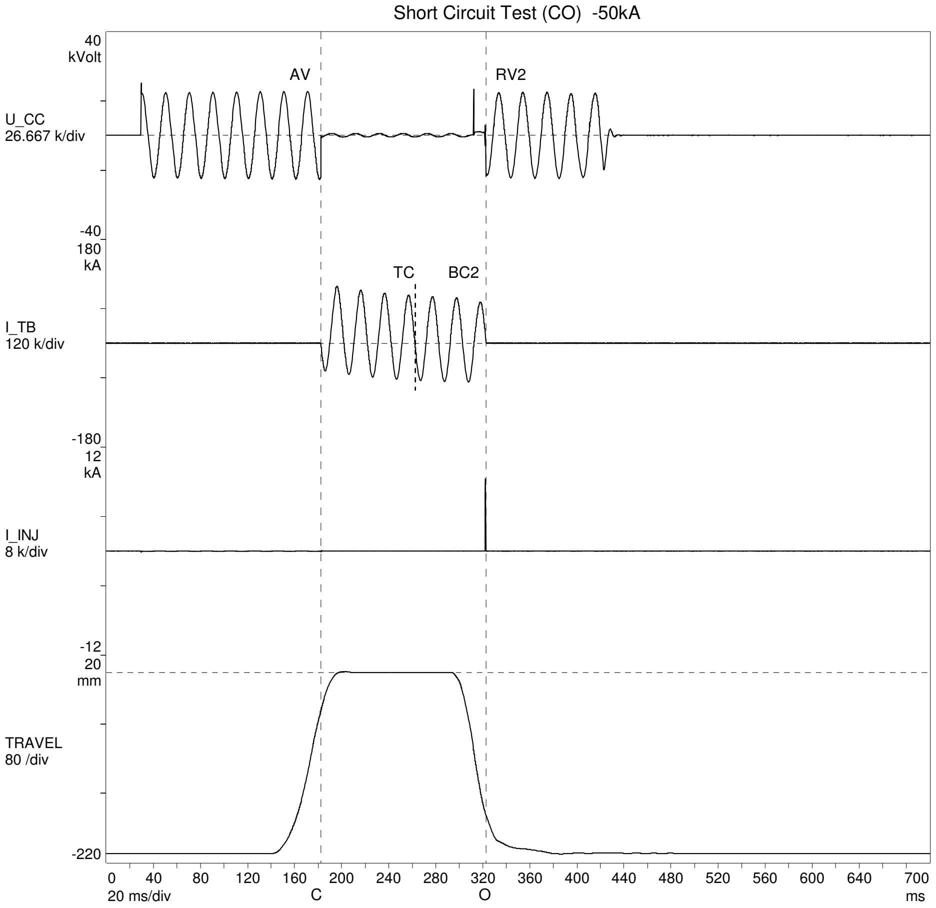
U_CC – voltage on tested breaker
I_TB – short-circuit current on tested breaker
I_INJ – injection current of high frequency
TRAVEL – contact travel

O – instant of contact separation
C – instant of contact closure

RV1 – recovery voltage after first opening
AV – applied voltage
RV2 – recovery voltage after second opening

BC1 – breaking current at 1st opening
BC2 – breaking current at 2nd opening
TC – transient current after 4 periods

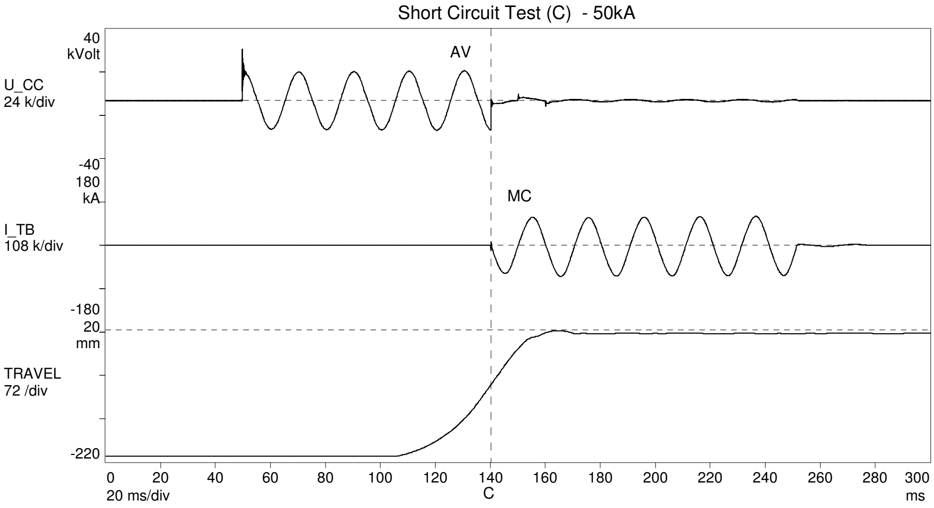
Figure 4.2 Oscilogram of the operating sequence O-CO (open-close-open) on SF$_6$ circuit breaker with test current of 50kA



U_CC – voltage on tested breaker
I_TB – short-circuit current on tested breaker
I_INJ – injection current of high frequency
TRAVEL – contact travel
AV – applied voltage
RV2 – recovery voltage after opening

O – instant of contact separation
C – instant of contact closure
BC2 – breaking current at opening
TC – transient current after 4 periods

Figure 4.3 Oscilogram of the operating sequence CO (close-open) on SF_6 circuit breaker with test current of 50kA



U_CC – voltage on tested breaker
I_TB – short-circuit current on tested breaker
TRAVEL – contact travel

C – instant of contact closure
AV – applied voltage
MC – making current at closing

Figure 4.4 Oscilogram of the operating sequence C (close) on SF_6 circuit breaker with test current of 50kA

4.2 Analyzing the collected data

All parameters collected from the three previously discussed parts are put together and typed in the table created in excel. When all fields are filled in and some parameters are re-calculated, it needs to be sorted out. Sorting runs under criteria as follows

1) generator usage
2) frequency
3) operating sequence
4) winding connection

Altogether, 300 tests have been collected from the archive within the time period of last 3 years and carefully analyzed. The number of tests collected for each possibility as well as its percentage proportion is shown in table 4.2.

Table 4.2 Number of analysed tests

Generator	**G1**		**G1//G2**	**Altogether**
Frequency	50Hz	60Hz	50Hz	
Number of tests	109	115	76	**300**
Percentage proportion	36.33%	38.33%	25.33%	**100%**

The huge summary table of excel file is not attached as an appendix to this thesis, since these data are confidential, but this summary is available to look in at the high power laboratory.

From this summary table can be seen that the excitation time of each operating sequence, and particular winding connection does not depend on the short-circuit current of the generator. Most of the time, each operating sequence contains wide range of the short-circuit breaking current and only one value of the excitation time is used for all variety of the type tests used within the same operating sequence, frequency and the same generator winding connection. Sometimes the excitation time differs from the other values, but this is due to different exciter voltage. As mentioned in chapter 3.3.3 the higher the exciter voltage is the shorter time is needed to obtain a certain generator voltage and vice versa. Therefore, after closer look at the transient characteristics of the particular oscilogram with two different excitation times and exciter voltages, no significant differences are observed and similar short-circuit breaking current and the shape of the transient characteristic is obtained. That is why the excitation time is generalized for the same use of frequency, winding connection and operating sequence not depending on the short-circuit current. Later on are studied the excitation times of all three operating sequences O, O-CO and C and the conclusions are drawn in the next part of this chapter.

4.3 Recommended excitation times

After careful analyses of the collected data from previous short-circuit tests of the high voltage equipment, mainly circuit breakers, final tables with the summary of the recommended excitation times are obtained for generator G1 and for parallel connection of both generators.

Main conclusion from this study is that the excitation time does not depend on the use of operating sequences O, O-CO and CO, and therefore it is possible to use the same excitation times for all three sequences within the same generator winding connection and frequency. Nowadays, the operating sequence O (open) is using shorter excitation time to excite the short-circuit generator to the certain voltage in comparison with O-CO sequence. This time is used because of the long time experience, and also from the historical point of view, since many decades ago O-CO sequence was not in use for short-circuit testing. When it has been introduced the excitation time had to be changed for a longer duration, because operating sequence O (open) uses short excitation time due to a short time sequence (80 ms), and therefore this excitation time does not have to be chosen so carefully. But operating sequence O-CO is more complex system since it is the longest sequence from all four sequences. In general it lasts for 560ms and therefore the excitation time has to be chosen more carefully in order to maintain more or less the same applied and recovery voltages of the generator and so not to excite so rapidly fast. Also the breaking current has to be within the margins for the basic short-circuit test duties as according to the IEC standard [7]. Hence, the excitation time of the operating sequence O-CO was chosen as the basic parameter and can be also used for the other two operating sequences. Since the operating sequence O is like the first part of the sequence O-CO and so the same excitation time has to work for both operating sequences. The operating sequence CO has a shorter time duration compared to the operating sequence O-CO but the excitation time has a similar duration since in this case the excitation time is taken as the generator field circuit breaker until the test breaker closes.

These three operating sequences has been generalized and their particular excitation times are recommended for the later use of the short-circuit testing on the high voltage equipment in the high power laboratory. Similar manner is done on operating sequence C, but this sequence is generalized with the excitation time used for the particular generator winding connection and frequency.

Following table 4.1 shows these recommended excitation times for the generator G1 depending on its winding connection and the frequency being used during the test. Table also contains values of previously used excitation times for each generator winding connection, frequency and operating sequence as O, O-CO, CO, and C. Similarly table 4.2 shows recommended excitation times obtained from this study for parallel connection of generator G1 and generator G2 and frequency 50Hz.

Table 4.1 Summary of the recommended excitation times from the study for 50 and 60Hz of generator G1.

