MODELLING AND STUDY OF EXCITATION PHENOMENA IN INDUCTION GENERATORS

BY

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DECLARATION

This is to certify that I carried out the work reported in this thesis in the Department of Electrical Engineering , Faculty of Enginnering, Ahmadu Bello University, Zaria, under the supervision of Dr. A.A. Jimoh , Dr. B.G. Ishaku and Dr. Z.O. Oyedokun. The work of other investigators is acknowledged and referred to accordingly. I declare that no part of this thesis has been submitted elsewhere by me for the award of a degree.

S. S. Adamu

Date 22/1/96

CERTIFICATION

This thesis titled " **MODELLING AND STUDY OF SELF-EXCITATION PHENOMENA IN INDUCTION GENERATORS** ", by S. S. ADAMU meets the regulations governing the award of the degree of Master of Science (MSc) of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literature presentation.

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ABSTRACT

The recent energy crisis has led to renewed interest in induction generators as sources of electrical power . This is due to certain advantages they possess. For example, they are of simple construction ; of low cost and rugged. Moreover, they can be easily coupled to many types of motive sources , thus they can be utilised in rural areas of developing countries. In such situations the reliability of the self excitation process is of paramount importance. The survey of previous works on induction generators indicated that most of the authors are concerned with, steady-state conditions , well after the machine has built-up. Furthermore, there is no adequate model that could be used to study the transient build-up stage. The aim of this work was to develop such a model with a view to study the effect of machine parameters and other external effects.

The machine is modelled in a quasi-stationary d-q reference frame in which the mutual inductances are considered non-linear . The derived machine equations are of the form already developed by other authors [40,65] for motor operation Appropriate changes are then carried out in order to investigate the induction generator conditions of excitation.

A computer program was then developed using PASCAL language in order to study various excitation methods ,with a unique attempt to study the possibility of excitation from the rotor side. The model indicated a need for further work in the area of excitation from the rotor side. Using the results of the simulations, suggestions are then given on how to improve the reliability of the self-excitation process.

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LIST OF SYMBOLS

λ_{qs}	stator q-axis flux linkage	Weber-turns
λ_{ds}	stator d-axis flux linkage	Weber-turns
λ_{qr}	rotor q-axis flux linkage	Weber-turns
λ_{dr}	rortor d-axis flux linkage	Weber-turns
Lss	stator unsaturated leakage inductance	Henry
Lrr	rotor unsaturated leakage inductance	Henry
Lm	unsaturated magnetising inductance	Henry
iqs	instantaneous stator q-axis current	Amperes
ids	instantaneous stator d-axis current	Amperes
iqr	instantaneous rotor q-axis current	Amperes
idr	instantaneous rotor d-axis current	Amperes
Te	instantaneous electromagnetic torque	Newton-meter
P	number of poles	
p	differential operator d/dt	
J	moment of inertia of the rotor	Kilogram-meter squared
Wr	rotor speed	Radian/second

Tm	damping or mechanical torque	Newton-meter
We	base electrical angular velocity	Radian/second
Ws	syncronous speed of reference frame	Radian/second
Vqs	stator q-axis voltage	Volts
Vds	stator d-axis voltage	Volts
vqr	rotor q-axis voltage	Volts
vdr	rotor d-axis voltage	Volts
ψ_{qs}=Weλ_{qs} etc		Volts
r_s	stator resistance	Ohms
r_r	rotor resistance	Ohms
Xss	unsaturated stator leakage reactance	Ohms
Xrr	unsaturated rotor leakage reactance	Ohms
Xmd	unsaturated d-axis magentising reactance	Ohms
Xmq	unsaturated q-axis magnetising reactance	Ohms
H	inertia constant in per-unit = (2/P) (1/We) J/Base Torque	
vdsr	d-axis open circuit residual voltage	Volts
vqsr	q-axis open circuit residual voltage	Volts
Koc	residual voltage constant	Volts -second/Radian
Vqc	q-axis capacitor voltage	Volts

Vdc	d-axis capacitor voltage	Volts
Xc	capacitive reactance	Ohms
K	saturation factor in per unit	
Xm'	saturated magnetising reactance	Ohms
Wo	resonant frequency	Radian/second

CHAPTER 1

INTRODUCTION

The possibility of using an induction machine as a generator has been realised as far back as 1921 [2]. Over the years, efforts have been made to make such schemes practicable, but nevertheless induction generators remained unpopular. This is due to certain factors; an induction machine regardless of its mode of operation requires reactive power for its excitation which has to come from other sychronous machines in the system [2,6,5,9,12,15,17] or capacitor-banks [1,2,3,,4,714,16,18,19, 21,22,25]. In the case of capacitor-excited machines, the voltage and speed regulations are poor especially with inductive loads [7,28], and possible voltage distortions because stable operation is under saturated conditions [25].

Despite these disadvantages, the recent energy crisis has led to renewed interest in induction generators as principal generation sources [44,51]. This is due to certain advantages; they are of simple construction, low cost and rugged. Control equipment required is simple and more importantly, induction generators offer better power-system dynamic performance [18,19]; and following a system fault, the short-circuit current is not sustained [1,2,4,8,17,25]. Moreover, with recent developments of static var sources the earlier-on problems can be eliminated and thus large-scale use of induction generators can be possible [17,18,19,61,62].

The application scenarios of induction generators include co-generation in process industries, wind and hydroschemes. The above mentioned advantages can perhaps

be best utilised in rural electrification schemes of developing countries with the induction generator used as a stand-alone unit. In such situations the self-excitation process and ways to maintain it are of paramount importance.

After conducting a literature review on induction generators, it was discovered that most of the researchers focused on steady-state conditions. Even in the cases of transient studies, a linear machine was mostly considered. However, it is well known that operation of an induction generator is under saturated conditions [1,2,4,7,24]. This necessitates the formulation of a machine model with saturation effects for both transient conditions, which occur during voltage-build up and the steady-state.

The work here is concerned with development of the equations of a smooth air-gap machine in order to study the self excitation process and transient performance of an isolated induction generator, taking into account saturation effects. After developing the model, various operating conditions and the possibility of other excitation methods were investigated. For example, in all the papers reviewed, the excitation of the machine was always considered with the excitation capacitors on the starter side, without ever investigating the excitation coming from the rotor side.

The subject of induction generator self-excitation has been a focus of interest of many researchers. Earlier considerations [1,7,28] considered that self-excitation process occurs in a similar manner to the voltage build-up in dc - self excited generator. The drawback here is that the theory could not be used to study transient conditions or even effects of other machine parameters. Kitav and Olrlov [4] and Elder et al [48] considered the phenomena as conforming to the laws of self oscillations in any physical system and used the equivalent circuit of the machine to draw some very

useful conclusions. In the same line, Melkebeek [64]. Us^tug and Demireklev [53] considered it to be an unstable phenomena concluding that the limit cycle of the system defines the frequency of the oscillations.

The approach adopted here is to represent the machine in a quasi-stationary d-q reference frame in which the mutual inductances are considered non-linear . Solution of the equations involves calculating the inductances from the magnetising current of the machine. In order to appreciate the technique presented here , both linear and non-linear simulations are considered. The derived machine equations are of the form already developed by other authors [40,65] though for motor operation. Appropriate changes are then carried out in order to investigate the induction generator conditions of excitation.

The work is presented in six chapters . The first chapter introduces the problem and briefly reviews past attempts at solution. In the second chapter the literature review carried out on induction generator theory, design, operation, and application is presented. Chapter three deals with the model development , while in chapter four the details of computer simulation carried out are presented. The results of the experiments carried out are presented in chapter five, while in chapter six discussions and conclusions reached are presented. In appendix one , the parameters of the induction machines, in per-unit are presented. Appendix two shows the computer programs for the solution of the equations, while in appendix three , the results of the computer simulations are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The idea of induction generators as power sources was known as early back as 1921 [1]. In this chapter, existing work in this field are reviewed, and presented under four main aspects; operation, design, application and analysis.

2.2 OPERATION OF INDUCTION GENERATORS

2.2.1 : THEORY

The theory of operation of induction generators was perceived along a similar line as that of induction motors. Thus, earlier activities were concerned with power-system connected induction generators (PSCIG), and thus considered the generator operation at speeds above synchronous speed, thus making the slip negative [6,28,29]. This led to an equivalent circuit identical to the motor operation with currents in reversed directions, as in fig 2.1.

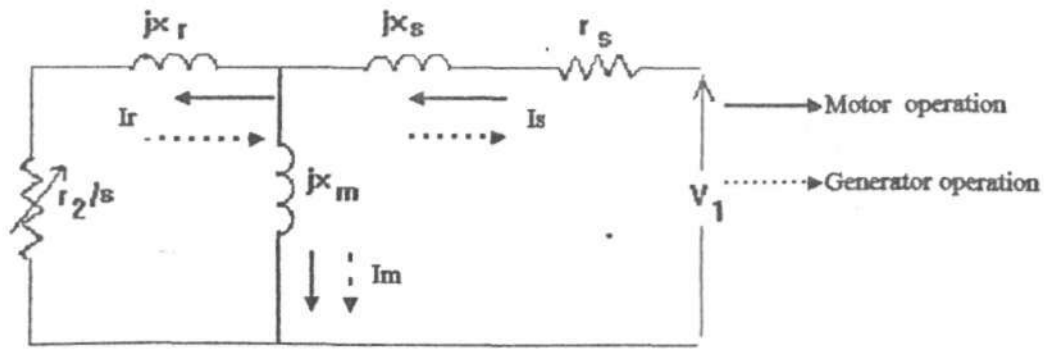


Fig2.1: Equivalent circuit of an induction generator

Lidgey [28] gave a circle diagram, fig 2.2, of the process. The machine initially motoring at point P moves along PAA'B into the generating mode as the speed increases. In the diagram OA' represents the reactive current needed for excitation and it remains in the same direction irrespective of the mode of operation, thus indicating the need for an external excitation source.

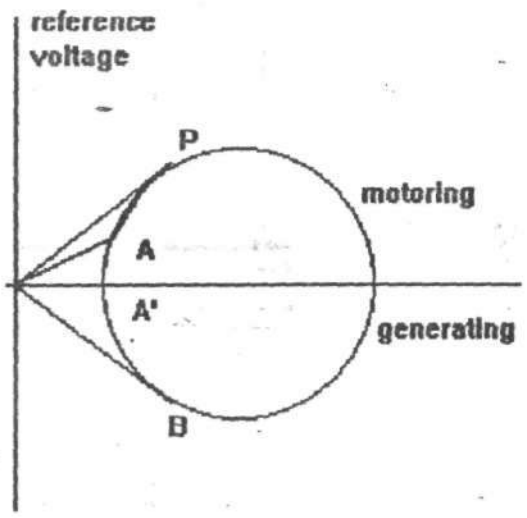


Fig 2.2: Circle diagram of induction machine [28].

2.2.2: EXCITATION METHODS

The excitation methods presently can be used as a basis of classifying types of operation modes of induction generators. These are, power-network connected induction generators (PNCIG), Capacitor-excited induction generator (CEIG) and control static var sources induction generator (CSUSIG).

The PNCIG was considered in [1,2,5,6,17,18] which the general conclusion was in favour of switching-in the machine at synchronous speed to the network. This switching will cause transient currents of several times the full load current but of short duration. Allan [6] carried out some tests to measure these currents at different speeds and concluded that during switching very close monitoring of the speed is unnecessary.

The case of CEIG operation is what is commonly referred to as operation under "self-excitation". The term "self-excited" refers to the fact that the terminal voltage of the machine is produced and maintained without any external periodic excitation source. Basset and Potter [1] considered CEIG with capacitor banks connected to the stator terminals and the machine externally driven, and proved the self-excitation process in a manner similar to the voltage build up in dc machines. The process relies on the presence of an initial charge on the capacitors or some residual voltage in the iron parts of the machines. Rotation of the rotor causes a reactive magnetising current to flow from the capacitor banks, and this increases the air-gap flux thereby developing higher air-gap voltage which in turn causes more current and so on. The final voltage is determined by the saturation curve of the machine and the capacitive reactance of the capacitor banks, as shown in fig 2.3 [1,28]. The dashed-line indicates the self-excitation process with the final build-up voltage at point A.

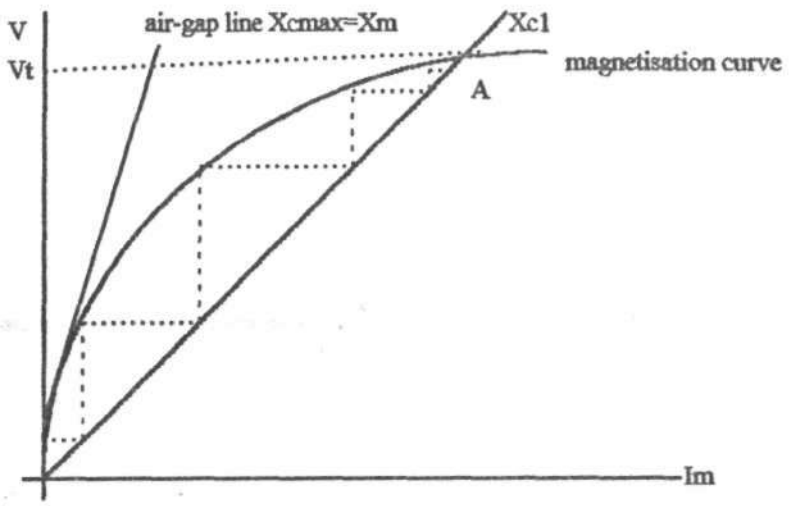


Fig. 2.3 : Self-excitation process of capacitor-excited induction generator

Recent developments of controlled static var sources (CSVS) with thyristor has opened new opportunities for large-scale use of self-excited induction generators [18,19]. Novotny et al [23,24] gave one form of thyristor in inverter excitation, where the commutation capacitors are used to provide the magnetising power exchange of the machine. Umida et al [61,62] considered the case where the inverters are substituted with dc converters to achieve both control of ac and reactive needs of the machine.

Of interest in the case of self-excited machines is what happens if the excitation is lost during operation, caused either by short circuit or too great a load. According to Basset and potter [1] voltage build-up may not be possible again. To restore the voltage they recommended three methods as follows:

1) running the machine as a motor from an existing ac system.

2) discharging a charged capacitor through the stator windings while the machine is running.

3) connecting a 6-v storage battery across two terminals of the machine at rest.

Loss of excitation may give rise to stator overheating [5] and high speeds [4].

2.2.3: NO-LOAD OPERATION

For PSCIG, operation at no-load occurs with the rotor externally driven above synchronous speed and only the machine losses are supplied. The CEIG at no-load runs at synchronous speed. Wagner [29] mentioned such an operation and gave a method to obtain the no-load excitation curve by varying the capacitance and measuring the terminal voltage. The air-gap magnetisation curve is then obtained by subtracting the leakage voltage drop from the no-load curve.

Since at no-load the slip is very small the generated frequency corresponds to the shaft frequency [29]. As the frequency increases, the terminal voltage for a given magnetising current increases in proportion, while the capacitor current varies inversely with the frequency. These effects combine to increase the terminal voltage. Oscillograms of the no-load terminal voltage obtained by Basset and Potter [1] and Wagner [29] proved the above assertion, and further showed that contrary to the belief that the terminal voltage will be highly distorted, it was in fact very close to a sine wave.

2.2.4: LOADING CONDITIONS

2.2.4.1: PSCIG UNDER LOAD

Loading a PSCIG is achieved by increasing its speed to change the electrical power output of the machine [6]. The PSCIG has no control upon the voltage and frequency which are entirely fixed by the power system.