	G1DS(122)50Hz		**G1YP(123)50Hz**		**G1DP(124)50Hz**	
	Excitation time (s)		Excitation time (s)		Excitation time (s)	
	Used Now	Used before	Used Now	Used before	Used Now	Used before
O	**1.62**	1.12	**2.14**	1.12	**1.74**	1.12
O-CO	**1.62**	1.62	**2.14**	2.14	**1.74**	1.74
CO	**1.62**	1.60 to 1.63	**2.14**	2.12 to 2.23	**1.74**	1.74 to 1.90
C	**-----**	-----	*) **1.10**	1.10 vs 1.26	**1.44**	1.44

*)1.26s used only for 63kA test

	G1DS(122)60Hz		**G1YP(123)60Hz**		**G1DP(124)60Hz**	
	Excitation time (s)		Excitation time (s)		Excitation time (s)	
	Used Now	Used before	Used Now	Used before	Used Now	Used before
O	**1.90**	1.11	**2.22**	1.11	**1.50**	0.92
O-CO	**1.90**	1.89 to 1.91	**2.22**	2.22	**1.50**	1.50
CO	**1.90**	1.90 to 2.08	**2.22**	2.20 to 2.34	**1.50**	1.84
C	**1.02**	1.02	**1.10**	1.10	**-----**	**-----**

Table 4.2 Summary of the recommended excitation times from the study for parallel connection of generators.

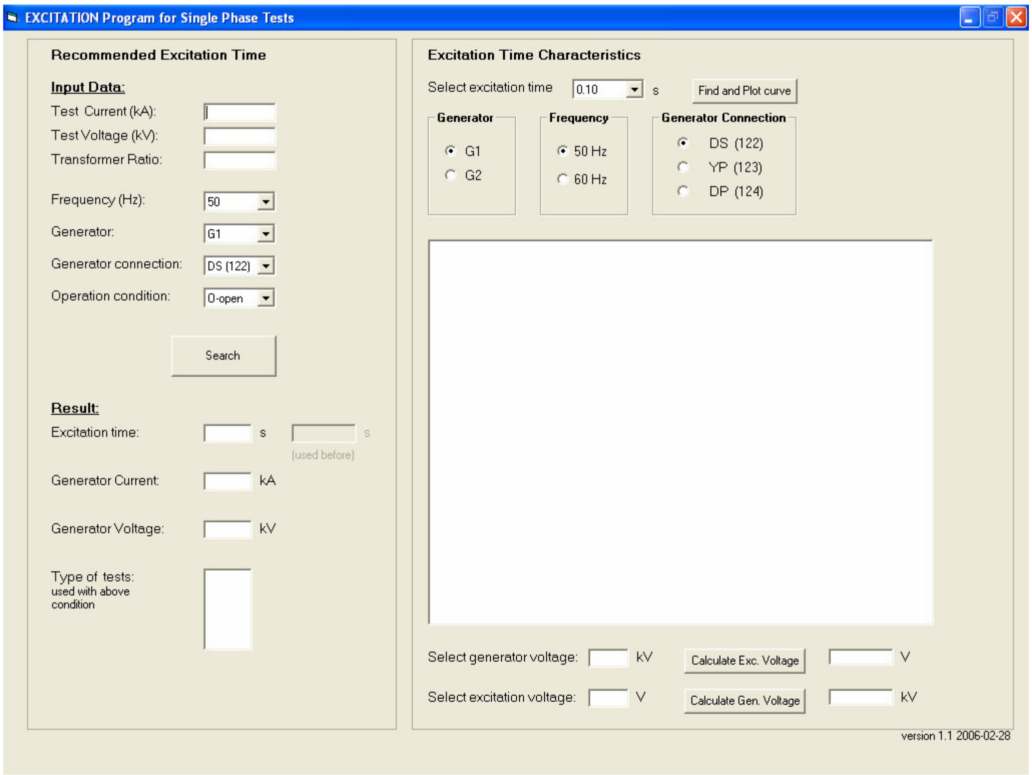
	G1//G2 50Hz			
	DS//YS(122//221)		**YP//YS(123//221)**	
	Excitation time (s)		Excitation time (s)	
	Used Now	Used before	Used Now	Used before
O	**1.62**	1.18	**-----**	-----
O-CO	**1.62**	1.62	**-----**	-----
CO	**1.62**	1.62	**-----**	-----
C	**1.16**	1.16	**1.13**	1.13

CHAPTER 5

Excitation parameters calculation software

5.1 Making a User Friendly Interface

The results from Chapter 3 and Chapter 4 are as main and basic input parameters in to the new program called Excitation program for single-phase tests, which has been programmed using the software Microsoft Visual Basic 5, in order to provide a user friendly interface to obtain a good visual approach. In figure 5.1 is shown the window of the program after running the file *Excitation_Program.exe*. The program is divided into two parts, based on the main parameters obtained from the results in previous two Chapters. The left hand side of the window with name of Recommended excitation time, consists of the results obtained in Chapter 4. Excitation time characteristics is the name for the right hand side of the window, where are programmed the characteristics of the excitation obtained from the no-load measurements on the high-power short-circuit generators analysed in Matlab. Both parts are as separate programs, but when the left hand side of the program is used, there is interaction in between.



EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:

Test Current (kA):

Test Voltage (kV):

Transformer Ratio:

Frequency (Hz): 50

Generator: G1

Generator connection: DS (122)

Operation condition: 0-open

Result:

Excitation time: s   s (used before)

Generator Current: kA

Generator Voltage: kV

Type of tests: used with above condition

Excitation Time Characteristics

Select excitation time 0.10 s

Generator: ● G1 ○ G2

Frequency: ● 50 Hz ○ 60 Hz

Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)

Select generator voltage: kV   V

Select excitation voltage: V   kV

version 1.1 2006-02-28

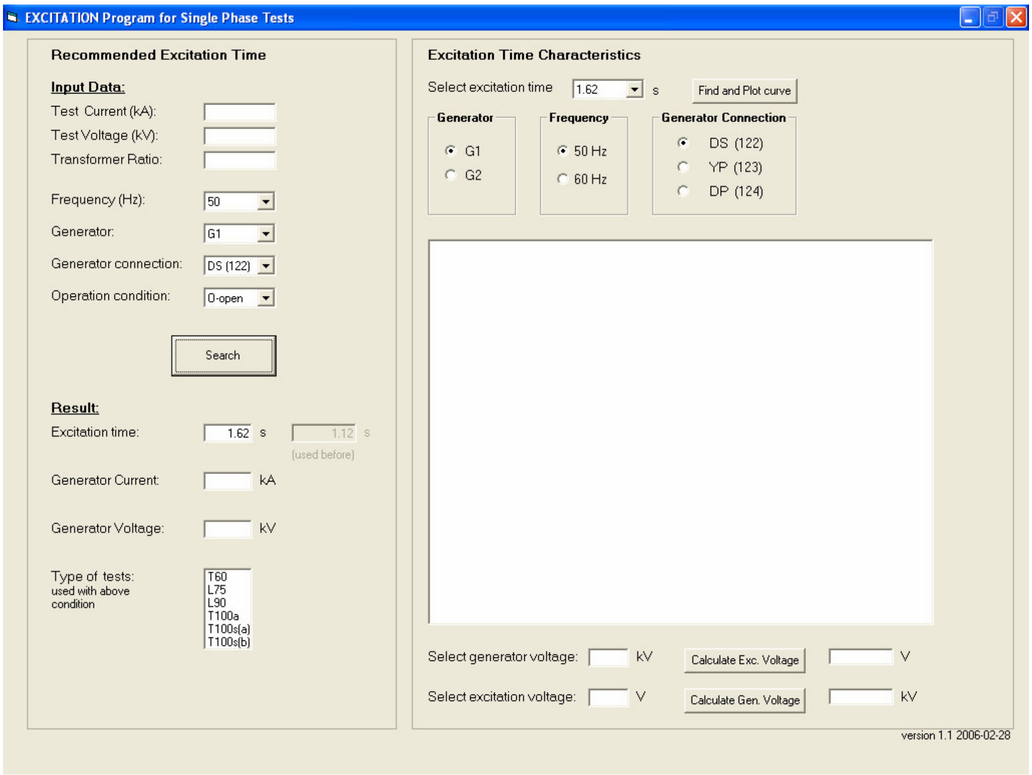
Figure 5.1 Main window of the program Excitation_Program.exe

5.2 Main features of the program

Now, let's describe all the main features of the program to demonstrate its functionality and simplicity of use. First, the left hand side of the program will be described and then the excitation time characteristics, which form the right hand side of the window, will be presented.

5.2.1 Recommended excitation time

As mentioned before, these data are obtained from the study that was described in more details in Chapter 4. Just to remind, all of the recommended values are assigned for the single-phase short-circuit tests. According to figure 5.2, if selecting various possibilities from the combo box depending on frequency, generator, generator connection and operation condition it will give us the recommended value of the excitation time after clicking on the button "Search" for the selected parameters. This is the main result of the search, but besides, value of previously used excitation time during the single-phase short-circuit test will be also shown for the selected conditions. Also a list of all types of tests that has been used for the selected parameters is shown as a result of the search.



EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:

Test Current (kA):

Test Voltage (kV):

Transformer Ratio:

Frequency (Hz): 50

Generator: G1

Generator connection: DS (122)

Operation condition: 0-open

Result:

Excitation time: 1.62 s 1.12 s (used before)

Generator Current: kA

Generator Voltage: kV

Type of tests: used with above condition

T60
L75
L90
T100a
T100s(a)
T100s(b)

Excitation Time Characteristics

Select excitation time 1.62 s

Generator: ● G1 ○ G2

Frequency: ● 50 Hz ○ 60 Hz

Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)

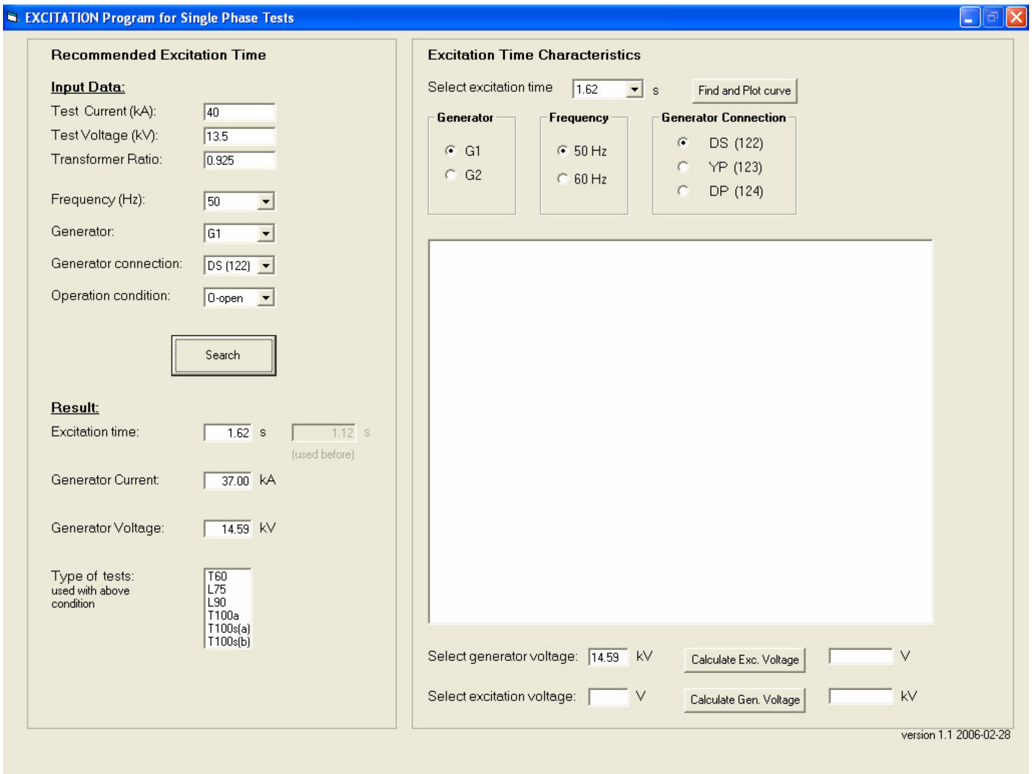
Select generator voltage: kV V

Select excitation voltage: V kV

version 1.1 2006-02-28

Figure 5.2 Main window of the program Excitation_Program.exe after clicking on the button "Search" from the left hand side of the window to search for recommended values of the excitation time for desired parameters chosen above the button

Next figure 5.3 shows the result after we input the values of test current, test voltage and transformer ratio. The only thing that changes after clicking on “Search” button is the recalculated generator current and voltage. We can say that this is a simple calculator that gives us values of generator current and voltage. After the generator voltage is calculated it also simply put this value to the right hand side of the program at the text box “Select generator voltage” for easier and faster calculation of excitation voltage from the characteristics. Also the result of excitation time is connected with the combo box “Select excitation time” at the right hand side of the program to find the excitation time characteristics faster and more comfortable.


EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:
Test Current (kA): 40
Test Voltage (kV): 13.5
Transformer Ratio: 0.925
Frequency (Hz): 50
Generator: G1
Generator connection: DS (122)
Operation condition: 0-open

Result:
Excitation time: 1.62 s 1.12 s (used before)
Generator Current: 37.00 kA
Generator Voltage: 14.59 kV
Type of tests: used with above condition: T60
L75
L90
T100a
T100s(a)
T100s(b)

Excitation Time Characteristics

Select excitation time 1.62 s
Generator: ● G1 ○ G2
Frequency: ● 50 Hz ○ 60 Hz
Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)
Select generator voltage: 14.59 kV
Select excitation voltage: V

version 1.1 2006-02-28

Figure 5.3 Main window of the program Excitation_Program.exe after clicking on the button “Search” from the left hand side of the window to search for recommended values of the excitation time for desired parameters chosen above the button and also a calculation of generator current and voltage

It is possible to choose various combinations from combo boxes to obtain the recommended value of excitation time like frequency if it is 50 or 60 Hz, generator G1 or parallel combination of G1//G2, generator winding connections depending on value of generator voltage that needs to be obtained during the short-circuit tests, and also operation conditions like O (open), O-CO, CO and C. Each value that is chosen at these combo boxes is connected to the right hand side of the program, Excitation time characteristics, under the radio buttons of generator, frequency and generator connections after the “Search” button is clicked. This connectivity is very convenient for not making mistakes and not setting up manually the parameters of generator, frequency and generator connection when finding the right curve of excitation time for the recommended times of excitation.

Figure 5.4 shows the value of excitation time as well as generator current and voltage, when generators are connected in parallel (G1//G2) after the “Search” button is clicked. Then the combo box of generator connection changes by itself to the programmed default value which is DS//YS (122//221). Current of each generator for these two parallel connections is then calculated as

1) DS//YS (122//221)

$$I_{G1} = 0.6 I_{test} N \tag{5.1}$$

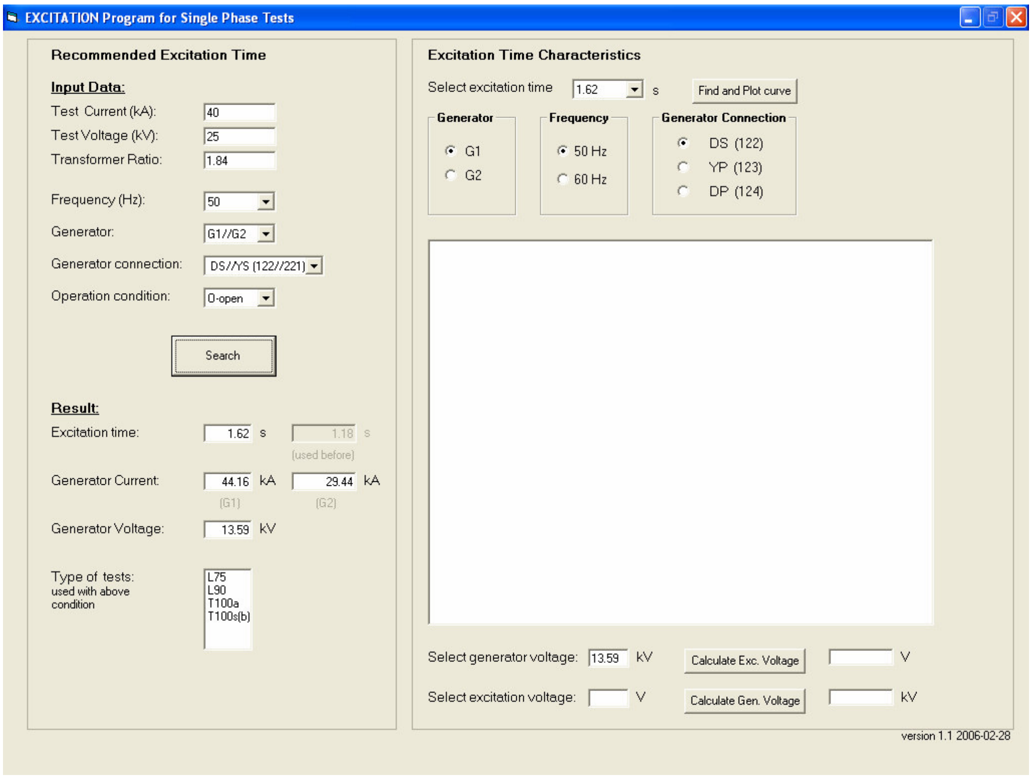
$$I_{G2} = 0.4 I_{test} N \tag{5.2}$$

2) YP//YS (123//221)

$$I_{G1} = 0.67 I_{test} N \tag{5.3}$$

$$I_{G2} = 0.33 I_{test} N \tag{5.4}$$

where N is transformer ratio and I_{test} is a test current in kA after the transformer.



EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:

Test Current (kA): 40

Test Voltage (kV): 25

Transformer Ratio: 1.84

Frequency (Hz): 50

Generator: G1//G2

Generator connection: DS//YS (122//221)

Operation condition: 0-open

Result:

Excitation time: 1.62 s | 1.18 s (used before)

Generator Current: 44.16 kA (G1) | 29.44 kA (G2)

Generator Voltage: 13.59 kV

Type of tests: used with above condition: L75 L90 T100a T100s(b)

Excitation Time Characteristics

Select excitation time 1.62 s

Generator: ● G1 ○ G2

Frequency: ● 50 Hz ○ 60 Hz

Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)

Select generator voltage: 13.59 kV

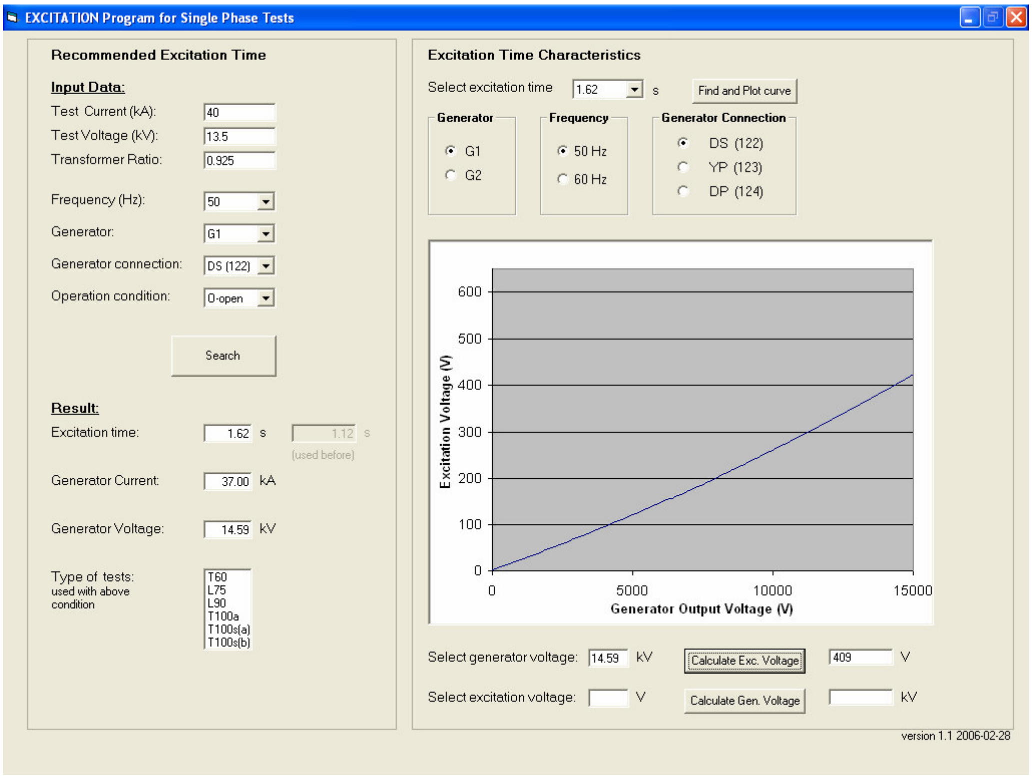
Select excitation voltage: V

version 1.1 2006-02-28

Figure 5.4 Main window of the program Excitation_Program.exe after clicking on the button “Search” from the left hand side of the window to search for recommended values of the excitation time for parallel connection of generators DS//YS (122//221) and also a calculation of generator current and voltage as shown at equations (5.1) to (5.4)