2.2.4.2: CEIG UNDER LOAD

With a load of unity power factor connected to CEIG, the terminal voltage falls off quite rapidly with increasing load if the capacitance and speed are constant [1,22,28,29]. Observations [1,29] showed that the voltage regulation is better for unity power factor loads (resistive) than for lagging loads (inductive). On the other hand, leading loads (capacitive) tend to hold up the voltage. This occurs due to a demagnetising component of magnetomotive force which appears in the rotor and has to be balanced by the terminal capacitance.

Thus, voltage control is essentially the balancing of demand and supply of reactive power. This can be done using automatic devices to increase the capacitance if economically justified [2]. Another method suggested by Basset and Potter [1] is called "compounding" where all the loads are made effectively capacitive by placing a series capacitance in the line. However, this causes the machine to lose its "natural" protection following a short-circuit in that a sustained current can flow.

In CEIG the frequency drops as the load increases due to increase in slip speed. According to Basset and Potter [1] to keep the frequency constant a drive whose speed increases with torque is required. Under loaded conditions, Wagner [29] showed that the voltages and currents are approximately sine waves with some distortions in the currents. Also if the load is non-linear according to Lidgey [28] the voltage is distorted.

2.2.5: POWER FACTOR, EFFICIENCY AND LOSSES

The power factor of induction generators is inherently low and is worse at light loads [10]. Normally the efficiency is taken to be less than that of induction motors due to increased core-losses and certain stray load-losses [17,18]. When compared with synchronous machines of similar ratings, it is normally said that the induction generator has lower efficiency. However, De Mello and Hannet [18] said this is not necessarily so as rotor circuits with sufficiently low losses can be designed.

The losses normally encountered in induction generators are the same as those in induction motors [12,13,14]. Basically they include the stator and rotor $I^2 R$ losses, stray-load loss, core-loss, friction and windage losses.

2.2.6: TRANSIENT CONDITIONS [1,2,4,8,17,25]

When an induction generator is short-circuited, studies have indicated that no sustained fault current flows due to loss of excitation. There are also no voltage surges.

Analysis of the short circuit conditions [4,8,17] was considered along a similar line to transient short circuit of a synchronous generator. The initial short circuit current has a high initial value but decreases rapidly in accordance with the short-circuit time constant of the generator (order 1 to 3 cycles) [8]. Thode and Azbill [17] further mentioned that there will be a unidirectional and ac components of the currents. With capacitor excitation the time constant increases [17,45], and the transient equivalent circuit is shown in fig 2.4 [4,8].

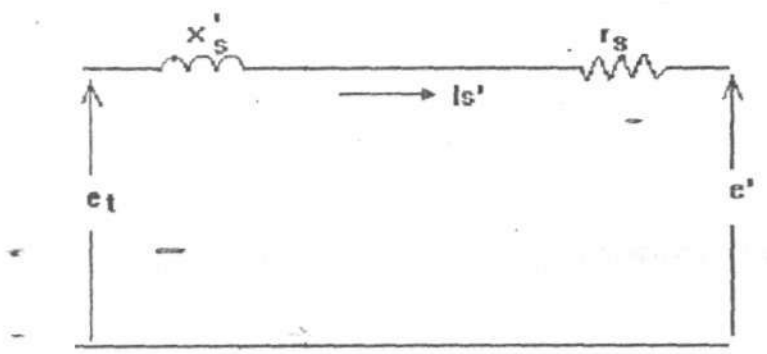


Fig 2.4: Transient equivalent circuit of induction machine

2.2.6.1: LOSS OF LOAD AND RECLOSING [17,32,33]

When an induction generator loses its load it will speed up unless overspeed protections are installed. In addition, transient torques and currents are produced. Smith and Sriharan [33] concluded that it is not even advisable to reclose the machine unless the loss is of very short duration. For CEIG dangerous over voltages may result [29].

2.2.7: SYSTEM STABILITY

2.2.7.1: HUNTING

Originally [2] it was thought that induction machines are free from hunting, but careful analysis [2,14] has shown that they have the tendency to hunt. Large machines have natural oscillation periods due to the leakage fluxes of very short duration [2]. Griffith and Owen [14] gave an equation for the natural hunting frequency as:

$$Fn=\frac{3520}{rpm}\sqrt{\frac{TsF}{WK^2}} \qquad (2.1)$$

Fn = natural frequency vibrations/min

Ts = synchronising Toque kw/rad

rpm = synchronous speed r/min

F = rated frequency

wk^2 = total inertia of all rotor connected bodies.

2.2.7.2: DYNAMIC STABILITY

Stability studies of considerable importance have been undertaken by Demello et al [18,19], where it was shown that isolated induction generators with static var controllers can have a better dynamic stability characteristics than synchronous generators for 3 cycles faults. Further conclusions reached indicated that power showings are similar to those of synchronous generators, though they can result in sustained speed deviations. However, they can be eliminated by proper rotor circuit designs [18].

Induction generators can operate in parallel together or with other synchronous machines [18,19,35]. Watson and Milne [35] concluded that optional load sharing is possible if the induction machines are identical and are driven at the same speed. In [19] a two machine system was studied and it was proved that induction machine exhibits inter machine oscillatory modes similar to those of synchronous machines and they are well damped. Stabilisation with auxilliary signals through static var sources controllers is also possible if employed correctly [19].

2.2.8 : CONTROL AND PROTECTION

2.28.1: LOAD AND VOLTAGE CONTROL

Induction generators are normally run with steady load over a long period of time , so facilities for load control are simple. For a PSCIG load control is achieved by varying the prime mover speed. When the speed of operation in excess of synchronous speed is by an amount equivalent to normal full-load slip when operating as a motor , the machine will deliver rated kW output[6,9].

In the case of isolated CEIG, the subject of load control is not fully addressed. In [68] however, mention was made of electronically switching power dumps comprising banks of resistors to absorb power in excess of consumers' requirements to maintain constant loading on the generator , thereby maintaining constant frequency and voltage. This switched resistance governor would only be satisfactory if the load is resistive (unity power factor) , but for inductive load use is made of switched capacitors or fixed excess capacitance to be selectively offset when required by the

variable inductance. The latter scheme was implemented in [18] using microprocessors.

Voltage control is considered only in the case of CEIG by varying the effective terminal capacitance [6,9,68] and/or speed . For CEIG there is a close-link between the terminal capacitance and the frequency (or speed),and more work is needed in this area. Recent developments of thyristor controllers has opened new effective means of control [61,62].

2.2.8.2: PROTECTION [4,5,9,27]

The subject of protection of induction generators has not been taken deeply by many authors. However the following protective devices could be found in medium capacity installations [8,27]

1) SHORT-CIRCUIT CURRENT AND OVERLOAD

For short-circuit, current limiting fuses are most common in medium voltage operations [9]. In low voltage circuits, circuit-breakers may be used [9]. Overload tripping can be provided by an overload relay having inverse time characteristics in order to minimise false trippings during starting or momentary overloads.

2) OVER-AND UNDER-VOLTAGES

The cost of adding such protections to the main circuit breaker is small [9]. For the under voltage relay it must have a time lag and be insensitive to short-

time voltage dips. Allan [6] provides another function for it, it guards against operation of low voltage, low power output and high speed stable conditions.

3) OVER SPEED

Kwain and Smith [27] recommended a simple centrifugal switch normally set at 120% above normal operating speed.

4) MOTORING

Knoernschuld [9] recommended a reverse power relay or an underspeed switch centrifugally operated at a predetermined, speed usually synchronous speed. Obviously, this does not apply to isolated operation.

5) MULTIMACHINE MASTER TRIP [27]

System conditions which produce overvoltages or loss of excitation are guard against by the use of a master trip relay arranged to operate the differential auxilliary relay of each machine.

6) OTHER PROTECTIONS

Other special protection devices that may be encountered as given by Kwain and Smith [27] include, vibration switch, bearing temperature relays, lubrication oil pressure switches, phase balance relays and annunciators. For large machines, Moore [10] recommended phase unbalance relays, winding over-temperature relays, generator ground-fault detectors, bearing cooling water flow detectors and others.

For CEIG, locating the capacitor banks such that no dangerous amount is isolated together with the machine is advocated by Ferguson and Barkle [4].

2.2.8.3: CIRCUIT BREAKERS AND RELAYING [4,5]

For selecting circuit breakers and system relaying it is important to ascertain the short circuit characteristics of the induction generators. Ferguson and Barkle [4] mentioned that an induction generator has no effect upon interrupting duty for 5 - or 8 cycle circuit breakers and can be neglected. The momentary current contributions should also be considered when designing bus work and in applying current transformers and relays. For differential relaying, a simple overcurrent or directional overcurrent relays may be used according to Ferguson and Barkle [4].

2.2.9: OTHER OPERATIONAL CONSIDERATIONS

Some operational considerations mentioned by some authors include single or three phase operation [1,29], system grounding [14] and the use of saturable reactors to effect voltage regulation [3,7,28]. In [1,29] it was concluded that both single and three phase operations are possible, though the effect of resulting unbalancing in the former situation was not investigated.

For the case of system grounding, in [14] it was concluded that PSCIG should receive the same considerations as an induction motor for the purpose of grounding since it is incapable of sustaining a fault voltage and therefore not grounded. The conclusion reached for a CEIG was that it should be grounded.

The use of saturable-reactors is mentioned in [3,7,28] to reduce the voltage regulation. The reactors effectively change the magnetisation characteristics of the induction machine.

2.3: APPLICATIONS OF INDUCTION GENERATORS

The various reported application scenario of induction generators are reviewed in this section.

2.3.1: APPLICATIONS IN WIND ENERGY CONVERSION SCHEMES

Wind-energy conversion schemes employing induction generators have been reported by many authors [20,36,37]. Application considerations which make induction generators attractive are:

1) Since wind speed fluctuates, the use of synchronous generators would require a blade pitch control mechanism which is expensive [36]. With induction generators, however, such a device is not necessary but a damping mechanism is needed at high wind speeds.

2) Due to considerations in (1) above, a synchronous generator coupled to a vertical-axis Darrieus wind turbine is not very satisfactory, because the turbine blade pitch control is not precise [20,36,37]. Another factor according to Jayadev [36] is that a Darrieus, for example has no starting torque and it may be necessary when using a synchronous generator to couple it to a low-efficiency savonius type to develop initial rotational

velocity. On the other hand, induction generator provides a simple machine since it could be started as a motor to assist in the starting. [36].

3) Dynamic studies carried out [36,37], indicated that damped coupling is necessary between a wind turbine and a synchronous generator; but using induction generators it is not necessary. There is also a stability problem in synchronous machines if the wind-electric power is significant compared with the capacity of the system [36].

4) Induction generators lack the ability to supply reactive power and have no control as voltage and frequency, Jayadev [36] gave some application options to overcome these disadvantages. These include:

i) VARIABLE SPEED-VARIABLE FREQUENCY (VSVF) SYSTEM

In order to achieve frequency control the output which is alternating (ac) is rectified to get a "dc" and then back to "ac" using inverters.

ii) VARIABLE SPEED-CONSTANT FREQUENCY (VSCF) FREQUENCY DOWN CONVERSION

A scheme where the power is generated at a modulated frequency much higher than the normal frequency, and then electronically processed down to the normal frequency.

iii) AC COMMUTATOR GENERATOR (ACCG)

A simple scheme where the field excitation is from the grid. The ACCG provides line-frequency because of the commutator. Commutation problems however limit the scheme.

iv) DOUBLE OUTPUT INDUCTION GENERATOR (DOIG)

Here the machine has a wound rotor whose external resistances are replaced by electronic circuit consisting of a three phase rectifier and a line-commutated inverter. A microprocessor can be used to adjust the SCR-triggering for the most prevailing wind speed, thus allowing operation on the most efficient power-speed curve.

2.3.2: INDUCTION GENERATORS IN HYDROELECTRIC SCHEMES

Some installations using water-driven induction generators have been reported [2,5,6,27]. Tsao [2] mentioned that simplicity of operation of an induction generator driven by low-speed water turbines, makes an ideal small hydro-power sources for 1000 to 5000 kW. Allan [6] has described an installed system in Scotland and mentioned numerous advantages:

1) Use of induction generators produce savings in capital cost arising from omission of governor actuators, automatic voltage regulators, as well as control panels and associated wirings thereby resulting in less building space.
2) Absence of synchronous governing brings about saving in conduits and pipelines because of reduced pressure-change requirements. Control and operation are much simplified, so staff attendance and operational costs are reduced.
3) Low constructional works lead to low total generation costs.

2.3.3: STEAM/GAS TURBINES-DRIVEN INDUCTION GENERATORS

This scheme should be of interest in rural electrification schemes. Tsao [2] reported an installation where the machine is gas turbine-driven to provide an ideal low-cost power unit since both the turbine and the generator require simple auxiliaries. Bolin [16] described an installation where the generator is driven by a gas engine and concluded that the overall efficiency of an engine-driven induction generator for isolated operation is higher than an engine-driven synchronous generator. Further advantages given include, excellent gas engine efficiency, unattended operation and low cost.

2.3.4: CO-GENERATION APPLICATIONS

Whenever electricity is generated only a proportion of the primary fuel energy is converted into useful power, the rest is normally rejected to the environment as exhaust gas or hot water. Similarly, much of the heat produced in a boiler or furnace is lost to the atmosphere. The recovery of these otherwise waste heat to do other useful functions is termed "cogeneration". World-wide emphasis on energy conservation has led to the increasing use of cogeneration schemes in situations where there is requirement for process heat as well as electric power [17]. This has led to benefits in the form of energy conservation, environmental benefits and reduced fuel costs.

Induction generators have been used successfully in the process industries to utilise their waste energy. Azbill et al [17] listed the various areas where they may be used. These include:

1) Wind power systems

2) Small water wheel generators

3) Hydraulic turbines and centrifugal pumps power recovery from liquid high pressure process streams, instead of throttling with a control value.

4) Expander turbines for

   a) energy recovery on the downhill side of a natural gas pipeline.

   b) energy recovery during throttling of natural gas for reduction in-plant application.

   c) energy recovery while reducing high pressure steam to low pressure applications, instead of throttling.

   d) heat recovery string used with fluidized bed catalytic converters (FCC) in petroleum industries.

Richard [12] described some industrial uses for induction generators in the 300 kW to 1250 kW sizes. One is for recovery of compression heat from gases, as in cryogen producing plant using single-stage steam turbine. Advantages given include: easy maintenance, unattended operation, using proven governor and safety controls and compactness. Breedlove and Harbough [13] described a co-generation scheme in a FCC unit. Owen and Griffith [14] described a power recovery train in a FCC unit and used an induction motor/generator set instead of a synchronous motor generator set because the selection of control and protective equipment for a motor/generator can be as confusing as the normal accessories used with a synchronous generator.

Parson [15] described and compared a synchronous generator and an induction generator co-generation schemes. His study revealed clearly the dominance of induction generators as shown by the comparison of protective control of the two schemes, in table 2.1.

TABLE 2.1 : Comparison of Synchronous and Induction Generator Co-generation Schemes

	SYNCHRONOUS GENERATOR	INDUCTION GENERATOR
1	Phase differential relays	Self-balancing differential relays
2	Ground fault relays	Instantaneous ground fault relays

3	Time overcurrent ground fault relays	Lockout relays
4	Lockout relays	Instantaneous and time overcurrent relays
5	Voltage restrained time overcurrent relays	Reverse power relays
6	Negative phase sequence current relay	Negative phase sequence current relay
7	loss of excitation relay	Wattmeter
8	Reverse power relay	Varmeter
9	Voltage balance relay	Watt-hour meter
10	Bearing and winding RTD monitors	Ammeter
11	Synchronism check relay	
12	Synchroscope	
13	Bus and generator voltmeters	
14	Bus and generator frequency meters	
15	Wattmeter	
16	Varmeter	
17	Watt-hour meter	
18	Ammeter	

2.3.5: OTHER APPLICATION SCENARIO

Demello et al [19] advocated the use of induction generation at locations with substantial var support, and generation that must use a few lines of EHV underground transmission. Richardson [5] mentioned the use of induction generators as short reactors. which he said, arises if the rate of installation of leading current sources necessary to charge transmission lines is higher than that of a generating plant, which in turn leads to stability problems.