5.2.1 Excitation time characteristics

This right hand side window of the program finds and shows the correct excitation time characteristics for the recommended excitation times found in the left hand side window as well as for excitation times selected at the combo box “Select excitation time” in the range of 0.1s up to 4s. These characteristics are obtained from the no-load measurements on each generator with different frequency and winding connections after analyzing the data in Matlab as described in Chapter 3. Excitation time characteristics can be shown after clicking on the button “Find and Plot curve”. This plot is first made in the excel file and by using a simple command, OLE automation from Microsoft visual basic, it can be very easily connected and shown here. As shown at figure 5.5, excitation time characteristic for recommended excitation time of 1.62s is plotted after clicking on button “Calculate Exc. Voltage” as well as value of excitation voltage is calculated from the parameters of this excitation time characteristic. Value of generator voltage was calculated previously at the left hand side of the window and input in this text box to calculate excitation voltage. Here, generator voltage can be easily changed with arbitrary value in the range of selected generator winding connection to obtain value of excitation voltage, which can be then set for the exciter to excite the generator. Similarly, if inputting the value of excitation voltage, it is possible to calculate the value of generator voltage after clicking on the button “Calculate Gen. Voltage”. This is shown in figure 5.6.



EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:

Test Current (kA): 40
Test Voltage (kV): 13.5
Transformer Ratio: 0.925

Frequency (Hz): 50
Generator: G1
Generator connection: DS (122)
Operation condition: 0-open

Result:

Excitation time: 1.62 s 1.12 s (used before)
Generator Current: 37.00 kA
Generator Voltage: 14.59 kV
Type of tests used with above condition: T60, L75, L90, T100a, T100s(a), T100s(b)

Excitation Time Characteristics

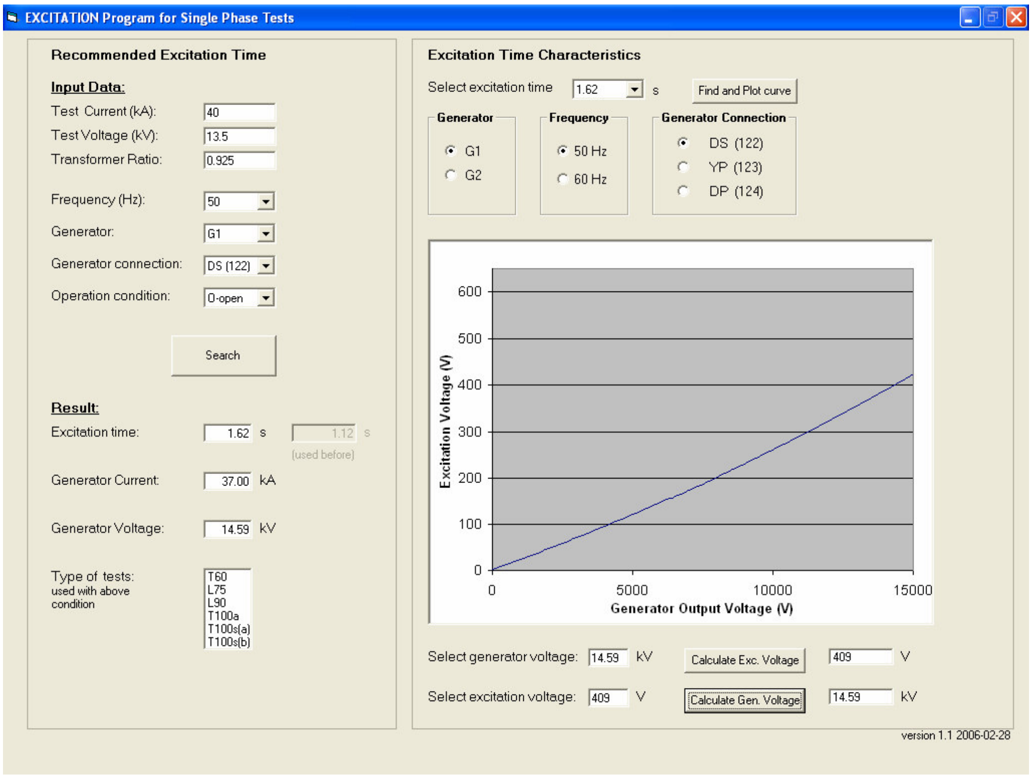
Select excitation time 1.62 s

Generator: ● G1 ○ G2
Frequency: ● 50 Hz ○ 60 Hz
Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)

Select generator voltage: 14.59 kV 409 V
Select excitation voltage: V kV

version 1.1 2006-02-28

Figure 5.5 Main window of the program Excitation_Program.exe after clicking on the button “Calculate Exc. Voltage” on the bottom right hand side of the window to show the excitation time characteristics for recommended values of excitation time found before as well as calculate the excitation voltage from the characteristic



EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:
Test Current (kA): 40
Test Voltage (kV): 13.5
Transformer Ratio: 0.925
Frequency (Hz): 50
Generator: G1
Generator connection: DS (122)
Operation condition: 0-open

Result:
Excitation time: 1.62 s 1.12 s (used before)
Generator Current: 37.00 kA
Generator Voltage: 14.59 kV
Type of tests: used with above condition: T60
L75
L90
T100a
T100s(a)
T100s(b)

Excitation Time Characteristics

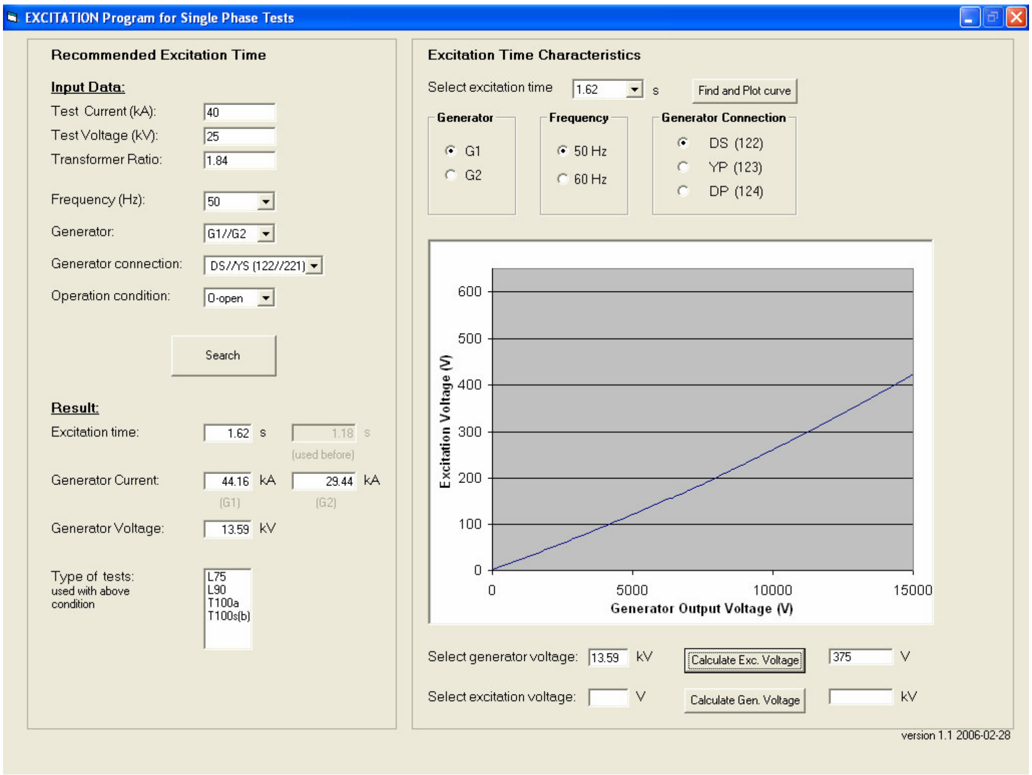
Select excitation time 1.62 s
Generator: ● G1 ○ G2
Frequency: ● 50 Hz ○ 60 Hz
Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)
Select generator voltage: 14.59 kV → 409 V
Select excitation voltage: 409 V → 14.59 kV

version 1.1 2006-02-28

Figure 5.6 Main window of the program Excitation_Program.exe after clicking on the button "Calculate Gen. Voltage" on the bottom right hand side of the window to calculate the generator voltage from the particular excitation time characteristic

Also from figure 5.6 can be seen that, if the same value of the excitation voltage is selected as the one that has been calculated by "Calculate Exc. Voltage" from the selected generator voltage, the same value of generator voltage is obtained as the one selected at the beginning. This example shows that the calculation is done correctly in both directions and it is possible to calculate any values for excitation voltage and generator voltage within the range.

Excitation time characteristics can be plotted for each generator, and so if parallel connection is chosen to find the recommended values of the excitation time from the left hand side of the window, the same excitation times apply for both generators. In order to find the correct excitation time curves and the excitation voltages for both generators, it is necessary to plot the excitation time characteristics and to find the excitation voltages for each generator and its winding connections one by one. Then the obtained values of excitation voltage can be set for each exciter, which is necessary to know before making a shot-circuit test. This principle is shown in figure 5.7 and figure 5.8.


EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:

Test Current (kA): 40
Test Voltage (kV): 25
Transformer Ratio: 1.84
Frequency (Hz): 50
Generator: G1//G2
Generator connection: DS//YS (122//221)
Operation condition: 0-open

Result:

Excitation time: 1.62 s 1.18 s (used before)
Generator Current: 44.16 kA (G1) 29.44 kA (G2)
Generator Voltage: 13.59 kV
Type of tests used with above condition: L75 L90 T100a T100s(b)

Excitation Time Characteristics

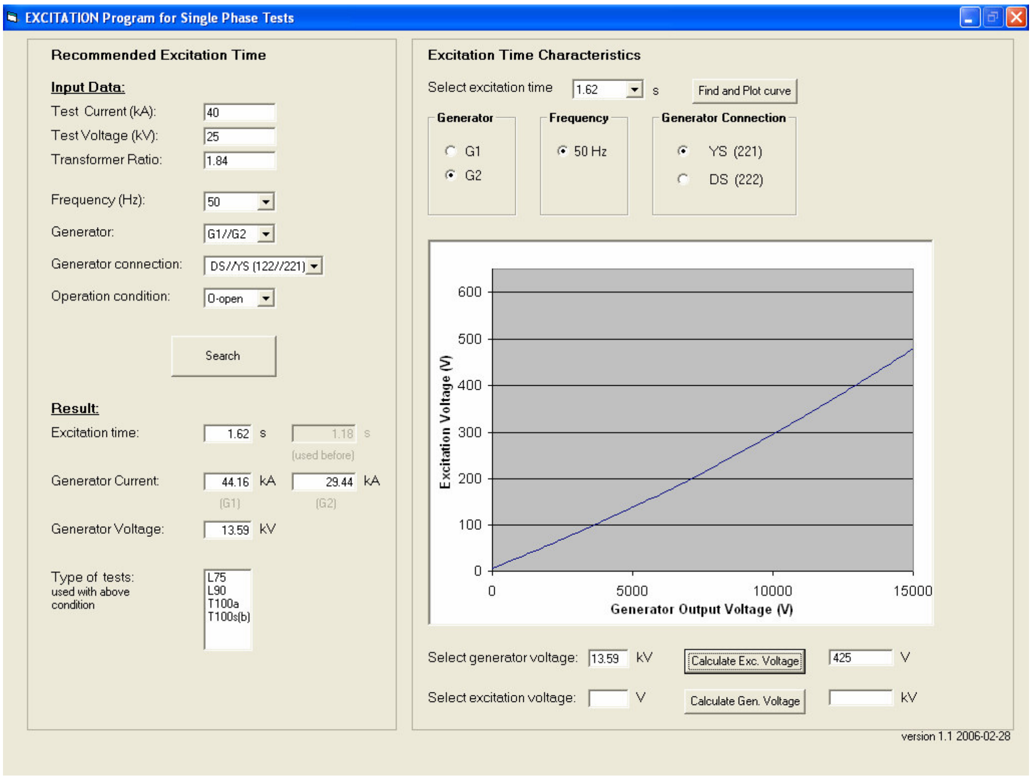
Select excitation time 1.62 s

Generator: ● G1 ○ G2
Frequency: ● 50 Hz ○ 60 Hz
Generator Connection: ● DS (122) ○ YP (123) ○ DP (124)

Select generator voltage: 13.59 kV → 375 V
Select excitation voltage: V → kV

version 1.1 2006-02-28

Figure 5.7 Main window of the program Excitation_Program.exe when parallel connection of the generators is chosen to find recommended excitation time in order to calculate correct excitation voltage from the excitation time characteristic for G1


EXCITATION Program for Single Phase Tests

Recommended Excitation Time

Input Data:

Test Current (kA): 40
Test Voltage (kV): 25
Transformer Ratio: 1.84
Frequency (Hz): 50
Generator: G1//G2
Generator connection: DS//YS (122//221)
Operation condition: 0-open

Result:

Excitation time: 1.62 s 1.18 s (used before)
Generator Current: 44.16 kA (G1) 29.44 kA (G2)
Generator Voltage: 13.59 kV
Type of tests used with above condition: L75 L90 T100a T100s(b)

Excitation Time Characteristics

Select excitation time 1.62 s

Generator: ○ G1 ● G2
Frequency: ● 50 Hz
Generator Connection: ● YS (221) ○ DS (222)

Select generator voltage: 13.59 kV → 425 V
Select excitation voltage: V → kV

version 1.1 2006-02-28

Figure 5.8 Main window of the program Excitation_Program.exe when parallel connection of the generators is chosen to find recommended excitation time in order to calculate correct excitation voltage from the excitation time characteristic for G2

CHAPTER 6

Conclusion

No-load measurements on the high power short-circuit generators and an excitation time study of the short-circuit characteristics has been performed in this thesis. The results were used as main and basic input parameters into a new program called Excitation program for single-phase tests, which has been programmed with use of the software Microsoft Visual Basic 5, in order to provide a user friendly interface with a good visual approach.

From the no-load measurements on both short-circuit generators it is now possible to substitute very old and not so precise excitation time characteristics, which have been in use for many years. Large parts of the old characteristics were obtained from the previous tests by extrapolation and interpolation. Since the new measurements have been done for all cases and analysed using Matlab, the excitation time characteristics of the generators will have higher accuracy over a wider range as compared to before. Therefore the exact values of the three main parameters such as excitation voltage, generator output rms voltage and the corresponding excitation curve will be easily found with the new tool. This new tool is a user friendly program in Microsoft Visual Basic 5, where all parameters will be easy to find as a function of the various combinations of the generator's winding connection, frequency and if generator 1 or generator 2 is chosen.

Result from Chapter 4 shows that it is possible to use the same excitation times for the sequences O, O-CO, and CO of the single phase-tests for the sequencer for the same generator winding connection, frequency and use of the generators (if only one generator or both generators in parallel are being used). These excitation time values are only recommended values and should be used as a starting point for making the particular single-phase short-circuit tests of the test duties T10, T30, T60, T100a, T100s(a), T100s(b) and also for tests L75 and L90.

The study on the excitation times does not cover three-phase short-circuit tests due to the small amount of available data from previous three-phase short-circuit tests and therefore it is not feasible to make final conclusion on this issue. Lack of time and availability of test plant did not permit short-circuit testing under three-phase conditions.

Other tests such as STC (short-time current withstand test) tests are also not covered, since these are much more complicated and were excluded from the study from the beginning. Further work can be done on the same lines to cover three-phase short-circuit tests, STC and other special tests.