Wood and Mcnaull [38] considered the use of a drag-cup induction generator to provide a simple way to record angular acceleration, using a two phase induction generator with one winding taking dc excitation. Doxey [7] described an application in Missiles launching where the machine is ideal for such use since in the ground it acts as a motor and when airborne, as a generator. Mcconnel [3] has developed a scheme for aircraft application using induction generators with magnetic amplifier-voltage regulators.

2.4: DESIGN ASPECTS OF INDUCTION GENERATORS

Not much has been written on the design of induction generators; it seems to be generally taken for granted to follow that of induction motor. However, for efficient and reliable operation, certain design features have been put forward.

2.4.1: ROTOR DESIGN

Careful design of the rotor will result in many benefits in the overall performance of the system. The following considerations have been noted:

i) If the induction machine is only going to be generating, it could be designed with a low rotor cage resistance; providing extra efficiency at the sacrifice of normal motor acceleration torque [8,12,54]. Malik et al [22] advocated low rotor resistance because this leads to reduced frequency drop, higher terminal voltage and higher maximum power output.

ii) The rotor circuit has an effect on the transient performance of the machine [18,58] because it affects its damping characteristics. In another work Demello et al [19] concluded that double cage designs do not provide any advantage from a dynamic performance point of view.

iii) High-speed induction generators are limited by practical mechanical design of laminated rotor construction [8]. Moore [8] proposed high strength non-magnetic steel rings to bolster against undue stresses of centrifugal forces.

2.4.2: STATOR DESIGN

Stator design of induction generator has not received much attention. However, according to [2] increase in stator resistance causes more dropping load characteristic and decreases the maximum output power. Recently, Murthy et al [51] studied the effect of some design parameters (core length, number of stator turns, air-gap length, core materials and rotor material) on performance. One conclusion reached is that increased core length and stator turns cause reduction in capacitive requirements. However, it is not clear whether this refers to capacitive requirements for excitation or on loading.

2.4.3: DIMENSIONS AND SPEED

Say [54] treated the selection of dimensions to be based on runaway speeds up to three times normal; lesser diameter and longer axial length for a comparable motor. The rotor bars are of taper or sash-bar sections and strongly wedged to achieve good compactness and ventilation.

High speed has beneficial effect of resulting in higher power factor and efficiency [8]. Tooth pulsation loss may however increase with speed, but can be reduced using totally enclosed slots, magnetic edges for stator slots and relatively large air-gaps [2].

2.4.4: AIR-GAP

The selection of air-gap size is very important from different performance considerations. Richardson [5] mentioned that increase in air-gap reduces the power factor and increases the magnetising current. Murthy et al [22] gave some benefits of smaller air-gaps as higher terminal voltage, higher maximum output power and for CEIG, a decrease in the capacitance needed for self-excitation. However, smaller air-gaps raise the question of ventilation due to overheating from eddy currents set up in the stator flux and mmf distribution [5].

2.4.5: HARMONICS

Not much has been written on the subject of harmonics specifically applied to induction generators. Harmonics give rise to abnormal torque and produce mechanical vibrations which cause noise. Generally there are three main sources; space winding distribution harmonics, the slot permeance harmonics and saturation. As induction generators are continuously employed, this subject will no doubt be taken up.

2.4.6: HEATING AND VENTILATIONS

Electrical machines are made up of solid bodies which are composed of many parts having different heat conductivities. Heat has to be transferred to the air in air-ducts, to the air at the end windings and to the air at the cylindrical surface of the core iron. In induction generators the main heat source include:

1) STATOR CORE-END HEATING

This is most important in large machines of low number of poles and high values of stator ampere-turn per pole. Richardson [2] attributed a large percentage of this to the end-leakage fields, which have radial, axial and tangential components.

2) ROTOR SURFACE HEATING

These are caused by:

i) Flux tufting : Which according to Richardson [2] arise due to short air-gap in respect of slot width and slot pitch, which causes pole-face losses to be induced in the rotor surface due to the tufting of the flux under each of the stator teeth.

ii) Phase-band distribution [5]: Due to the spatial distribution of stator phase bands eddy currents are induced in the rotor surface while the stator windings are carrying currents.

iii) Slot ampere-turn concentration [5]:As slot pitch increases these losses increase rapidly and may impose careful selection of air-gap and number of slots.

iv) Stray losses [43]:These originate according to Jimoh et al [43] from magnetic property limitations of iron material, geometric structure of the machine and industrial imperfections. The stray losses are generally made up of two components:

a) Fundamental frequency components which originate from eddy current losses, leakage fluxes and skewing.

b) High-frequency components with origin from harmonics.

These losses could be reduced during the design process by using slot wedges and larger airgaps[43].

2.4.7: OTHER DESIGN CONSIDERATIONS

The above discussions point to the need of a comprehensive analysis of design aspects of induction generators. With large machines, the heating could be the deciding factor, while in other situations the dynamic or even steady-state performance may dictate the design. In conclusion, the ultimate design would be every design-engineers' dream: Optimum performance at a minimum cost.

2.5: ANALYSIS OF INDUCTION GENERATORS

The analysis of induction generators is usually performed along the same lines as that of induction motors. The techniques employed can be broadly categorised into:

i) equivalent-circuit analysis and (ii) generalised machine theory approach.

2.5.1 : EQUIVALENT-CIRCUIT ANALYSIS

The equivalent circuit shown in fig. 2.1 is the one generally used, with some simplifying modifications in accordance to the aim of the analysis. The power-system connected induction generator (PSCIG) has not received much attention; it is generally considered to be an induction motor driven above the synchronous speed [5,6,10]. The bulk of the considerations treated capacitor-excited induction generators (CEIG) and thyristor-controlled ones.

Wagner [29] used the equivalent circuit similar to that of fig. 2.1 to analyse a CEIG performance at no-load, three-phase and single-phase loading conditions. By summing separately, the real powers and imaginary powers (reactive power) in the whole network including the load, two equations resulted which, because of saturation, can be solved by cut-and-try method [29]. For single-phase loading, symmetrical components method was used to arrive at performance prediction. Watson and Milne [29] also used the equivalent circuit to study autonomous and paralleled operations of CEIG. Two useful results were presented; a criteria for voltage sustainance at no-load and when loaded, and an optimum load sharing strategy for parallel generators.

Malik et al [22] undertook a steady-state analysis of CEIG using Newton-Raphson method to find the terminal voltage and frequency for a given capacitance, speed and load conditions. The operational equivalent circuit used is shown in fig. 2.5.

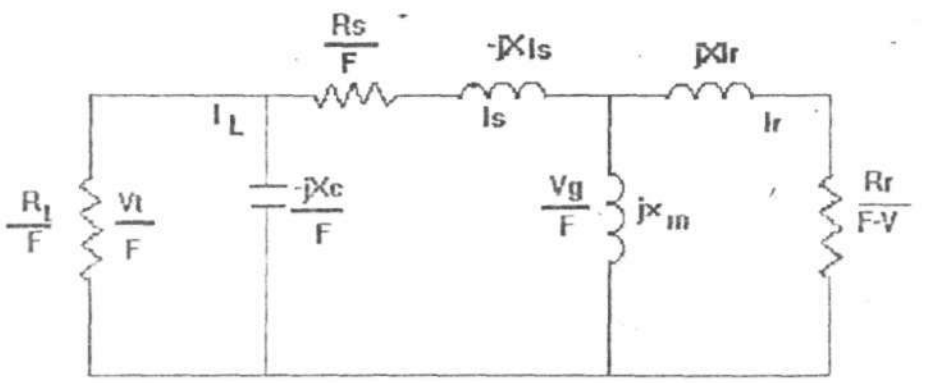


Fig. 2.5 : Steady-state operational equivalent circuit under load [22]

By neglecting the core-loss and considering that only the magnetising is affected by saturation, the close-loop operational impedance, Z_s from fig. 2.7 is given by

$$Z_s = \frac{-jX_c R_L / F^3}{R_L / F - j(X_c / F^2)} + (\frac{R_s}{F} + jX_{ss}) + \frac{jX_m\left(\frac{R_r}{F - V} + JX_{sr}\right)}{\frac{R_r}{F - v} + j(X_m + X_{Lr})} \quad (2.2)$$

Since there is no external source,

$$ZsIs = 0 \quad (2.3)$$

By noting that at steady-state Is is not zero then Zs must be zero which leads to the real and imaginary parts of equation (2.2) to be zero separately. Equating them to zero yielded two equations which were then solved by Newton-Raphson technique [22]. Macpherson and Quazane [21] analysed their machine in practically the same manner. A useful power-flow diagram was included which is reproduced in fig. 2.6 [21].

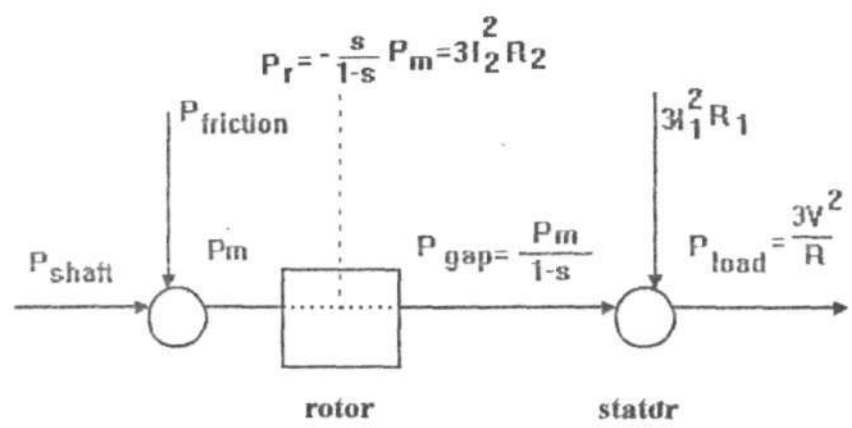


Fig 2.6: Power flow in induction generator

Malik and Raina [20] analysed a wind-energy conversion scheme incorporating models of the wind-turbine, the induction machine, a controlled converter and a bridge rectifier. The use of the electronics components necessitate the need of carrying a harmonic analysis to study their effects on performance. In the harmonic analysis, the system was represented as shown in fig. 2.7, with n denoting the order of the harmonic. I_{nic} and I_{L1} are the rectifier bridge and converter currents respectively.

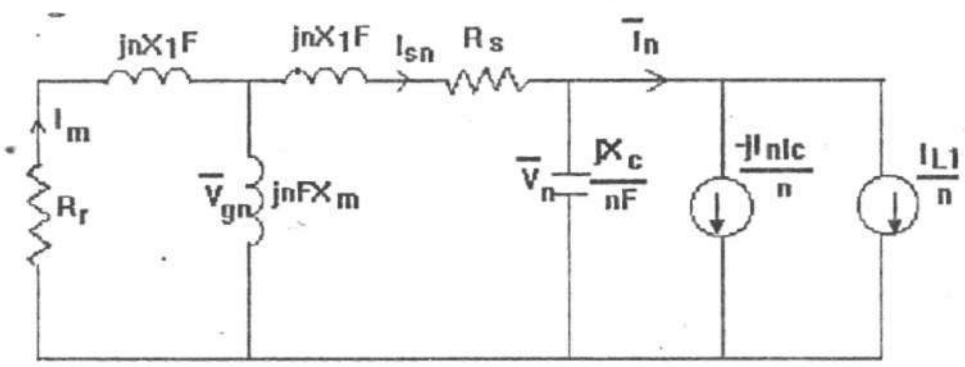


Fig 2.7 : Steady-state harmonic equivalent circuit of induction generator

Tandon et al [44] carried out a steady-state analysis in line with that of [22]. The exception is that use was made of a positive.- sequence operational equivalent circuit shown in fig. 2.8.

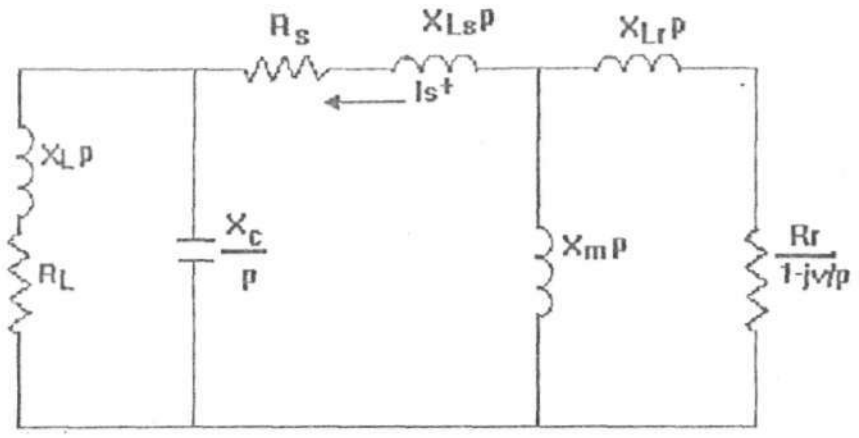


Fig 2.8 : Positive sequence operational equivalent circuit of induction generator

The current I_s^+ is the instantaneous positive sequence stator current related to the winding currents Isa, Isb and Isc by

$$I_s = \frac{1}{\sqrt{3}}\left(I_{sa} + aI_{sb} + a^2 I_{sc}\right) \tag{2.4}$$

Where $a = e^{j\frac{2\pi}{3}}$

The close-loop operational impedance ,from fig.2.8 was found to be:

$$Z_s = \frac{(Xmp[X_{lr}p + \frac{R_r}{1 - jv/p}])}{X_m + R_r\left(1/(1 - V/p)\right) + X_{Lr}p} + R_s + X_{Ls}p + \frac{\left(R_L + X_l p\right)X_c/p}{R_L + X_L p + X_c/p} \tag{2.5}$$

which upon equating to zero gave a fourth-order characteristic equation whose roots were found repeatedly by decreasing Xm until a root was found which gave zero. This root was then used on the imaginary axis to determine the steady-state output frequency, and other calculations followed. Malik and Hague [39] followed the same procedure but included the core-loss as a resistance in parallel with the magnetising reactance. Of importance, was considerations for designing static exciters of the type shown in fig. 2.9, i.e. fixed-capacitor-thyristor controlled reactor (FC-TCR), for voltage control. θ in the figure is the firing angle of phase controlled indicator of the static exciter.

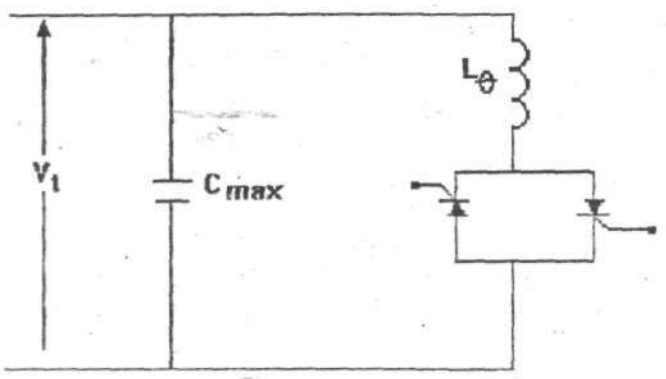


Fig 2.9 :Basic diagram of FC-TCR exciter

Malik and Mazi [25] assessed the capacitive requirements using similar models of fig. 2.5 and fig. 2.8. Similar considerations as in [22] were followed to arrive at these two equations:

$$P(X_m, F) = A_1F^3 + A_2F^2 + A_3F + A_4 = 0 \qquad (2.6)$$

$$Q(X_m, F) = B_1F^4 + B_2F^3 + B_3F^2 + B_4F + B_5 = 0 \qquad (2.7)$$

Where

$$A_1 = (a_1 X_m + a_2) \qquad A_2 = (a_3 X_m + a_4) \qquad A_3 = (a_5 X_m + a_6)$$

$$A_4 = (a_7 X_m + a_8)$$

$$B_1 = (b_1 X_m + b_2) \qquad B_2 = (b_3 X_m + b_4) \qquad B_3 = (b_5 X_m + b_6)$$

$$B_4 = (b_7 X_m + b_8) \qquad B_5 = (b_9 X_m + b_{10})$$

The minimum capacitance needed for self-excitation was then calculated by assuming a value for it and then solving equations (2.6) and (2.7) for Xm and F numerically. The process was repeated by gradually decreasing the capacitance and plotting Xm us C from which the minimum capacitance was found. Another procedure given was to use the operational equivalent of fig. 2.8 to obtain a characteristic equation and the solution proceeded as in [44].