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Appendix A

Matlab Code

A.1 Same Sampling Time

---MATLAB CODE--

```
%==========================================
% Evaluating measured data on generators
%
% by MARIAN KINCES
%===========================================

%CASE G1YP50Hz==============================================================
% Do NOT start to run the programme from the beginning because it
% takes too much time to calculate all the points in the RMS voltage
% matrice since I have very big sampling frequency and so, so many
% samples. I have saved the arrays in the file arrays6sEnough, so first
% open it in the workspace and then you can directly makes plots. Now go
% to CONTINUE.
%========================================================================


%=================
% SKIP THIS PART
%=================
clc
close all
clear all

%%% files with dt=50us (up to 6s)
load U_R010_70.txt
M(:,1)=U_R010_70(1:120000);
load U_R011_90.txt
M(:,2)=U_R011_90(1:120000);
load U_R012_110.txt
M(:,3)=U_R012_110(1:120000);
load U_R013_130.txt
M(:,4)=U_R013_130(1:120000);
load U_R014_150.txt
M(:,5)=U_R014_150(1:120000);
load U_R015_170.txt
M(:,6)=U_R015_170(1:120000);

%%% files with dt=50us (up to their original length and the rest is  full fill with NaN – not a number up to 6s)

load U_R016_190.txt
size1=length(U_R016_190);
M_1=U_R016_190;
M_1(size1:120000)=NaN;
M(:,7)=M_1;
load U_R017_210.txt
size2=length(U_R017_210);
M_2=U_R017_210;
M_2(size2:120000)=NaN;
M(:,8)=M_2;
load U_R018_230.txt
size3=length(U_R018_230);
M_3=U_R018_230;
```

```
M_3(size3:120000)=NaN;
M(:,9)=M_3;
load U_R019_250.txt
size4=length(U_R019_250);
M_4=U_R019_250;
M_4(size4:120000)=NaN;
M(:,10)=M_4;
load U_R020_270.txt
size5=length(U_R020_270);
M_5=U_R020_270;
M_5(size5:120000)=NaN;
M(:,11)=M_5;
load U_R021_290.txt
size6=length(U_R021_290);
M_6=U_R021_290;
M_6(size6:120000)=NaN;
M(:,12)=M_6;
load U_R022_310.txt
size7=length(U_R022_310);
M_7=U_R022_310;
M_7(size7:120000)=NaN;
M(:,13)=M_7;
load U_R023_330.txt
size8=length(U_R023_330);
M_8=U_R023_330;
M_8(size8:120000)=NaN;
M(:,14)=M_8;
load U_R024_350.txt
size9=length(U_R024_350);
M_9=U_R024_350;
M_9(size9:120000)=NaN;
M(:,15)=M_9;
load U_R025_370.txt
size10=length(U_R025_370);
M_10=U_R025_370;
M_10(size10:120000)=NaN;
M(:,16)=M_10;
load U_R026_390.txt
size11=length(U_R026_390);
M_11=U_R026_390;
M_11(size11:120000)=NaN;
M(:,17)=M_11;
load U_R027_410.txt
size12=length(U_R027_410);
M_12=U_R027_410;
M_12(size12:120000)=NaN;
M(:,18)=M_12;
load U_R028_430.txt
size13=length(U_R028_430);
M_13=U_R028_430;
M_13(size13:120000)=NaN;
M(:,19)=M_13;
load U_R029_450.txt
size14=length(U_R029_450);
M_14=U_R029_450;
M_14(size14:120000)=NaN;
M(:,20)=M_14;
load U_R030_470.txt
size15=length(U_R030_470);
M_15=U_R030_470;
M_15(size15:120000)=NaN;
M(:,21)=M_15;
load U_R031_490.txt
```

```
size16=length(U_R031_490);
M_16=U_R031_490;
M_16(size16:120000)=NaN;
M(:,22)=M_16;
load U_R032_510.txt
size17=length(U_R032_510);
M_17=U_R032_510;
M_17(size17:120000)=NaN;
M(:,23)=M_17;
load U_R033_530.txt
size18=length(U_R033_530);
M_18=U_R033_530;
M_18(size18:120000)=NaN;
M(:,24)=M_18;
load U_R034_550.txt
size19=length(U_R034_550);
M_19=U_R034_550;
M_19(size19:120000)=NaN;
M(:,25)=M_19;
load U_R035_570.txt
size20=length(U_R035_570);
M_20=U_R035_570;
M_20(size20:120000)=NaN;
M(:,26)=M_20;
load U_R036_590.txt
size21=length(U_R036_590);
M_21=U_R036_590;
M_21(size21:120000)=NaN;
M(:,27)=M_21;
load U_R037_610.txt
size22=length(U_R037_610);
M_22=U_R037_610;
M_22(size22:120000)=NaN;
M(:,28)=M_22;

%==========================================================================
% Calculation of RMS voltage
%==========================================================================
Nfile=28; % number of files loaded
fsys=50;
fsamp=20000;
dt=1/fsamp;
samp=fsamp/fsys;
len=length(M(:,28)); % change column if different total time

for ij=1:Nfile % change the number of columns
    RMSM(:,ij)=rms(M(:,ij),samp)';
End
t=25e-6:dt:dt*(len-1)+25e-6;

%============= CONTINUE ==================================================
% You can start running the programme from here because all the other
% important calculation were saved into the workspace since it takes
% long time to calculate the RMS voltage due to too many samples
%==========================================================================

figure(1)
plot(t,RMSM(:,1),'k'),grid
xlabel('Excitation time (s)'),
ylabel('Instantaneous RMS output voltage (V)'),
title('G1YP50Hz excited with 70V')

figure(21)
```

```
plot(t,RMSM(:,1:6)),grid
xlabel('Excitation time (s)'),
ylabel('Instantaneous RMS output voltage (V)'),
title('G1YP50Hz excited with 70V to 170V')
legend('70V','90','110','130','150', '170',2)

figure(2)
plot(t,RMSM(:,1:9)),grid
xlabel('Excitation time (s)'),
ylabel('Instantaneous RMS output voltage (V)'),
title('G1YP50Hz excited with 70V to 230V')
h_legend=legend('70V','90','110','130','150', '170','190','210','230',2);
set(h_legend,'FontSize',7)

figure(3)                    %no load figure
subplot(3,1,1)
plot(t,M(:,6)),grid, xlim([1.4 2]), ylim([-15000 15000])
title('No-load characteristics for different excitation voltage')
%xlabel('Excitation time(s)')
ylabel('No-load output voltage(V)'),
legend('170V',3)

subplot(3,1,2)
%figure(31)
plot(t,M(:,7)),grid,xlim([1.4 2]),ylim([-15000 15000])
%title('No-load characteristic for excitation voltage 190V')
%xlabel('Excitation time(s)')
ylabel('No-load output voltage(V)'),legend('190V',3)

subplot(3,1,3)
%figure(32)
plot(t,M(:,8)),grid,xlim([1.4 2]), ylim([-15000 15000])
%title('No-load characteristic for excitation voltage 210V')
xlabel('Excitation time (s)'),ylabel('No-load output voltage(V)'),
legend('210V',3)

figure(32)                    %no load figure
subplot(3,1,1)
plot(t,M(:,6)),grid
title('No-load characteristic for excitation voltage 170V')
%xlabel('Excitation time(s)')
ylabel('No-load output voltage(V)'),

subplot(3,1,2)
%figure(31)
plot(t,M(:,7)),grid
title('No-load characteristic for excitation voltage 190V')
%xlabel('Excitation time(s)')
ylabel('No-load output voltage(V)'),

subplot(3,1,3)
%figure(32)
plot(t,M(:,8)),grid
title('No-load characteristic for excitation voltage 210V')
xlabel('Excitation time(s)'),ylabel('No-load output voltage(V)'),


%========================================================================
% calculation of excitation time and making plots for output volt. vs Excitation Voltage
%========================================================================
t_exc=0.1:0.1:0.9;
Nt=t_exc/dt;
Nfile1=length(Nt);
```

```
% for ii=1:Nfile1
%     outpUall(ii,2:Nfile+1)=RMSM(Nt(1,ii),:);
% end              %%%it says Subscript indices must either be real
%positive integers or logicals

for ii=1:Nfile1
     outpUall(ii,2:Nfile+1)=RMSM(round(Nt(1,ii)),:);
end

exitUall=[0,70,90,110,130,150,170,190,210,230,250,270,290,310,330,350,370,390,410,430,450,470,490,510,
            530,550,570,590,610];

figure(4)
plot(outpUall,exitUall,'+','MarkerSize',3),grid,
title({'G1YP50Hz',' Excitation Curve of t=0.1s to 0.9s with dt=0.1s'})
xlim([0, 13000]), ylim([0 650])
xlabel('Instantaneous RMS output voltage (V)'),
ylabel('Excitation voltage (V)')


%excitation time 0.92 to 3s with dt=0.02s
t_exc1_2=0.92:0.02:3;
Nt1_2=t_exc1_2/dt;
Nfile2=length(Nt1_2);

for ik=1:Nfile2
     outpUall09_3(ik,2:Nfile+1)=RMSM(round(Nt1_2(1,ik)),:);
end

figure(5)
plot(outpUall,exitUall,'+',outpUall09_3,exitUall,'+','MarkerSize',3),grid,
title({'G1YP50Hz','Excitation Curve of t=0.1s to 3s with dt=0.1s and dt=0.02s'})
xlim([0,14000]), ylim([0 650])
xlabel('Instantaneous RMS output voltage (V)'),ylabel('Excitation voltage (V)'),

%excitation time 3.1 to 4s with dt=0.1s
t_exc2_4=3.1:0.1:4;
Nt2_4=t_exc2_4/dt;
Nfile3=length(Nt2_4);

for ia=1:Nfile3
     outpUall3_4(ia,2:Nfile+1)=RMSM(round(Nt2_4(1,ia)),:);
end

figure(6)
plot(outpUall3_4,exitUall,'+','MarkerSize',3),grid,
title('Excitation Curve of t=3s to 4s with dt=0.1s')
xlim([0, 14000]), ylim([0 400])
xlabel('Output voltage(V)'),ylabel('Excitation voltage(V)'),

figure(7)
plot(outpUall,exitUall,'+',outpUall09_3,exitUall,'+',outpUall3_4,exitUall,'+','MarkerSize',3),grid,
title('Excitation Curve of t=0.1s to 4s')
xlim([0, 14000]), ylim([0 650])
xlabel('Output voltage(V)'),ylabel('Excitation voltage(V)'),
%========================================================================

%========================================================================
% calculating the parameters a,b,c of quadratic equation ax^2+bx+c from
% 0.1s to 0.9s with step dt=0.1s
%========================================================================
for m=1:9
x=outpUall(m,:)';
```

```
c_excl=x(~isnan(x));     %excluding the NaN numbers from the matrix
cc=c_excl;
ccc=cc';
N=length(ccc);
cf = fit(ccc',exitUall(1:N)','poly2'); %fitting by polynomial of 2nd degree
ft(m,:)=getfield(struct(cf),'coeffValues'); %getting coefficients (a,b,c) of the fitted curve
end

%===========================================================================
% calculating the parameters a,b,c of quadratic equation ax^2+bx+c from
% 0.92s to 3s with step dt=0.02s
%===========================================================================
for m1=1:105
x1=outpUall09_3(m1,:)';
c_excl1=x1(~isnan(x1));
cc1=c_excl1;
ccc1=cc1';
N1=length(ccc1);
cf1 = fit(ccc1',exitUall(1:N1)','poly2') ;
ft1(m1,:)=getfield(struct(cf1),'coeffValues');
end

c2_1=outpUall09_3(36,:);              %1.62s
c2_1excl=c2_1(~isnan(c2_1));
N=length(c2_1excl);
figure(21)
plot(c2_1excl,exitUall(1:N),'*k'),ylim([0 650]);
hold on
cf_21 = fit(c2_1excl',exitUall(1:N)','poly2'); %fitting by polynomial of 2nd degree
h_21 = plot(cf_21,'r','fit', 0.95);
fit_coeff=struct(cf_21);
f3(1,:)=getfield(fit_coeff,'coeffValues');
xlabel('Instantaneous RMS output voltage (V)'),ylabel('Excitation voltage (V)')
title('Excitation time characteristic')

c2_02=outpUall09_3(1,:);                %0.92s
c2_02excl=c2_02(~isnan(c2_02));
N2=length(c2_02excl);
plot(c2_02excl,exitUall(1:N2),'*k'),ylim([0 650]);
cf_202 = fit(c2_02excl',exitUall(1:N2)','poly2');
h_202 = plot(cf_202,'fit', 0.95);

c2_03=outpUall(1,:);                    %0.1s
c2_03excl=c2_03(~isnan(c2_03));
N3=length(c2_03excl);
plot(c2_03excl,exitUall(1:N3),'*k'),ylim([0 650]);
cf_203 = fit(c2_03excl',exitUall(1:N3)','poly2');
h_203= plot(cf_203,'fit', 0.95);

c2_04=outpUall(5,:);                    %0.5s
c2_04excl=c2_04(~isnan(c2_04));
N4=length(c2_04excl);
plot(c2_04excl,exitUall(1:N4),'*k'),ylim([0 650]);
cf_204 = fit(c2_04excl',exitUall(1:N4)','poly2');
h_204= plot(cf_204,'fit', 0.95);

c2_05=outpUall3_4(10,:);                %4s
c2_05excl=c2_05(~isnan(c2_05));
N5=length(c2_05excl);
plot(c2_05excl,exitUall(1:N5),'*k'),ylim([0 650]);
cf_205 = fit(c2_05excl',exitUall(1:N5)','poly2');
h_205= plot(cf_205,'fit', 0.95);
hold off
```

```
xlabel('Instantaneous RMS output voltage (V)')
ylabel('Excitation voltage (V)')
title('Excitation time characteristic - G1YP50Hz')

%============================================================================
% calculating the parameters a,b,c of quadratic equation ax^2+bx+c from
% 3.1s to 4s with step dt=0.1s
%============================================================================
for m2=1:10
x2=outpUall3_4(m2,:)';
c_excl2=x2(~isnan(x2));
cc2=c_excl2;
ccc2=cc2';
N2=length(ccc2);
cf2 = fit(ccc2',exitUall(1:N2)','poly2') ;
ft2(m2,:)=getfield(struct(cf2),'coeffValues');
end


%======double check==========================================================
% calculating the parameters a,b,c of quadratic equation from 0.1s to
% 0.9s with step dt=0.1s with different method
%============================================================================
c2_01=outpUall(1,:);
c2_01excl=c2_01(~isnan(c2_01));
N=length(c2_01excl);
figure(201)
plot(c2_01excl,exitUall(1:N),'*'),ylim([0 650]);
hold on
cf_201 = fit(c2_01excl',exitUall(1:N)','poly2');    %fitting by polynomial of 2nd degree
h_201 = plot(cf_201,'fit', 0.95);
hold off
f(1,:)=getfield(struct(cf_201),'coeffValues');

c2_02=outpUall(2,:);
c2_02excl=c2_02(~isnan(c2_02));
N2=length(c2_02excl);
figure(202)
plot(c2_02excl,exitUall(1:N2),'*'),ylim([0 650]);
hold on
cf_202 = fit(c2_02excl',exitUall(1:N2)','poly2');
h_202 = plot(cf_202,'fit', 0.95);
hold off
f(2,:)=getfield(struct(cf_202),'coeffValues');

c2_03=outpUall(3,:);
c2_03excl=c2_03(~isnan(c2_03));
N3=length(c2_03excl);
figure(203)
plot(c2_03excl,exitUall(1:N3),'*'),ylim([0 650]);
hold on
cf_203 = fit(c2_03excl',exitUall(1:N3)','poly2');
h_203 = plot(cf_203,'fit', 0.95);
hold off
f(3,:)=getfield(struct(cf_203),'coeffValues');

c2_04=outpUall(4,:);
c2_04excl=c2_04(~isnan(c2_04));
N4=length(c2_04excl);
figure(204)
plot(c2_04excl,exitUall(1:N4),'*'),ylim([0 650]);
hold on
cf_204 = fit(c2_04excl',exitUall(1:N4)','poly2');
```

```
h_204 = plot(cf_204,'fit', 0.95);
hold off
f(4,:)=getfield(struct(cf_204),'coeffValues');

c2_05=outpUall(5,:);
c2_05excl=c2_05(~isnan(c2_05));
N5=length(c2_05excl);
cf_205 = fit(c2_05excl',exitUall(1:N5)','poly2');
f(5,:)=getfield(struct(cf_205),'coeffValues');

c2_06=outpUall(6,:);
c2_06excl=c2_06(~isnan(c2_06));
N6=length(c2_06excl);
cf_206 = fit(c2_06excl',exitUall(1:N6)','poly2');
f(6,:)=getfield(struct(cf_206),'coeffValues');

c2_07=outpUall(7,:);
c2_07excl=c2_07(~isnan(c2_07));
N7=length(c2_07excl);
cf_207 = fit(c2_07excl',exitUall(1:N7)','poly2');
f(7,:)=getfield(struct(cf_207),'coeffValues');

c2_08=outpUall(8,:);
c2_08excl=c2_08(~isnan(c2_08));
N8=length(c2_08excl);
cf_208 = fit(c2_08excl',exitUall(1:N8)','poly2');
f(8,:)=getfield(struct(cf_208),'coeffValues');

c2_09=outpUall(9,:);
c2_09excl=c2_09(~isnan(c2_09));
N9=length(c2_09excl);
cf_209 = fit(c2_09excl',exitUall(1:N9)','poly2');
f(9,:)=getfield(struct(cf_209),'coeffValues');

%======================================================================
% calculating the parameters a,b,c of quadratic equation from 3.1s to
% 4s with step dt=0.1s with the method above
%======================================================================
c2_1=outpUall3_4(1,:);
c2_1excl=c2_1(~isnan(c2_1));
N=length(c2_1excl);
figure(21)
plot(c2_1excl,exitUall(1:N),'*'),ylim([0 400]);
hold on
cf_21 = fit(c2_1excl',exitUall(1:N)','poly2'); %fitting by polynomial of 2nd degree
h_21 = plot(cf_21,'fit', 0.95);
hold off
fit_coeff=struct(cf_21);
f3(1,:)=getfield(fit_coeff,'coeffValues');

c2_2=outpUall3_4(2,:);
c2_2excl=c2_2(~isnan(c2_2));
N2=length(c2_2excl);
figure(22)
plot(c2_2excl,exitUall(1:N2),'*'),ylim([0 400]);
hold on
cf_22 = fit(c2_2excl',exitUall(1:N2)','poly2');
h_22 = plot(cf_22,'fit', 0.95);
hold off
fit_coeff2=struct(cf_22);
f3(2,:)=getfield(fit_coeff2,'coeffValues');
```

```
c2_3=outpUall3_4(3,:);
c2_3excl=c2_3(~isnan(c2_3));
N3=length(c2_3excl);
figure(23)
plot(c2_3excl,exitUall(1:N3),'*'),ylim([0 400]);
hold on
cf_23 = fit(c2_3excl',exitUall(1:N3)','poly2');
h_23 = plot(cf_23,'fit', 0.95);
hold off
fit_coeff3=struct(cf_23);
f3(3,:)=getfield(fit_coeff3,'coeffValues');

c2_4=outpUall3_4(4,:);
c2_4excl=c2_4(~isnan(c2_4));
N4=length(c2_4excl);
figure(24)
plot(c2_4excl,exitUall(1:N4),'*'),ylim([0 400]);
hold on
cf_24 = fit(c2_4excl',exitUall(1:N4)','poly2');
h_24 = plot(cf_24,'fit', 0.95);
hold off
fit_coeff4=struct(cf_24);
f3(4,:)=getfield(fit_coeff4,'coeffValues');

c2_5=outpUall3_4(5,:);
c2_5excl=c2_5(~isnan(c2_5));
N5=length(c2_5excl);
cf_25 = fit(c2_5excl',exitUall(1:N5)','poly2');
f3(5,:)=getfield(struct(cf_25),'coeffValues');

c2_6=outpUall3_4(6,:);
c2_6excl=c2_6(~isnan(c2_6));
N6=length(c2_6excl);
cf_26 = fit(c2_6excl',exitUall(1:N6)','poly2');
f3(6,:)=getfield(struct(cf_26),'coeffValues');

c2_7=outpUall3_4(7,:);
c2_7excl=c2_7(~isnan(c2_7));
N7=length(c2_7excl);
cf_27 = fit(c2_7excl',exitUall(1:N7)','poly2');
f3(7,:)=getfield(struct(cf_27),'coeffValues');

c2_8=outpUall3_4(8,:);
c2_8excl=c2_8(~isnan(c2_8));
N8=length(c2_8excl);
cf_28 = fit(c2_8excl',exitUall(1:N8)','poly2');
f3(8,:)=getfield(struct(cf_28),'coeffValues');

c2_9=outpUall3_4(9,:);
c2_9excl=c2_9(~isnan(c2_9));
N9=length(c2_9excl);
cf_29 = fit(c2_9excl',exitUall(1:N9)','poly2');
f3(9,:)=getfield(struct(cf_29),'coeffValues');

c2_10=outpUall3_4(10,:);
c2_10excl=c2_10(~isnan(c2_10));
N10=length(c2_10excl);
cf_210 = fit(c2_10excl',exitUall(1:N10)','poly2');
f3(10,:)=getfield(struct(cf_210),'coeffValues');
```