Doxey [7] used a modified equivalent circuit, in which the magnetising branch was at the machine terminals to simplify the calculations. Two equations were obtained in a manner similar to that of Wagner [29] to calculate the slip and the terminal voltage. Of interest here, is the inclusion of saturable reactors (represented as non-linear inductors) to improve the voltage regulation. The use of star-delta connected reactors to cancel some predominant harmonics was also considered.

The analysis of Barkle and Ferguson [4] was also with the use of equivalent circuit. A modified synchronous machine. transient theory was used to study the process of self-excitation. They gave the basic equation:

$$e + T_0 \frac{de'}{dt} = 0 \qquad (2.8)$$

where

e = Per-unit voltage that will be induced in the steady-state conditions for zero stator current and a rotor current equal to the instantaneous value of rotor current.

e'= Per-unit voltage at terminal of machine if the stator current were suddenly made zero and is proportional to the rotor flux linkages.

T_o = Open-circuit time constant of rotor , $T_o = \frac{x_r + x_m}{\omega r_r}$

starting from equation (2.8) and for any loading conditions, the equation for the terminal voltage could be derived to show decay or increase [4]. Further analytical expressions to find the self-excitation region in terms of real and imaginary power plots were given.

Arrilaga and Watson [11] analysed an induction machine with static power converters (three-phase, six pulse bridge rectifiers) used in order to eliminate frequency problems. Novotny et al [23] studied an induction machine solely excited by voltage source inverters. The modelling include both the equivalent circuit and the generalised theory ($\alpha - \beta$) approaches.

Recently, Murthy et al [51] highlighted a steady-state analysis taking into account the magnetisation (B/H) curve to represent the magnetising reactance. Also included, was computer algorithm to simulate the effects of some design parameters on performance. Bhattacharya and Woodward [52] used symmetrical component method together with the standard equivalent circuit to compute voltage regulation and derating factors under single-phase loading of the machine. One interesting conclusion reached was that single-phase loading is possible and what is termed C-2C-ZERO (one-unit capacitance across two lines, two-unit capacitance across the two remaining lines) improves derating factor without any effect on the machine [52].

2.5.2: GENERALISED THEORY ANALYSIS

From earlier considerations, it appears that a sizable number of publications treated steady-state analysis or approximate transient-analysis based on the equivalent circuit of the machine. Past attempts at using the generalised-machine theory include that of Sriharan and Smith [33], where a d-q reference frame fixed to the stator was used. Of interest was the inclusion of saturation by a coupling term in both axes. In [53], synchronous reference frame model was used then later simplified using singular perturbation theory.

Other notable considerations, though for induction motor operation have been made. Analogue computers have been used to solve the dq reference frame equations by, for example, Demello and Watsh [31], Hughes and Aldred [32], Krause [40], Jordan [41], Lawrenson and Stephenson [50]. Digital computers have been applied in [30,33,34,42]. With little modifications these approaches could be

applied in induction generator analysis. In the near future this would have to be considered as recent developments [53,64] have indicated.

2.6 : RECENT PUBLICATIONS

Recent work into induction generator indicate trends towards performance considerations. In [70], Malik et al, analysed a steady-state model of induction generator including core-loss. Using Newton-Raphson technique, it was shown that capacitive requirements increases with decrease in speed, load impedance and load power factor. They also advocated the use of a fixed-capacitor thyristor control reactor (FC-TCR) as an easy way of having smooth variations of terminal capacitance. S.S.Murthy et al [71] studied the effects of the variation of the system conditions on the performance of grid-connected induction generators and assessed their stability for such applications. Using four machines of different rating for an 11-kV grid system, effect of grid voltage, grid frequency, power input and the value of terminal capacitance on the system efficiency, power factor, machine copper loss were studied. Important observations made include:

i) Deterioration of performance due to fluctuations in grid voltage and frequency is not very appreciable.

ii) By connecting a terminal capacitor of suitable value the system power factor can be improved to about 0.95 at nominal power input, with further improvement in system efficiency.

iii) Induction generators can be used with varying power input (as with a wind turbine), with maximum power being limited by machine capacitance.

iv) There is a possibility of self-excitation if the machine is disconnected from the grid coupled with over-speeding, thus necessitating appropriate protection.

Al Jabir and Alolah [73] used "operational equivalent circuit" model of an induction generator to study variations of voltage and power for wide range of varying elements (speed, terminal capacitance and load impedance). From their modelling, they concluded that there is an optimal choice of speed, terminal capacitance and load impedance values that gives maximum output power.

Along the same line, S.P.Singh, B. Singh, and M.P. Jain [74] investigated self-excited induction generator to obtain performance characteristics, capacitive var requirements, number of capacitor steps for a given specific voltage limit and optimum capacity utilization of the machine, using Newton-Raphson algorithm and steady-state equivalent circuit. Single variable optimization approach was used to select the optimum voltage corresponding to maximum output of the machine for its optimum utilization. Their study showed that the optimum voltage is slightly less than the rated voltage of the machine, and also there is a possibility of producing output power greater than the rated power for a wide range of terminal voltage.

An unusual operating condition was presented by Al-Bahrani and Malik [75] where the induction generator is excited with only one capacitor and a single-phase load is connected across this excitation capacitor. Using an equivalent circuit model, it was shown that for this mode of operation, there are certain ranges over which the

values of terminal capacitance, machine speed and load impedance have to be kept in order to maintain self-excitation. It was also shown that the terminal capacitance has the strongest influence on the performance.

The subject of transient behaviour upon connecting an induction generator from the power grid was studied in [72]. It was shown that the degree of terminal compensation determines the transient nature and final steady-state voltages, currents, and rotational speeds. As observed in [71], the paper recommended voltage relays in combination with overspeed relays properly coordinated to protect against the over-voltages and overspeed that results.

A transient model of an induction generator was presented in [76] by Hallerius et al. the theory of saturated smooth-air gap machine was applied to analyse the transient performance. Use is made of saturated magnetising inductance,

$$L_m = \frac{|\psi_m|}{|\bar{I}_m|} \quad \text{and its derivative} \quad \frac{dL_m}{d|\bar{I}_m|} \tag{2.9}$$

using the general machine equations, self-excitation, switching-in of resistive load and series RL. load were studied. The model compared very well with practical tests.

CHAPTER 3

MODELLING OF INDUCTION GENERATOR

3.1: INTRODUCTION

Following the review of the last chapter, the model of the induction generator will now be presented. The machine equations will be developed using the generalised theory approach including where appropriate the unique nature of induction generator.

3.2: PROPOSED MODEL

The model proposed here for the study of the self-excitation in induction generators is based on the work of Krause and Thomas [40], and Ojo et al. [65] with their considerations confined to motoring mode. By adopting a technique in line with their approach and introducing appropriate changes to accommodate the induction generator self-excitation process a model will be developed, which can then be subjected to various operating conditions.

3.2.1: ASSUMPTIONS AND BASIC EQUATIONS

The machine is a polyphase symmetrical type with the following assumed features [40]:

1) uniform air-gap

2) linear magnetic circuit

3) identical stator windings, distributed so as to produce a sinusoidal mmf wave in space with the phases so that only one rotating mmf wave is established by balanced stator currents .

4) rotor coils or bars arranged so that, for any fixed time, the rotor mmf wave can be considered to be a space sinusoid having the same number of poles as the stator mmf wave.

Such an indealised machine is enough to predict the transient self-excitation performance of an induction generator but certain important factors which affect an actual machine have been left out. These include:

1) Saturation effects

2) Temperature effects

3) Harmonic content of the mmf wave.

It will be shown later in the chapter how to include saturation effects in the model.

A symmetrical 3-phase induction machine is as shown in fig 3.1.

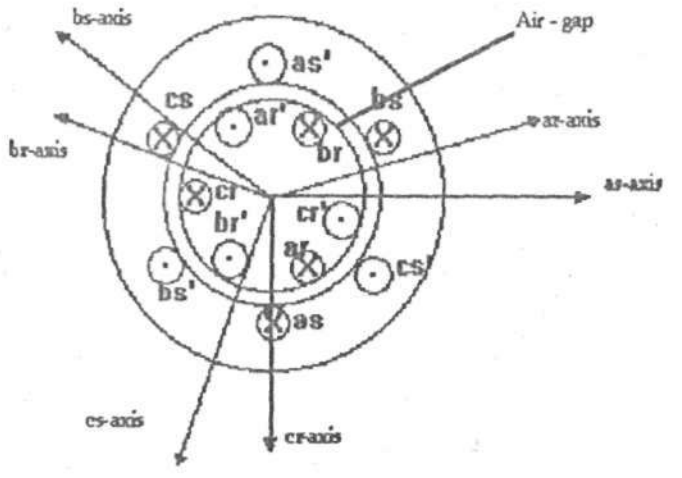


Fig.3.1: A 2-pole , 3-phase symmetrical Induction macine

Due to sinusiodal variations of mutual waves with respect to displaced angle θ_r, time varying coefficients will appear in the voltage equations. These can be eliminated by transforming the machine into an equivalent d-q form in which these coefficients are eliminated. A d-q equivalent of the machine is shown in fig.3.2 [77].

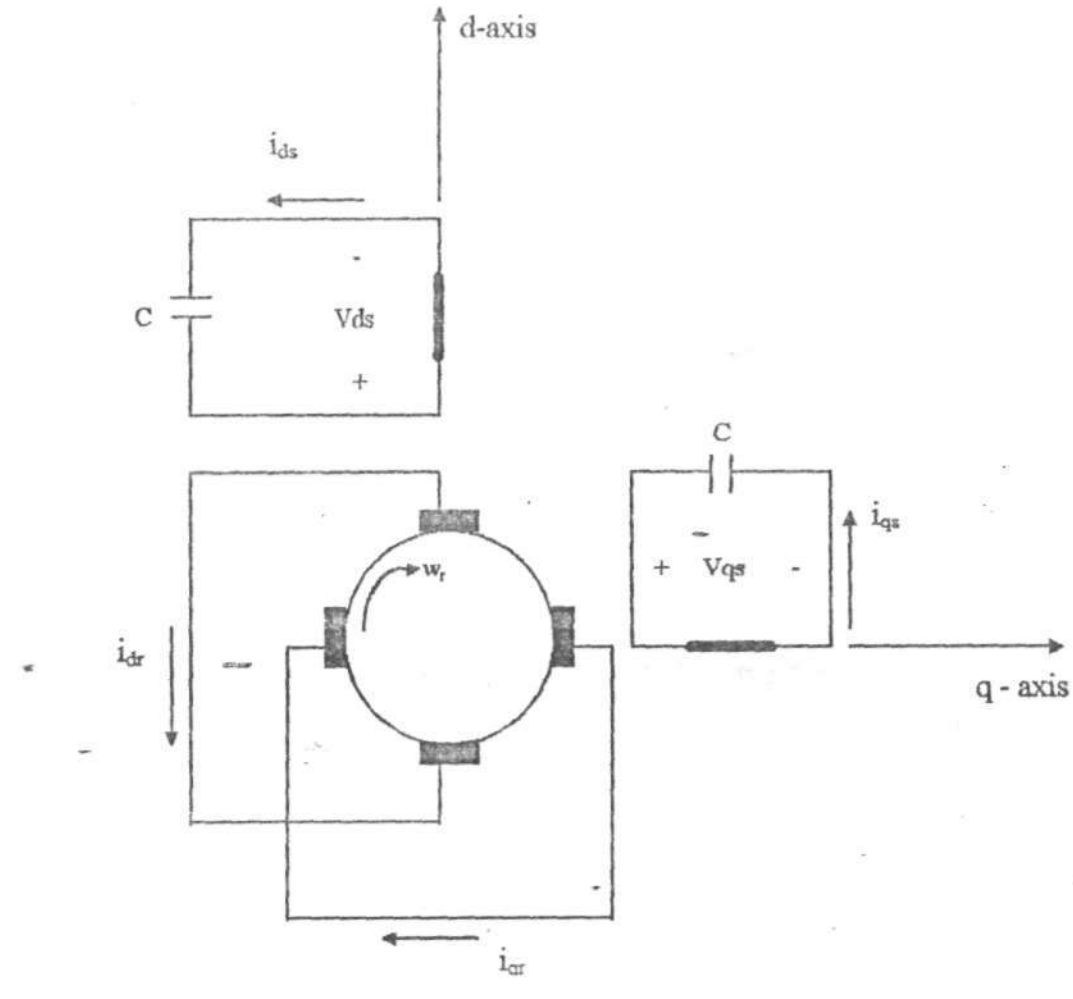


Fig. 3.2 : The self-excited induction generator in stationary reference frame

The basic equations can be developed by first looking at Krause's d-q equivalent circuit which is shown in fig. 3.3 in arbitrary reference frame:

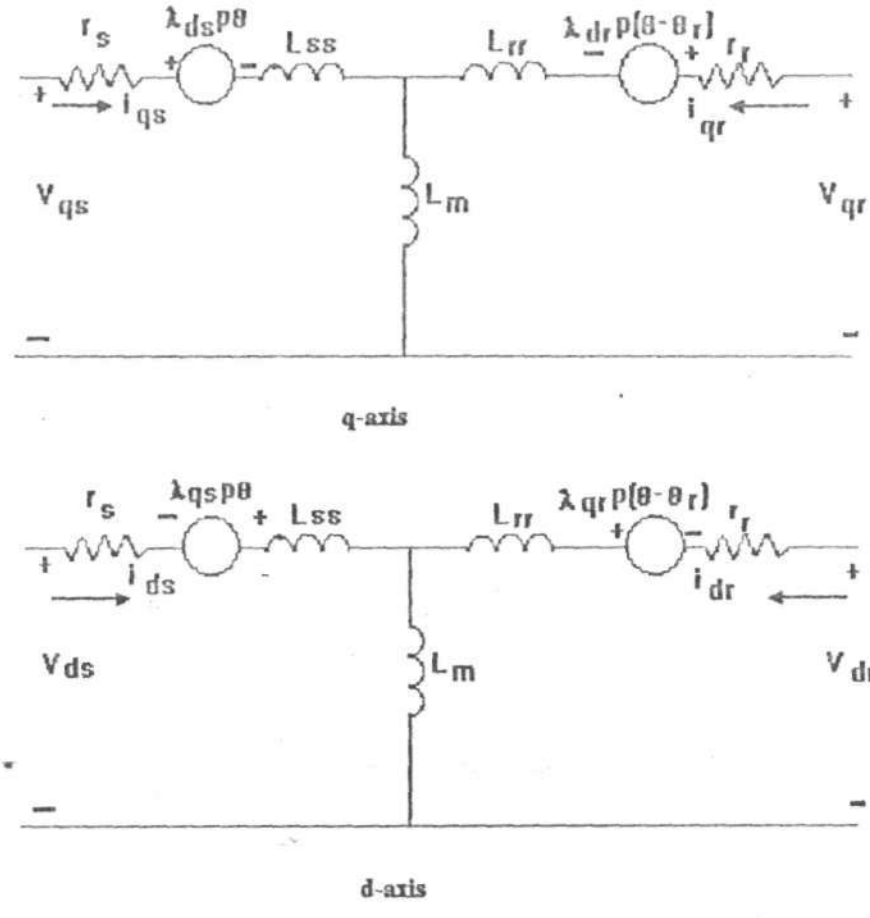


Fig. 3.3: The D and Q equivalent circuit of symmetrical induction machine, arbitrary reference frame[40].

By looking at this equivalent circuit, it is obvious that it is made assuming the machine to be operating as a motor. Based on physical reasoning of induction generator operation [47,48] the following equivalent circuit is proposed as shown in fig. 3.4.

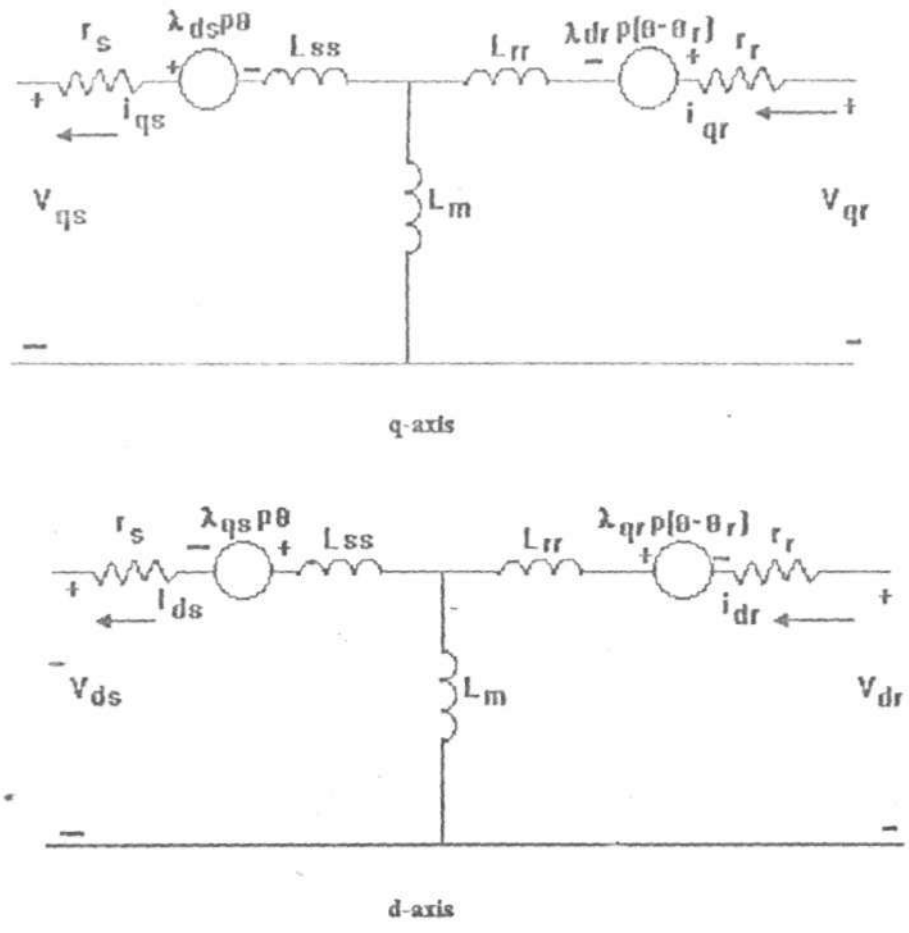


Fig. 3.4: D and Q equivalent circuit of induction generator in arbitrary reference frame.

From the equivalent circuit, the following equations can be derived in arbitrary reference frame:

$$p\lambda_{qs} = v_{qs} + r_s i_{qs} - \lambda_{ds} p\theta \tag{3.1}$$

$$p\lambda_{ds} = v_{ds} + r_s i_{ds} + \lambda_{qs} p\theta \tag{3.2}$$

$$p\lambda_{qr} = v_{qr} - r_r i_{qr} - \lambda_{dr} p(\theta - \theta_r) \tag{3.3}$$

$$p\lambda_{dr} = v_{dr} - r_r i_{dr} + \lambda_{qr} p(\theta - \theta_r) \tag{3.4}$$

where the flux linkages are defined by:

$$\lambda_{qs} = -L_{ss} i_{qs} - L_m (i_{qs} - i_{qr}) \tag{3.5}$$

$$\lambda_{ds} = -L_{ss} i_{ds} - L_m (i_{ds} - i_{dr}) \tag{3.6}$$

$$\lambda_{qr} = +L_{rr} i_{qr} - L_m (i_{qs} - i_{qr}) \tag{3.7}$$

$$\lambda_{dr} = +L_{rr} i_{dr} - L_m (i_{ds} - i_{dr}) \tag{3.8}$$

The instantaneous electromagnetic torque is given by:

$$T_e = (3/2)(P/2)(\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}\} \tag{3.9}$$

and, in order to obtain the dynamic characteristic, the torque-speed relation is given by:

$$Jp\omega_r = (P/2)(T_e - T_m) \tag{3.10}$$

Thus, equations (3.1) to (3.10) form the basis for the solution of self-excitation phenomena in induction generators. For easier convergence in a computer simulation however, it is desirable to express these equations in per unit.

3.2.2: EQUATIONS IN PER-UNIT

If we multiply equations (3.1) to (3.10) by the base electrical angular velocity, ω_e and then define our base quantities as given in Appendix 1; The following equations results in per unit [66].

$$p\psi_{qs} = \omega_e (v_{qs} + r_s\, i_{qs} - \psi_{ds}\omega_s) \tag{3.11}$$

$$p\psi_{ds} = \omega_e (v_{ds} + r_s\, i_{ds} + \psi_{qs}\omega_s) \tag{3.12}$$

$$p\psi_{qr} = \omega_e (v_{qr} - r_r\, i_{qr} - \psi_{dr}(\omega_s - \omega_r)) \tag{3.13}$$

$$p\psi_{dr} = \omega_e (v_{dr} - r_r\, i_{dr} + \psi_{qr}(\omega_s - \omega_r)) \tag{3.14}$$

solving equation (3.5) to (3.8) for the currents we get:

$$i_{qs} = -\frac{\psi_{qs} + \psi_{mq}}{X_{ss}} \tag{3.15}$$

$$i_{ds} = -\frac{\psi_{ds} + \psi_{mq}}{X_{ss}} \tag{3.16}$$

$$i_{qr} = \frac{\psi_{qr} + \psi_{mq}}{X_{rr}} \tag{3.17}$$

$$i_{dr} = \frac{\psi_{dr} + \psi_{mq}}{X_{rr}} \tag{3.18}$$

where

$$\psi_{mq} = X_m(i_{qs} - i_{qr}) \tag{3.19}$$

$$\psi_{md} = X_m(i_{ds} - i_{dr}) \tag{3.20}$$

From equations (3.15) to (3.20) ψ_{mq} and ψ_{md} can be written as:

$$\psi_{mq} = -X_{mq}(\frac{\psi_{qs}}{X_{ss}} + \frac{\psi_{qr}}{X_{rr}}) \tag{3.21}$$

$$\psi_{md} = -X_{md}(\frac{\psi_{ds}}{X_{ss}} + \frac{\psi_{dr}}{X_{rr}}) \tag{3.22}$$

where

$$X_{mq} = X_{md} = \frac{1}{(\frac{1}{X_{ss}} + \frac{1}{X_{rr}} + \frac{1}{X_m})} \tag{3.23}$$

The per-unit torque equation now becomes:

$$T_e = \frac{P}{2}\frac{1}{\omega_e}(\psi_{qr} i_{dr} - \psi_{dr} i_{qr}) \tag{3.24}$$

and the per-unit dynamic equation is now:

$$p\omega_r = \frac{(T_e - T_m)}{2H} \tag{3.25}$$

Thus, equations (3.11) to (3.25) constitute the basis of computer analysis of self-excitation of induction generators. The only variables yet to be defined are the terminal voltages which depend on the type of machine problem to be studied.

An independent voltage source which is present and needed for self-excitation is the internal residual voltage [47,48], which is given by [48]:

$$v_{qsr} = k_{oc}\, \omega_r \sin(\omega_r \omega_e t) \tag{3.26}$$

$$v_{dsr} = k_{oc}\, \omega_r \cos(\omega_r \omega_e t) \tag{3.27}$$

where $w_e t$ is the per-unit value of time [66].

Equations (3.26) and (3.27) suggest that the internal voltage is a function of speed and magnetic properties of the machine.

For a machine excited from the stator terminal voltages are given by:

$$v_{qs} = v_{qsr} + v_{qc} \tag{3.28}$$

$$v_{ds} = v_{dsr} + v_{dc} \tag{3.29}$$

.where

$$pv_{qc} = \omega_e X_c\, i_{qs} \tag{3.30}$$

$$pv_{dc} = \omega_e X_c\, i_{ds} \tag{3.31}$$

Equations (3.30) and (3.31) must be incorporated in the computer solution of the problem.

3.2.3: SATURATION EFFECTS

The linear model developed in the earlier section is enough for the study of self-excitation phenomena, as past considerations [7,22,23,24,29,44,46,47,48] have all agreed that saturation came into effect well after build-up has occurred. However, effects of saturation can be included by using the technique of saturation factors [31,60] where it is assumed only the main flux paths are saturated. The saturation curve of the induction machine is obtained from the no-load test .Under that condition , the effect of rotor circuit is very negligible leaving only the stator leakage and the magnitising branch to contribute to the excitation characteristics (see fig.5.2)

The stator leakage-flux path is largely air and therefore its associated reactance is linear. The air-gap flux common to both rotor and stator is largely contained in the stator and rotor magnetic steel. The magnetising reactance , Xm , due to this flux has a non-linear region as dictated by the magnetic saturation characteristics of the steel in the composite air-steel magnetic circuit.

The reactance associated with any given point on the magnetisation curve is proportional to the slope of a line from the origin through the given point. The reactance of the linear portion is Xm. ′Consequently , the reactance X'_m of any given point on the magnetisation curve may be expressed as :

$$X'_m = KX_m$$

where

$$K = \frac{\text{Slope of X'm line}}{\text{Slope of line from origin through that point}}$$

Figs.5.2 and 5.3 show the magnetising reactance curve along with its ' saturation factor ' curve K. Another definition of saturation factor K is given by Leander[77] uses the potier reactance, and is defined as " ratio of the resultant mmf for the air-gap plus iron to that for the air-gap alone under the magnetic conditions determined by the potier voltage ."

Using this technique, equations (3.21) and (3.22) become:

$$\psi_{mq} = -KX_{mq}\left(\frac{\psi_{qs}}{X_{ss}} + \frac{\psi_{qr}}{X_{rr}}\right) \tag{3.32}$$

$$\psi_{md} = -KX_{md}\left(\frac{\psi_{ds}}{X_{ss}} + \frac{\psi_{dr}}{X_{rr}}\right) \tag{3.33}$$

K is the saturation factor defined by :

$$K = \frac{X'_m}{X_m} \tag{3.34}$$

With K plotted as a function of the per unit total magnetising flux linkage, ψ_m we have a "saturation factor curve" from which different values of K can be interpolated to follow the saturation curve of the machine during the integration. The procedure is that at each step find.

$$\psi_m = \sqrt{\psi^2_{mq} + \psi^2_{md}} \tag{3.35}$$

and then adjust Xmq and Xmd using K Vs Ψm curve

3.2.4: EQUATIONS IN REFERENCE FRAME ATTACHED TO THE STATOR

If we attach the reference frame to the stator the following equations results:

$$p\psi_{qs} = \omega_e(v_{qs} + r_s\, i_{qs}) \tag{3.36}$$

$$p\psi_{ds} = \omega_e(v_{ds} + r_s\, i_{ds}) \tag{3.37}$$

$$p\psi_{qr} = \omega_e(v_{qr} - r_r\, i_{qr} + \psi_{dr}\omega_r) \tag{3.38}$$

$$p\psi_{dr} = \omega_e(v_{dr} - r_r\, i_{dr} - \psi_{qr}\omega_r) \tag{3.39}$$

$$p\omega_r = \frac{(T_e - T_m)}{2H} \tag{3.40}$$

$$T_e = \frac{P}{2}\frac{1}{\omega_e}(\psi_{qr}\, i_{dr} - \psi_{dr}\, i_{qr}) \tag{3.41}$$

$$i_{qs} = -\frac{\psi_{qs} + \psi_{mq}}{X_{ss}} \tag{3.42}$$

$$i_{ds} = -\frac{\psi_{ds} + \psi_{mq}}{X_{ss}} \tag{3.43}$$

$$i_{qr} = \frac{\psi_{qr} + \psi_{mq}}{X_{rr}} \tag{3.44}$$

$$i_{qs} = \frac{\psi_{dr} + \psi_{mq}}{X_{rr}} \tag{3.45}$$

$$\psi_{mq} = -X_{mq}\left(\frac{\psi_{qs}}{X_{ss}} + \frac{\psi_{qr}}{X_{rr}}\right) \tag{3.46}$$

$$\psi_{md} = -X_{md}\left(\frac{\psi_{ds}}{X_{ss}} + \frac{\psi_{dr}}{X_{rr}}\right) \tag{3.47}$$

$$X_{mq}' = X_{md} = \frac{1}{\left(\frac{1}{X_{ss}} + \frac{1}{X_{rr}} + \frac{1}{X_m}\right)} \tag{3.48}$$

Equations 3.36 to 3.48 will be used in the next chapter to develop computer programs required for the simulations.

CHAPTER 4

COMPUTER SIMULATIONS

4.1: INTRODUCTION

In this chapter, the various simulations carried out using the developed model are presented. The machine parameters were obtained from [67] and converted into per unit.

4.2: COMPUTER PROGRAMS

Equations (3..376) to (3.48) are used to develop computer programs necessary to carry out the simulations. All the programs were developed using TURBO-PASCAL and are reproduced in Appendix 2. They include:

i) SATFAC - a program to calculate and plot the curve from the no-load test carried out and also saturation factor curve.

ii) The main program for the solution of the equations and comprises of the following:

a) Runge-Kutta integration Routine for solution of initial value problems.

b) A spline interpolation routine [69].

4.3: SIMULATIONS STUDY

In this section, the various simulations carried out are described together with the necessary conditions to establish that particular operating condition.

4.3.1: EXCITATION WITH CAPACITORS ON THE STATOR SIDE

This is the usual method of exciting an induction generator, as in most cases the stator terminals are the ones most easily available. For this condition the rotor voltages are zero, that is:

$$v_{qr} = v_{dr} = 0 \tag{4.1}$$

i) EFFECT OF CAPACITANCE

From theory [48] we know that for self-excitation to occur,

$$\frac{\omega_o}{\omega_r} < 1 \tag{4.2}$$

where

$$\omega_o = \sqrt{\frac{X_c}{(X_m + X_s)}} \tag{4.3}$$

that is we must have enough capacitance connected. So we try simulation with small value of capacitance (so that $\frac{X_c}{(X_m + X_s)} > 1$),and fig. 4.1 a,b,c d, and e show the result. These results indicated that the no build-up can occur if the capacitance is small. The

oscillatory results of figs.4.1a,b, and c come from the residual magnetic system of the machine.