A.2 Different Sampling Time

```
----------------------------------------------------------------------------------------------MATLAB CODE------------------------------------------------------------------------------
%===============
% CASE G1DS50Hz
%===============
clc
close all
clear all

%==============================
% files with dt=100us (up to 6s)
% ============================
load U_R873_60.txt
M(:,1)=U_R873_60(1:60000);
load U_R874_70.txt
M(:,2)=U_R874_70(1:60000);
load U_R875_90.txt
M(:,3)=U_R875_90(1:60000);
load U_R876_110.txt
M(:,4)=U_R876_110(1:60000);
load U_R877_130.txt
M(:,5)=U_R877_130(1:60000);

%==========================================================================
% files with dt=50us (up to their original length and the rest is fulfil with NaN-not a number up to 6s)
%==========================================================================
load U_R878_150.txt
size1=length(U_R878_150);
M1_1=U_R878_150;
M1_1(size1:120000)=NaN;
M1(:,1)=M1_1;
load U_R879_170.txt
M1_2=U_R879_170(1:size1);
M1_2(size1:120000)=NaN;
M1(:,2)=M1_2;
load U_R880_190.txt
size3=length(U_R880_190);
M1_3=U_R880_190;
M1_3(size3:120000)=NaN;
M1(:,3)=M1_3;
load U_R881_210.txt
size4=length(U_R881_210);
M1_4=U_R881_210;
M1_4(size4:120000)=NaN;
M1(:,4)=M1_4;
load U_R882_230.txt
size5=length(U_R882_230);
M1_5=U_R882_230;
M1_5(size5:120000)=NaN;
M1(:,5)=M1_5;
load U_R883_250.txt
size6=length(U_R883_250);
M1_6=U_R883_250;
M1_6(size6:120000)=NaN;
M1(:,6)=M1_6;
load U_R884_270.txt
size7=length(U_R884_270);
M1_7=U_R884_270;
M1_7(size7:120000)=NaN;
M1(:,7)=M1_7;
load U_R885_290.txt
```

```
size8=length(U_R885_290);
M1_8=U_R885_290;
M1_8(size8:120000)=NaN;
M1(:,8)=M1_8;
load U_R886_310.txt
size9=length(U_R886_310);
M1_9=U_R886_310;
M1_9(size9:120000)=NaN;
M1(:,9)=M1_9;
load U_R887_330.txt
size10=length(U_R887_330);
M1_10=U_R887_330;
M1_10(size10:120000)=NaN;
M1(:,10)=M1_10;
load U_R888_350.txt
size11=length(U_R888_350);
M1_11=U_R888_350;
M1_11(size11:120000)=NaN;
M1(:,11)=M1_11;
load U_R889_370.txt
size12=length(U_R889_370);
M1_12=U_R889_370;
M1_12(size12:120000)=NaN;
M1(:,12)=M1_12;
load U_R890_390.txt
size13=length(U_R890_390);
M1_13=U_R890_390;
M1_13(size13:120000)=NaN;
M1(:,13)=M1_13;
load U_R891_410.txt
size14=length(U_R891_410);
M1_14=U_R891_410;
M1_14(size14:120000)=NaN;
M1(:,14)=M1_14;
load U_R892_430.txt
size15=length(U_R892_430);
M1_15=U_R892_430;
M1_15(size15:120000)=NaN;
M1(:,15)=M1_15;
load U_R893_450.txt
size16=length(U_R893_450);
M1_16=U_R893_450;
M1_16(size16:120000)=NaN;
M1(:,16)=M1_16;
load U_R894_470.txt
size17=length(U_R894_470);
M1_17=U_R894_470;
M1_17(size17:120000)=NaN;
M1(:,17)=M1_17;
load U_R895_490.txt
size18=length(U_R895_490);
M1_18=U_R895_490;
M1_18(size18:120000)=NaN;
M1(:,18)=M1_18;
load U_R896_510.txt
size19=length(U_R896_510);
M1_19=U_R896_510;
M1_19(size19:120000)=NaN;
M1(:,19)=M1_19;
load U_R897_530.txt
size20=length(U_R897_530);
M1_20=U_R897_530;
M1_20(size20:120000)=NaN;
```

```
M1(:,20)=M1_20;
%==========================================================================
% Calculation of RMS voltage for M
%==========================================================================
Nfile=5; % number of files loaded
fsys=50;
fsamp=10000;
dt=1/fsamp;
samp=fsamp/fsys;
len=length(M(:,5)); % change colomn if different total time

for ij=1:Nfile          % change the number of columns
    RMSM(:,ij)=rms(M(:,ij),samp)';
end

t=50e-6:dt:dt*(len-1)+50e-6;

%==========================================================================
% Calculation of RMS voltage for M1(different sampling time)
%==========================================================================
Nfile1=20; % number of files loaded
fsamp1=20000;
dt1=1/fsamp1;
samp1=fsamp1/fsys;
len1=length(M1(:,20)); % change column if different total time

for ij1=1:Nfile1            % change the number of columns
     RMSM1(:,ij1)=rms1(M1(:,ij1),samp1)';
end

t1=25e-6:dt1:dt1*(len1-1)+25e-6;
% RMSM1(41000:125000,17)=NaN;
% RMSM1(74000:125000,8)=NaN;

%======CONTINUE=============================================================
% You can start running the programme from here because all the other
% important calculation were saved into the workspace since it takes
% long time to calculate the RMS voltage due to too many samples
%==========================================================================
figure(1)
plot(t,RMSM(:,2)),grid
xlabel('Excitation time(s)'),
ylabel('Instantaneous RMS output voltage for 70 V'),
title('Excitation voltage 70V')

figure(2)
plot(t1,RMSM1(:,13)),grid
xlabel('Excitation time(s)'), xlim([0 2]),
ylabel('Instantaneous RMS output voltage for 390 V'),
title('Excitation voltage 390V')

figure(3)
plot(t,RMSM(:,1:5)),grid
xlabel('Excitation time(s)'),
ylabel('Instantaneous RMS output voltage for 60V to 130V'),
title('Excitation voltage 60V to 130V')

figure(4)                    %no load figure
plot(t1,M1(:,8)),grid,xlim([0 3]),
title('No-load characteristic for excitation voltage 290V')
xlabel('Excitation time(s)'),ylabel('No-load output voltage(V)'),
```

```
%===========================================================================
% calculation of excitation time and making plots for output volt. vs excitation voltage
%===========================================================================
t_exc=0.1:0.1:0.9;    %exc. time 0.1 to 0.9s
Nt=t_exc/dt;
Nt1=t_exc/dt1;
Nfile2=length(Nt);
Nfile_2=length(Nt1);

for ii=1:Nfile2
     outpUallM(ii,2:Nfile+1)=RMSM(round(Nt(1,ii)),:);
end

for ii1=1:Nfile2
     outpUallM1(ii1,1:Nfile1)=RMSM1(round(Nt1(1,ii1)),:);
end

outpUall(:,1:6)=outpUallM;
outpUall(:,7:26)=outpUallM1;

exitUall=[0,60,70,90,110,130,150,170,190,210,230,250,270,290,310,330,350,370,390,410,430,450,470,490,
            510, 530];

figure(5)
plot(outpUall,exitUall,'+','MarkerSize',3),grid,
title('Excitation Curve of G1DS15kV t=0.1s to 0.9s with dt=0.1s')
xlim([0 13000]), ylim([0 550])


t_exc1_2=0.92:0.02:3;   %exc. time 0.92 to 3s
Nt1_2=t_exc1_2/dt;
Nt1_2_1=t_exc1_2/dt1;
Nfile3=length(Nt1_2);
Nfile_3=length(Nt1_2_1);

for ik=1:Nfile3
    outpUall09_3M(ik,2:Nfile+1)=RMSM(round(Nt1_2(1,ik)),:);
end

for ik1=1:Nfile_3
     outpUall09_3M1(ik1,1:Nfile1)=RMSM1(round(Nt1_2_1(1,ik1)),:);
end

outpUall09_3(:,1:6)=outpUall09_3M;
outpUall09_3(:,7:26)=outpUall09_3M1;

figure(6)
plot(outpUall,exitUall,'+',outpUall09_3,exitUall,'+','MarkerSize',3),grid,
title('Excitation Curve of G1DS15kV t=0.1s to 3s with dt=0.1s and dt=0.02s')
xlim([0 16000]), ylim([0 550])
xlabel('Output voltage(V)'),ylabel('Excitation voltage(V)'),

t_exc2_4=3.1:0.1:4;  %exc. time 3.1 to 4s
Nt2_4=t_exc2_4/dt;
Nt2_4_1=t_exc2_4/dt1;
Nfile4=length(Nt2_4);
Nfile_4=length(Nt2_4_1);

for ia=1:Nfile4
     outpUall3_4M(ia,2:Nfile+1)=RMSM(round(Nt2_4(1,ia)),:);
```

```
end

for ia1=1:Nfile_4
outpUall3_4M1(ia1,1:Nfile1)=RMSM1(round(Nt2_4_1(1,ia1)),:);
end

outpUall3_4(:,1:6)=outpUall3_4M;
outpUall3_4(:,7:26)=outpUall3_4M1;

figure(7)
plot(outpUall3_4,exitUall,'+','MarkerSize',3),grid,
title('Excitation Curve of G1DS15kV t=3.1s to 4s with dt=0.1s')
xlim([0 15000]), ylim([0 550])
xlabel('Output voltage(V)'),ylabel('Excitation voltage(V)'),

figure(8)
plot(outpUall,exitUall,'+',outpUall09_3,exitUall,'+',outpUall3_4,exitUall,'+','MarkerSize',3),grid,
title('Excitation Curve G1DS15kV of t=0.1s to 4s')
xlim([0 16000]), ylim([0 550])
xlabel('Output voltage(V)'),ylabel('Excitation voltage(V)')

%==========================================================================
% calculating the parameters a,b,c of quadratic equation ax^2+bx+c from
% 0.1s to 0.9s with step dt=0.1s
%==========================================================================
for m=1:9
  x=outpUall(m,:)';
  c_excl=x(~isnan(x));     %excluding the NaN numbers from the matrix
  cc=c_excl;
  ccc=cc';
  N=length(ccc);
  cf = fit(ccc',exitUall(1:N)','poly2'); %fitting by polynomial of 2nd degree
  ft(m,:)=getfield(struct(cf),'coeffValues'); %getting coefficients (a,b,c) of the fitted curve
end

%==========================================================================
% calculating the parameters a,b,c of quadratic equation ax^2+bx+c from
% 0.92s to 3s with step dt=0.02s
%==========================================================================
for m1=1:105
  x1=outpUall09_3(m1,:)';
  c_excl1=x1(~isnan(x1));
  cc1=c_excl1;
  ccc1=cc1';
  N1=length(ccc1);
  cf1 = fit(ccc1',exitUall(1:N1)','poly2') ;
  ft1(m1,:)=getfield(struct(cf1),'coeffValues');
end

%==========================================================================
% calculating the parameters a,b,c of quadratic equation ax^2+bx+c from
% 3.1s to 4s with step dt=0.1s
%==========================================================================
for m2=1:10
  x2=outpUall3_4(m2,:)';
  c_excl2=x2(~isnan(x2));
  cc2=c_excl2;
  ccc2=cc2';
  N2=length(ccc2);
  cf2 = fit(ccc2',exitUall(1:N2)','poly2') ;
  ft2(m2,:)=getfield(struct(cf2),'coeffValues');
end
------------------------------------------------------------------------------------------------------------------------------------------------------
```

A.3 RMS Function

```
-----------------------------------------------------------------------MATLAB CODE of RMS--------------------------------------------------------
%===================================
% Calculation of RMS for same sampling time
% =================================
function [Urms]= rms(volt,samp)
vlen=length(volt);
samp0=samp-1;
num=vlen-samp0;       %number of rms value

%calculation of rms value for each phase

u2=volt.*volt;
for kk=1:num
    Urms(kk+samp0)=sqrt(sum(u2(kk:samp0+kk))/samp);
end
for ii=1:samp0
    Urms(ii)=Urms(samp);
End
```

```
-----------------------------------------------------------------------MATLAB CODE of RMS1-------------------------------------------------------
%=========================================================
% Calculation of RMS1 when in the measurement two different sampling times
% ========================================================
function [Urms]= rms1(volt,samp1)
vlen=length(volt);
samp0=samp1-1;
num=vlen-samp0;       %number of rms value

%calculation of rms value for each phase

u2=volt.*volt;
for kk=1:num
    Urms(kk+samp0)=sqrt(sum(u2(kk:samp0+kk))/samp1);
end
for ii=1:samp0
    Urms(ii)=Urms(samp1);
end
-------------------------------------------------------------------------------------------------------------------------------------------------
```