Next we simulate with enough capacitance (so that $\frac{X_c}{(X_m + X_s)} < 1$ and fig. 4.2 a,b,c,d and e show the result. These results clearly confirm the occurrence of self-excitation though in unbounded manner, because as mentioned earlier it is saturation which limits the growth of the machine voltages and fluxes. Of particular interest are figs 4.2 d, and e which showed the rotor speed and electrical torque variations respectively. They are indication of the fact that for constant speed operation, the induction generator needs a prime mover whose torque increases as the speed falls.

ii) EFFECT OF SERIES LOAD

To include the effect of load which is in series with the stator resistance Rs, we add R_L to Rs in equation (3.36) and (3.37). Figs 4.3 a,b, show the result when R_L of 1.0p.u. is added. The curves indicate possibility of current and voltage build-up but due to the presence of the series resistance the self-excitation failed to occur. The results then clearly indicate the need for proper selection of connecting cables between the generator and the capacitors. Figs 4.4c,and d show the result with Rl of 0.5 p.u. Though the build-up has occured it can be seen that the time to reach the same values of fig. 4.2 a and b is longer. That is the resistors have increased the effective time constant of the system. Note that only Vqs and Iqs results are included.

4.3.2: EXCITATION WITH CAPACITORS ON THE ROTOR SIDE

This is a theoretical investigation to see the effect of connecting capacitors on the rotor side. The stator conditions to be considered are stator open, connected to a resistive load and then connected to a capacitor load.

To simulate the case when the stator is open we let Rs $\longrightarrow$ ∞ in equations (3.36) and (3.37) and for the rotor side we have:

$$pv_{qr} = \omega_e X_{cr}\, i_{qr} \qquad (4.4)$$

$$pv_{dr} = \omega_e X_{cr}\, i_{dr} \qquad (4.5)$$

Fig 4.4 shows the result when the stator is open. The responses are highly unstable indicating probability of blow-up of the machine if such a situation is to be attempted. It should be noted that from fig 4.4a the terminal voltage remains very small and $i_{qs} = 0$.

For the case of stator terminated with a resistance R_L the following equations are used:

$$v_{qs} = R_L\, i_{qs} \qquad (4.6)$$

$$v_{ds} = R_L\, i_{ds} \qquad (4.7)$$

Fig 4.5 shows the result.The same situation of unstable operation are presented only in figs 4.4a to e.

For the case of stator having terminal capacitance we have:

$$pv_{qs} = \omega_e X_{cs}\, i_{qs} \qquad (4.8)$$

$$pv_{ds} = \omega_e X_{cs}\, i_{ds} \qquad (4.9)$$

Fig 4.6 shows the result The same situation of instability are indicated. Note also that there is great deal of difference to the response of when we had resistive load connected to the stator.

4.4 : SATURATION

Case i of section 4.3.1 was tried and fig 4.7 indicates the effect. The results clearly confirm the self-excitation phenomena in which saturation plays a significant role. The voltage Vs (fig 4.7a) is seen to build-up and is bounded; the same thing with the current but it is accompanied with spikes due to non-linear effects. The nature of the speed and torque responses indicate that the speed falls after the self-excitation and the torque contains a large amount of torque spikes which will later be damped.

CHAPTER 5

TESTS AND MEASUREMENTS

5.1: INTRODUCTION

In this chapter, the various experiments carried out are presented. Details of apparatus and procedures are omitted because they conform to standard cases.

5.2: SATURATION CURVE AND CONSTANTS K

No-load test was carried out in-order to obtain the saturation curves of the two machines. The results obtained were plotted as shown in figures 5.1 and 5.2.

Also at open circuit with the machines running at their sychronous speed, the constant K was measured for each one and is recorded on each curve of saturation.

5.3: EXPERIMENTAL VERIFICATIONS

Due to lack of suitable measuring instruments the model developed could not be fully verified experimentally. To obtain results that could be convincing, a set-up similar to the one shown in fig 5.5 is needed, which is obviously for a wound-rotor machine.

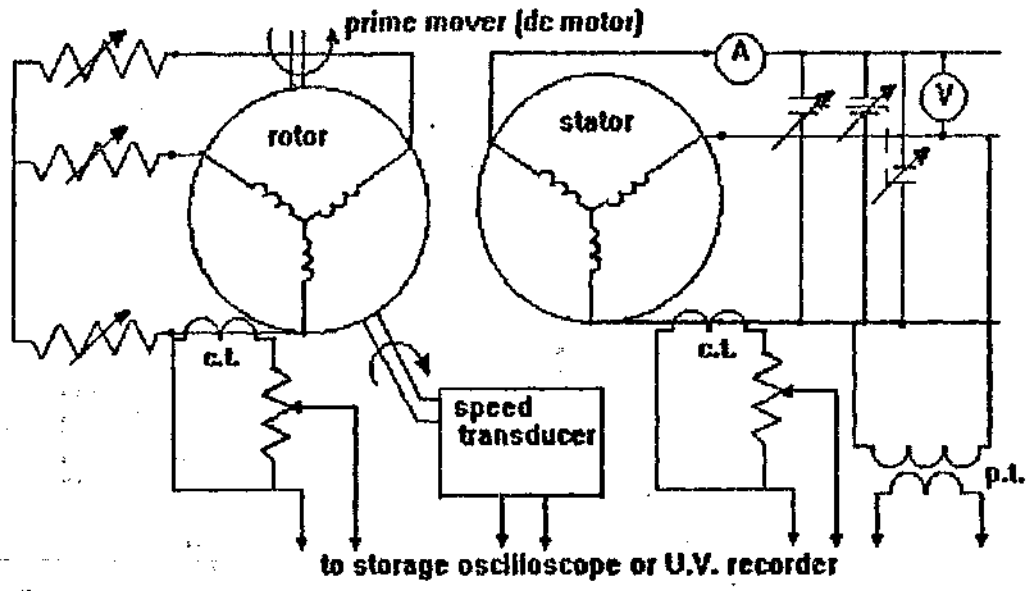


Fig. 5.5 : Experimental set-up for the study of self-excitation phenomena of induction generator

Measurements were taken of the current in phase a, the line-to-phase voltage Vab and the rotor current (in the case of wound rotor. machine). a UV recorder was used but the outputs were too faint to be presented directly or reproduced for this report. Consequently a digital storage oscilloscope was then used to observe the results where upon most of the results of the previous chapter were observed. It should also be noted that due to lack of a suitable speed transducer the transient build up of the speed was not observed. But

a) The initial self-excitation process was recorded.

b) After build up, the speed of the machine was reduced until excitation failed.

These measurements were carried out using a digital frequency meter, voltmeter and an analogy tachometer.

The procedure is that after build-up, machine speed is reduced until excitation failed.

The following tables show the result obtained for the measurement carried out after build-up..

TABLE 5.1 : Experimental Results - Generated Voltage vs Speed -Squirrel - Cage Induction Generator

SQUIRREL-CAGE MACHINE

CAPACITANCE =34mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
210	50	1510
185	47	1420
150	44	1345
116		

CAPACITANCE = 51mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
250	51	1520
220	47	1505
160	49	1410
140	39	1170

CAPACITANCE = 68mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
280	52	1565
270	51	1535
255	49	1525
230	45	1495

CAPACITANCE = 85mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
265	51	1550
243	49	1505
180	39	1170
120	31	900

TABLE 5.2 : Experimental Results - Generated Voltage vs Speed -Wound -Rotor Induction Generator

WOUND-ROTOR MACHINE

CAPACITANCE = 34mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
210	50	1000
180	48	945
140	45	930
stall	39	800

CAPACITANCE = 51mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
230	50	1000
215	49	960
185	45	920
165	42	890

CAPACITANCE = 68mF

GENERATED VOLTAGE (V)	FREQUENCY (HZ)	SPEED (RPM)
240	51	1000
225	49	980
190	47	940
180	44	900

5.4:EXCITATION FROM THE ROTOR SIDE

An attempt was made to practically excite a wound - rotor machine from the rotor side by connecting the three-phase capacitor banks , and then driving the machine at synchronous speed. There was no voltage build-up as predicted by the simulations. This may be explained by considering the equivalent circuits of figs 3.3 and 3.4. It can be seen that at synchronous speed the rotor side is like an open-circuit because Ws=Wr, indicating no possiblity of current flow to the capaciors. Because the simulations results indicate an unstable situation at speeds higher than syncronous speed, no attempt was made to run the machine beyond the syncronous speed, for fear of possible damage to the machine, especially as the author was not able to find any literature indicating that such an attempt has been made. Consequently, no practical readings were obtained to plot a graph showing a comparison between the practical results and computer simulations..

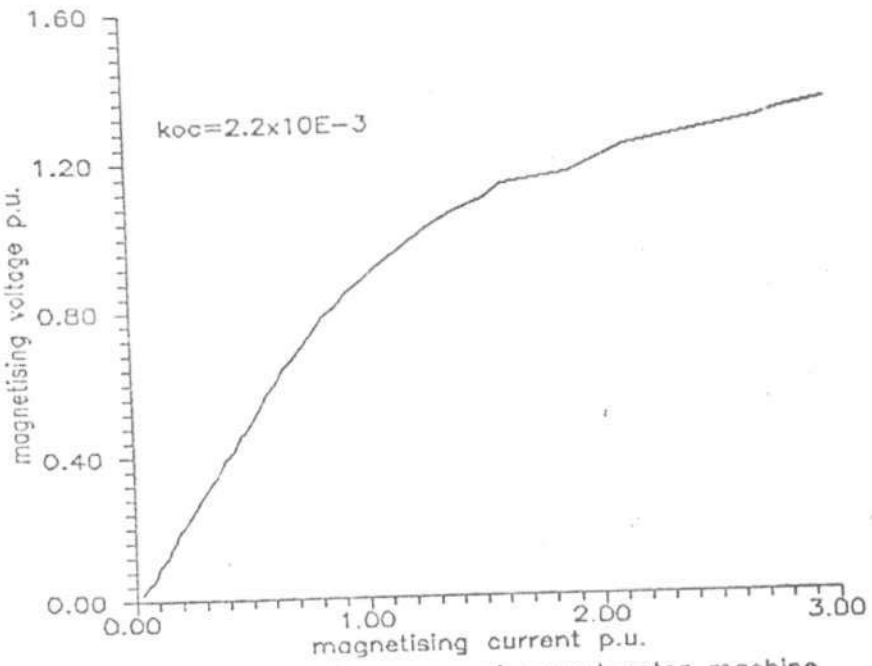


fig 5.3:saturation curve of wound-rotor machine

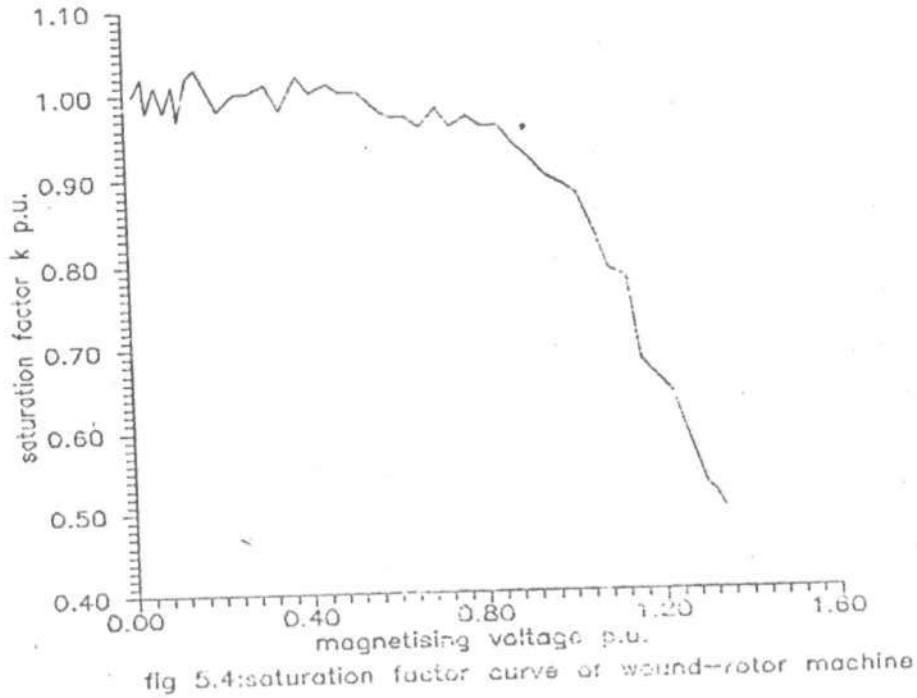


fig 5.4:saturation factor curve of wound-rotor machine

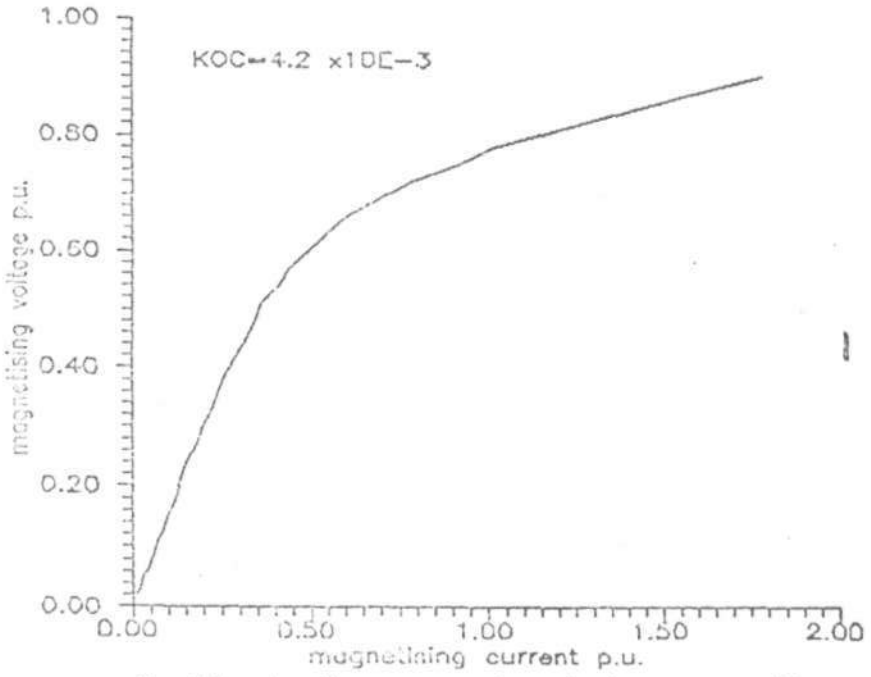


fig 5.1:saturation curve of squirrel-cage machine

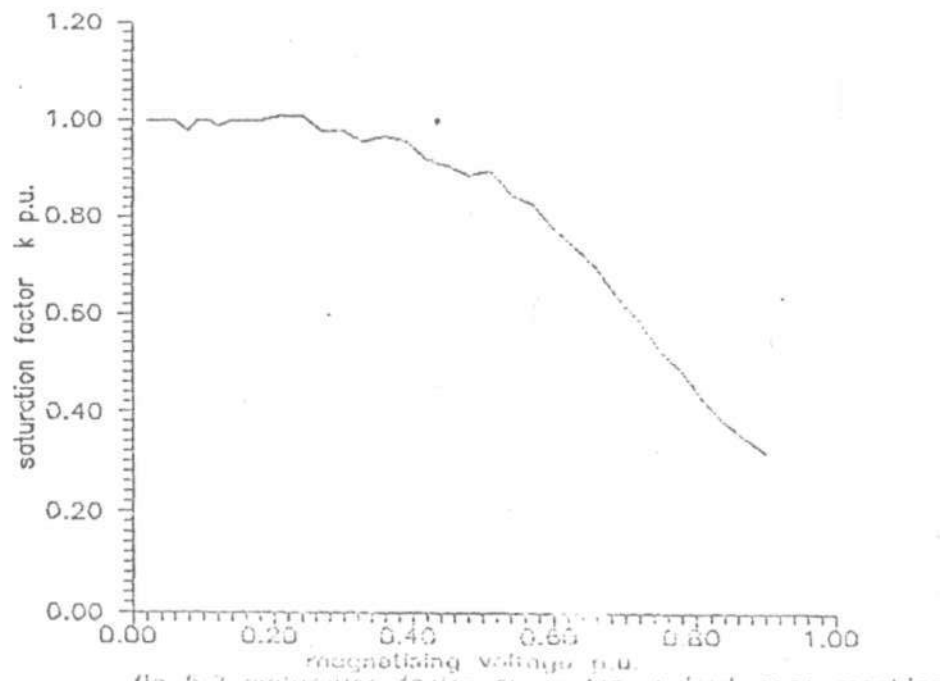


fig 5.2 saturation factor curve for squirrel-cage machine

CHAPTER 6

DISCUSSIONS AND CONCLUSIONS

6.1: MODELLING

From the results of the simulations and what was observed practically, it is obvious that the model has successfully predicted the transient stage of the build-up of an isolated induction generator with capacitor excitation. The linear model has predicted voltage build-up but indicated an unbounded growth of machine electrical quantities. The non-linear model can be seen to present a more realistic picture of the self-excitation phenomena. Certain machine parameters could be optimised as suggested from the various simulations.

As far as the self-excitation phenomena is concerned an isolated induction generator could be analysed from two viewpoints; the generalised machine concept and the self-oscillatory concept based on physical observations. This work effectively made use of both to predict the self-excitation process by making use of both a d-q model and the concept of resonant frequency. In ref [68], the value of the capacitance was arbitrarily chosen, whereas here the capacitance was chosen to get the resonant frequency around the sychronous frequency. The analysis of the self-excitation process from the two viewpoints briefly follows.

As it is known [47] an oscillatory system is made up of system components as shown in fig. 6.1.

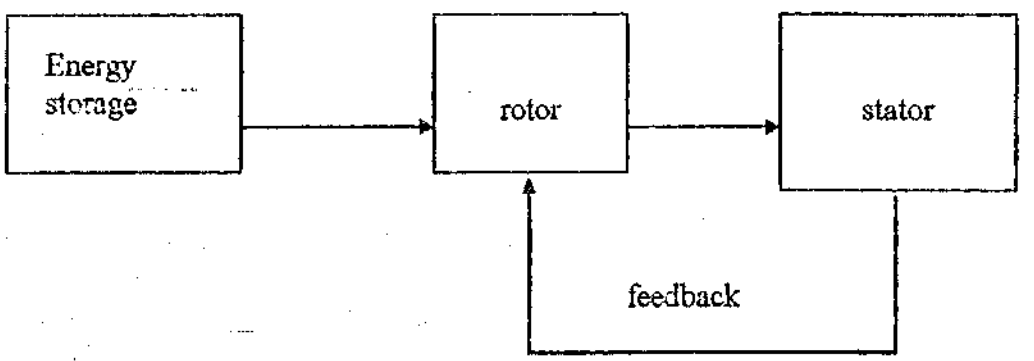


Fig. 6.1: TYPICAL OSCILLATORY SYSTEM [47].

Depending on the "energy store" and "feedback" we can have non-decaying oscillations which can be held at a definite level if the system is non-linear. To start such a system oscillation, an external applied force must be present.

In a capacitor-excited induction generator all the above "oscillator" components are present. The energy source is the prime mover; the oscillatory system is the loop of capacitance and machine inductances, and the feedback loop is formed by the electromagnetic coupling between the rotor and stator circuits through the magnetic flux of the machine. The rotor in this system acts as the "valve" or "energy storage system". In order to get sinusoidal oscillations, the machine is set into rotation by the prime mover and capacitors are then connected to the stator terminals. If the rotor rotational speed exceeds the resonance frequency of the oscillatory circuit the machine operates as a generator with negative "slip" and develops useful electrical power. The analogy to a dc shunt generator is obvious with the role of the oscillatory system being performed by the inductances of the armature and field circuits.

The other approach viewed the induction generator as a magnetically coupled circuit and is very well suited for computer aided simulations. The terminal capacitors in this case, are constraints which shape or govern how the machine behaves. It is obvious that both approaches have to be considered in order to explain the self-excitation process in induction generators: The "oscillatory circuit viewpoint helps in establishing the conditions, while the d-q model shows the transient nature of the building-up process and allows the incorporation of saturation effects. A recent paper [68] has the machine analysed using a d-q model with cross magnetisation effects included.

The model developed in this work is capable of demonstrating two forms of exciting an induction generator:

i) Variable capacitance with constant speed, or

ii) Fixed capacitance with speed increased to self-excitation point.

The attempt to try simulation with the excitation capacitors as the rotor can be seen to produce an unstable phenomena (figs 4.4 to 4.6). This might be due to the failure to achieve the set up suggested in fig. 6.1; that is, we now have a situation where the "valve" and the "oscillatory system" are present without any feedback. In the case when both the stator and the rotor have capacitors connected, the system of fig 6.1 is established though with possibilities of additional oscillatory loops which may have lead to the bizarre behaviour. This area may be holding the clue for new process of self-exciting an isolated induction generator.

The modelling presented here also provides a means of studying induction generator operating conditions. Equations 3.12 to 3.26, together with external system models could be integrated to provide a set of equations that could be used to study, for example, short-circuit, stability, voltage regulations and even parallel operations problems.

The results of the modelling (figs 4.1 to 4.3) suggest ways to improve or even ensure self-excitation. These include:

1) Ensuring that remanent magnetism is sufficient. This could be achieved using any way of establishing residual magnetism in electrical machines.

2) Switching charged capacitors at the machine terminals will immediately establish the necessary exciting current.

3) Provided the machine's rotor and bearings have the capabilities, the machine speed can be increased to above rated value.

4) No load should be connected prior to self-excitation as suggested in results of figs 4.3. This implies also that capacitor leads and connectors should be as short as possible and joints should be of low resistance.

5) A machine to be selected should be of low stator resistance and leakage reactance.

One disadvantage discovered with the modelling was the time it takes to run on the computer; though to some extent, this depends on the computing facilities. For example, an APPLE machine (2e) takes up to 30 minutes (real time) while an IBM compatible (AT) takes approximately half that time. It is possible to reduce the

time by optimising the program or using a faster machine (80386 or 80486) as an example. The use of commercial subroutines may also reduce the time as the ones used in this project were developed by the author without any optimisation considered. However , the subroutne SPLINE could be use in other programs because it was developed and compiled as a unit.

6.2: PRACTICAL ASPECTS

Though lack of suitable measuring test instruments prevented adequate practical investigations, nevertheless some were attempted. A major problem encountered was in self-excitation of the machines. While the squirrel-cage machine is always building-up, difficulties were generally encountered when exciting the slip-ring machine. This was attributed to the two macines's ability to retain remanent magnetism even though the squirrel-cage machine retains better than the other. Another reason could be due to the voltage drop on the slip-ring brushes in the case of the wound-rotor macine.

The opportunity was also taken to investigate the load performance of a 2kw induction machine connected with terminal 7kvar capacitors and driven by a 3bhp-diesel-engine. The machine excited successfully but carried a load of only 500W of lighting load. This was attributed to the high-losses present in the set-up and the smaller power of the diesel drive. Some practical effects noticed included over voltages when the load is over thrown and high bearing temperatures.

6.3: CONCLUSIONS

In this work, a model to predict the transient excitation phenomena in induction generators was developed successfully. There is good agreement between the theory and the observed practical results carried out. As mentioned earlier, the high reliability and low-cost of induction machine could be used, especially in developing countries, to harness their power sources. With simple models as presented in this work, it is possible to incorporate other system components in order to provide an over-all low cost and effective system. For example, with the present low-cost of static var sources, an induction generator system could be fully utilized in an isolated rural area.

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APPENDIX 1
MACHINES PARAMETERS:

These parameters were obtained from [67].

A. WOUND ROTOR INDUCTION MACHINE

Machine rating: 3 hp, 6 pole 3-phase, 400 v, 50Hz ,10AΔ -connected.

Stator resistance	1.6800 ohms
Stator leakage reactance	2.1400 ohms
Rotor resistance	9.2000 ohms
Rotor leakage reactance	4.5000 ohms
Unsaturated magnetising reactance	31.3800 ohms

B. SQUIRREL CAGE INDUCTION MACHINE

Machine rating: 5 hp, 3-phase, 4-pole, 220/240-380/420v,12.8/7.4A.

Machine type: ac motor type KNX-C213 made by Associated Electrical Industries Ltd.,

Stator resistance	1.86 ohms
Stator leakage reactance	3.57 ohms
Rotor resistance	1.60 ohms
Rotor leakage reactance	3.57 ohms
Unsaturated magnetising reactance	91.600 ohms

C. PER UNIT VALUES

Base quantities are defined as in [66] and are given in table A1

TABLE A1: ELECTRICAL BASE QUANTITIES FOR THE INDUCTION MACHINES

		WOUND ROTOR	SQUIRREL CAGE
Vao	**(V)**	282.9	311.1
Iao	**(A)**	8.2A	10.5
Pao	**(W)**	3464.1	4877.5
We	**(Rad/s)**	104.7	157.1

Other Derived Quantities are given below[66]: in table A2

TABLE A2: DERIVED BASE QUANTITIES FOR THE INDUCTION MACHINES

		WOUND RCTOR	SQUIRREL CAGE
Ido = (3/2)Iao	**A**	12.3	15.7
Vdo =Vao	**V**	282.9	311.1
Iqo = (3/2)Iao	**A**	12.3	15.7
Vqo=Vao	**V**	282.9	311.1
t_o=1/We	**Sec**	0.01	0.0064
ψ_0=Vao	**V**	34.9	52.4
Wmo=Wo/pp	**Rad/s**	99.2	93.2
Teo=Pao/Wmo	**Nm**	34.6	29.8
Jo=Pao/WoW^{2}mo	**Kg.m^2**	0.0271	0.0113

Using the above base values the machine parameters are as given in table A3

TABLE A3: PARAMETERS OF THE INDUCTION MACHINES IN PER UNIT

	WOUND ROTOR	SQUIRREL CAGE
Rs	0.0487	0.0622
Xs	0.0620	0.1193
Rr	0.2667	0.0535
Xm	0.9096	2.4822
H	1.0	1.0

APPENDIX 2

COMPUTER PROGRAMS

```
PROGRAM TEST;
 USES  CRT,SSINTERP;(*A UNIT CREATED BY S S ADAMU*)
 CONST PERIOD='.';
 TYPE
  X1=ARRAY[1..10] OF REAL;
  VAR
   OUTFILE:TEXT;
   TITLE:STRING;
   F,Y,XO:X1;
   THPTS,KPTS:NPOINTS;
   N,I,J,NPTS:INTEGER;
   K,THM,XSS,XRR,XM,THMQ,THMD,XMQ,XMD,HH,IQS,IDS,IDR,IQR,IAS,IAR,VDS,
   VQS,VDR,VQR,XC1,XC2,VM,RS,RR,WX,WS,WE,WO,KOC,XC,XCP,T,H,TE,TM:REAL;
   G1,G2,G3,G4,G5,G6:TEXT;

PROCEDURE INIT;
      (*SETTING-UP INPUT AND OUTPUT FILES AND CONSTANTS*)
 BEGIN
      (*CREATNG  AND OPENING  OUTPUT DATA FILES*)
  ASSIGN(G1,'A:\SQGRF1.DAT');REWRITE(G1);
  ASSIGN(G2,'A:\SQGRF2.DAT');REWRITE(G2);
```

```
ASSIGN(G3,'A:\SQGRF3.DAT');REWRITE(G3);
ASSIGN(G4,'A:\SQGRF4.DAT');REWRITE(G4);
ASSIGN(G5,'A:\SQGRF5.DAT');REWRITE(G5);
ASSIGN(G6,'A:SQFAC.DAT');RESET(G6);
N:=9;
XSS:=0.1193;
RR:=0.0535;XRR:=0.1193;
XM:=2.4822;WE:=157;WS:=157;
WRITELN('INPUT H,HH,TM,XC1,XC2,RS,IEND');
READLN(H,HH,TM,XC1,XC2,RS,IEND);
WRITELN('READING INTERPLATION POINTS..');
READLN(G6,NPTS);
FOR I:=1 TO NPTS DO
 BEGIN
  READLN(G6,THPTS[I],KPTS[I]);
  WRITELN(I,THPTS[I]:10:4,KPTS[I]:10:4)
 END; CLOSE(G6);
 T:=0.0;
 KOC:=(4.23E-3/220.0)*WE;
 XMD:=1/((1/XM)+(1/XSS)+(1/XRR));
 XMQ:=XMD
 END;(*INIT*)
PROCEDURE INIT2;
BEGIN
```

```
THM:=SQRT(THMQ*THMQ+THMD*THMD);
SPLINE(THPTS,KPTS,NPTS,IEND,THM,K,FLAG);
    (*SPLINE IS  IN A UNIT SSINTERP*)
    (* IT RETURNS K WHICH IS 1 IF LINEAR MODEL*)
THMQ:=-K*XMQ*(Y[1]/XSS+Y[3]/XRR);
THMD:=-k*XMD*(Y[2]/XSS+Y[4]/XRR);
IQS:=-(Y[1]+THMQ)/XSS;
IDS:=-(Y[2]+THMD)/XSS;
IQR:=(Y[3]+THMQ)/XRR;
IDR:=(Y[4]+THMD)/XRR;
TE:=(Y[3]*IDR-Y[4]*IQR)*(1/WE)*(POLE/2);
VQS:=KOC*Y[5]*SIN(WS*Y[5]*T)+Y[8];
VDS:=KOC*Y[5]*COS(WS*Y[5]*T)+Y[9];
VDR:=0.0;VQR:=0.0;
F[1]:=WE*(VQS+RS*IQS);
F[2]:=WE*(VDS+RS*IDS);
F[3]:=WE*(VQR+(Y[5]*Y[4])-RR*IQR);
F[4]:=WE*(VDR-(Y[5]*Y[3])-RR*IDR);
F[5]:=(TE-TM)/(2*HH);
END;(*INIT2*)

PROCEDURE ORBIT(Y:X1;T:REAL;VAR F:X1);
    (*DIFFENTIAL CALCULATIONS *)
BEGIN
```

```
 INIT2;
 F[8]:=WE*XC*IQS;
 F[9]:=WE*XC*IDS;
 F[6]:=0.0;
 F[7]:=-Y[5];
END;(*ORBIT*)

PROCEDURE RUNGE(T1:REAL;XO:X1;VAR XEND:X1);
      (*RUNGE-KUTTA INTEGRATION ROUTINE *)
 VAR
 XWRK:ARRAY [1..4,1..10] OF REAL;
 TT:REAL;
BEGIN
 ORBIT(XO,T1,F);
 FOR I:=1 TO N DO
 BEGIN
  XWRK[1,I]:=H*F[I];
  XEND[I]:=XO[I]+XWRK[1,I]/2.0
 END;
TT:=T1+H/2.0;
ORBIT(XEND,TT,F);
FOR I:=1 TO N DO
 BEGIN
  XWRK[2,I]:=H*F[I];
```

```
 XEND[I]:=XO[I]+XWRK[2,I]/2.0
 END;
ORBIT(XEND,TT,F);
FOR I:=1 TO N DO
 BEGIN
 XWRK[3,I]:=H*F[I];
 XEND[I]:=XO[I]+XWRK[3,I]
 END;
TT:=T1+H;
ORBIT(XEND,TT,F);
FOR I :=1 TO N DO
 XWRK[4,I]:=H*F[I];
FOR I:=1 TO N DO
 XEND[I]:=XO[I]+(XWRK[1,I]+2.0*(XWRK[2,I]+XWRK[3,I])+XWRK[4,I])/6.0;
END;(*RUNGE*)
```

```
 PROCEDURE NAME;
(*INITIAL CONDITIONS*)
 BEGIN
 INIT;
 FOR I:=1 TO N DO BEGIN
 XO[I]:=0.0;Y[I]:=0.0 END;
 IQS:=0.0;IQR:=0.0;IDS:=0.0;IDR:=0.0;TE:=0.0;
 VQS:=0.0;VDS:=0.0;VDR:=0.0;VQR:=0.0;
```

```
  XC:=2.2;
  WO:=SQRT(XC/(XSS+XM));
  XO[5]:=1.0;Y[5]:=1.0;
  THMQ:=0.0;THMD:=0.0;
  THM:=SQRT(THMQ*THMQ+THMD*THMD)
 END;(*NAME*)

BEGIN(*MODEL*)
 NAME;(*SET INITIAL CONDITIONS*)
 WRITELN(' T      VDS     ISA     IRA     WM      TE      WO');
 WRITELN(T:7:4,Y[8]:10:4,IQS:10:4,IQR:10:4,Y[5]:10:4,TE:10:4,WO:10:4);
 REPEAT
 IF T<0.05 THEN
  XC:=XC1
 ELSE
  XC:=XC2;
 XCP:=0.0;
 WO:=SQRT(XC/(XSS+XM));
 RUNGE(T,XO,Y);
 FOR I:=1 TO N DO  XO[I]:=Y[I];
 T:=T+H;
  THMQ:=-K*XMQ*(Y[1]/XSS+Y[3]/XRR);
  THMD:=-k*XMD*(Y[2]/XSS+Y[4]/XRR);
  IQS:=-(Y[1]+THMQ)/XSS;
```

```
IDS:=-(Y[2]+THMD)/XSS;
IQR:=(Y[3]+THMQ)/XRR;
IDR:=(Y[4]+THMD)/XRR;
TE:=(Y[3]*IDR-Y[4]*IQR)*(1/WE)*(POLE/2);
IAR:=COS(WE*Y[7])*IQR-SIN(WE*Y[7])*IDR;
WRITELN(T:7:4,Y[8]:10:4,IQS:10:4,IQR:10:4,Y[5]:10:4,TE:10:4,WO:10:4);
WRITELN(G1,T:7:4,Y[8]:10:4);
WRITELN(G2,T:7:4,IQS:10:4);
WRITELN(G3,T:7:4,IQR:10:4);
WRITELN(G4,T:7:4,Y[5]:10:4);
WRITELN(G5,T:7:4,TE:10:4);
UNTIL KEYPRESSED;
      (*CLOSE OPEN FILES*)
CLOSE(G1);CLOSE(G2);CLOSE(G3);CLOSE(G4);CLOSE(G5)
END.(*MODEL*)
```

```
UNIT SSINTERP;

      (*THIS UNIT CONTAINS THE SPLINE INTERPOLATION ROUTINE*)

 INTERFACE

 TYPE

  NPOINTS =ARRAY[1..40] OF REAL;

 VAR

  NPTS,I,J,IEND:INTEGER;

  XINT,THM,YOUT,FLAG:REAL;

  X,Y:NPOINTS;

  AQ:STRING;G:TEXT;


PROCEDURE SPLINE(X,Y:NPOINTS;NPTS:INTEGER;XOUT:REAL;VAR F:REAL);

PROCEDURE FUNC(X,Y:NPOINTS;NPTS:INTEGER;VAR A,B,C,D:NPOINTS);

--

IMPLEMENTATION


PROCEDURE FUNC(X,Y:NPOINTS;NPTS:INTEGER;VAR A,B,C,D:NPOINTS);

TYPE

 Y1=ARRAY[1..40] OF REAL;

 Y2=ARRAY[1..40,1..4] OF REAL;

VAR

 I,J,NM2,NM1:INTEGER;

 DXN1,DXN2,DX1,DX2,DY1,DY2:REAL;

 AC:Y2;
```

```
S:Y1;


BEGIN (*FUNC*)
 NM2:=NPTS-2;NM1:=NPTS-1;
 DX1:=X[2]-X[1];
 DY1:=(Y[2]-Y[1])/DX1*6.0;
 FOR I:=1 TO NM2 DO
 BEGIN
  DX2:=X[I+2]-X[I+1];
  DY2:=(Y[I+2]-Y[I+1])/DX2*6.0;
  AC[I,1]:=DX1;
  AC[I,2]:=2.0*(DX1+DX2);
  AC[I,3]:=DX2;
  AC[I,4]:=DY2-DY1;
  DX1:=DX2;
  DY1:=DY2
 END;
 IF IEND = 3 THEN
 BEGIN
  DX1:=X[2]-X[1];
  DX2:=X[3]-X[2];
  AC[1,2]:=(DX1+DX2)*(DX1+2.0*DX2)/DX2;
  AC[1,3]:=(DX2*DX2-DX1*DX1)/DX2;
 DXN2:=X[NM1]-X[NM2];
```

```
 DXN1:=X[NPTS]-X[NM1];
 AC[NM2,1]:=(DXN2*DXN2-DXN1*DXN1)/DXN2;
 AC[NM2,2]:=(DXN1+DXN2)*(DXN1+2.0*DXN2)/DXN2
 END
ELSE IF IEND = 2 THEN
 BEGIN
 AC[1,2]:=AC[1,2]+X[2]-X[1];
 AC[NM2,2]:=AC[NM2,2]+X[NPTS]-X[NM1]
 END;
FOR I:=2 TO NM2 DO
 BEGIN
 AC[I,2]:=AC[I,2]-AC[I,1]/AC[I-1,2]*AC[I-1,3];
 AC[I,4]:=AC[I,4]-AC[I,1]/AC[I-1,2]*AC[I-1,4]
 END;
AC[NM2,4]:=AC[NM2,4]/AC[NM2,2];
 FOR I:=2 TO NM2 DO
  BEGIN
  J:=NM1-I;
  AC[J,4]:=(AC[J,4]-AC[J,3]*AC[J+1,4])/AC[J,2]
  END;
 FOR I:=1 TO NM2 DO
  S[I+1]:=AC[I,4];
 IF IEND = 3 THEN
  BEGIN
```

```
 S[1]:=((DX1+DX2)*S[2]+DX1*S[3])/DX2;
 S[NPTS]:=((DXN2+DXN1)+S[NM1]-DXN1*S[NM2])/DXN2
 END
ELSE IF  IEND = 2 THEN
 BEGIN
 S[1]:=S[2];
 S[NPTS]:=S[NPTS-1]
 END
ELSE
 BEGIN
 S[1]:=0;
 S[NPTS]:=0
 END;
(*CALCULATING COEFFICIENTS*)
FOR I:=1 TO NM1 DO
 BEGIN
 A[I]:=(S[I+1]-S[I])/(6.0*(X[I+1]-X[I]));
 B[I]:=S[I]/2.0;
 C[I]:=((Y[I+1]-Y[I])/(X[I+1]-X[I]))-(X[I+1]-X[I])*
      (2.0*S[I]+S[I+1])/6.0;
 D[I]:=Y[I]
END;
A[NPTS]:=A[NPTS-1];
B[NPTS]:=S[NPTS]/2.0;
```

```
C[NPTS]:=C[NPTS-1];
D[NPTS]:=Y[NPTS]
END;(*FUNC*)

PROCEDURE SPLINE(X,Y:NPOINTS;NPTS:INTEGER;XOUT:REAL;VAR F:REAL);
LABEL 69;
VAR
 A,B,C,D:NPOINTS;
 DX:REAL;
 J:INTEGER;
 LIMIT :BOOLEAN;
BEGIN (*FUNC*)
 FUNC(X,Y,NPTS,A,B,C,D);
 LIMIT :=( XOUT < X[1]) OR ( XOUT > X[NPTS]) ;
 IF LIMIT THEN
  BEGIN WRITELN('ERROR..');FLAG:=1;EXIT END
 ELSE IF XOUT = X[1] THEN
  BEGIN F:=Y[1] END
 ELSE IF XOUT >= X[NPTS] THEN
  BEGIN F:=Y[NPTS] END;
 J:=2;
69: IF XOUT-X[J] < 0 THEN
  BEGIN
   DX:=XOUT-X[J];
```

```
F:=D[J]+DX*(C[J]+DX*(B[J]+DX*A[J]))
END
ELSE IF XOUT-X[J] = 0 THEN
 BEGIN F:=D[J] END
ELSE
 BEGIN
  J:=J+1;
  GOTO 69
 END;
END;(*FUNC*)
 BEGIN
 END.
```

APPENDIX 3

SIMULATIONS RESULTS

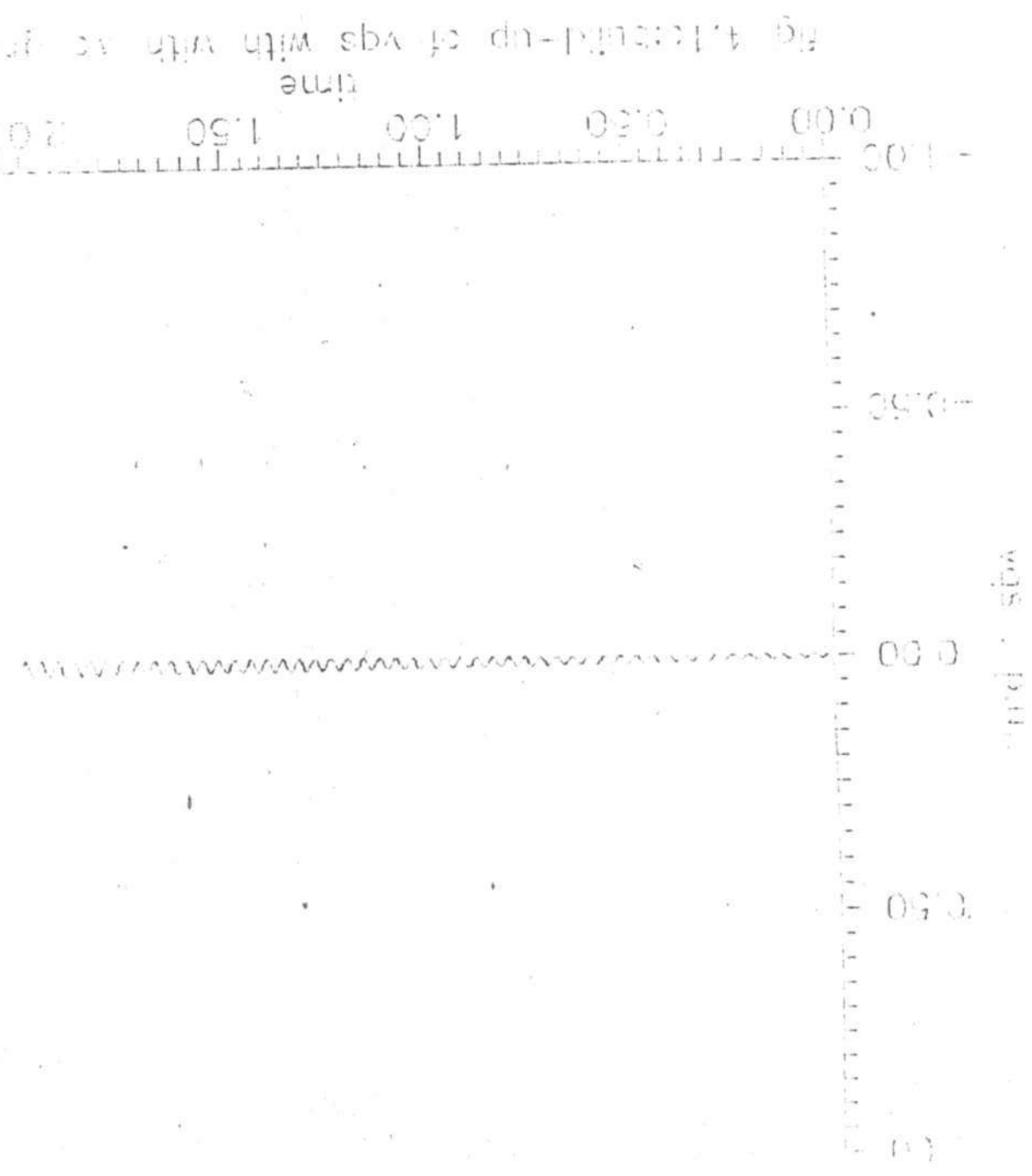
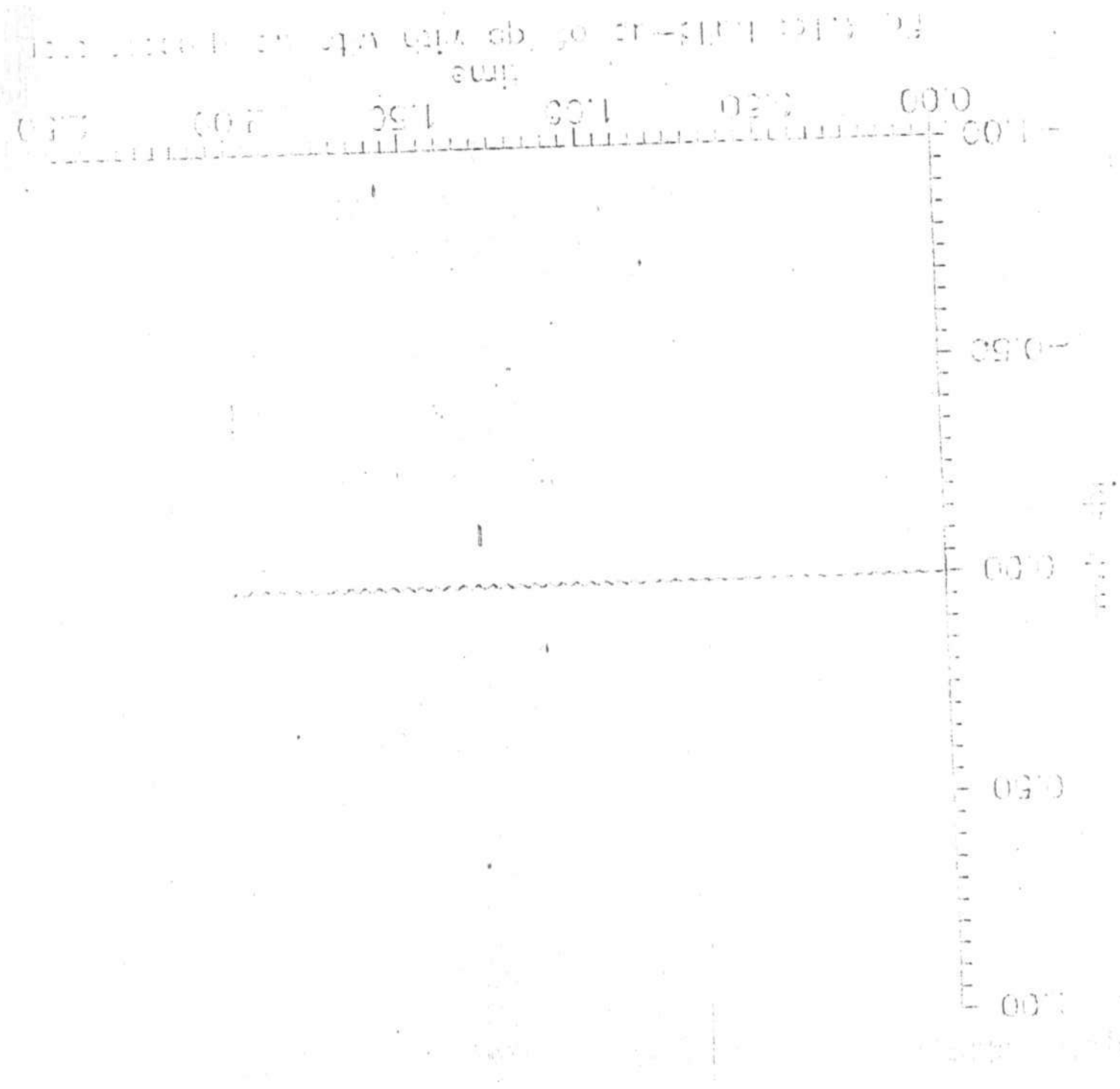


Fig 4.1 Stretched-up of vgs with vth vs transfer from 1



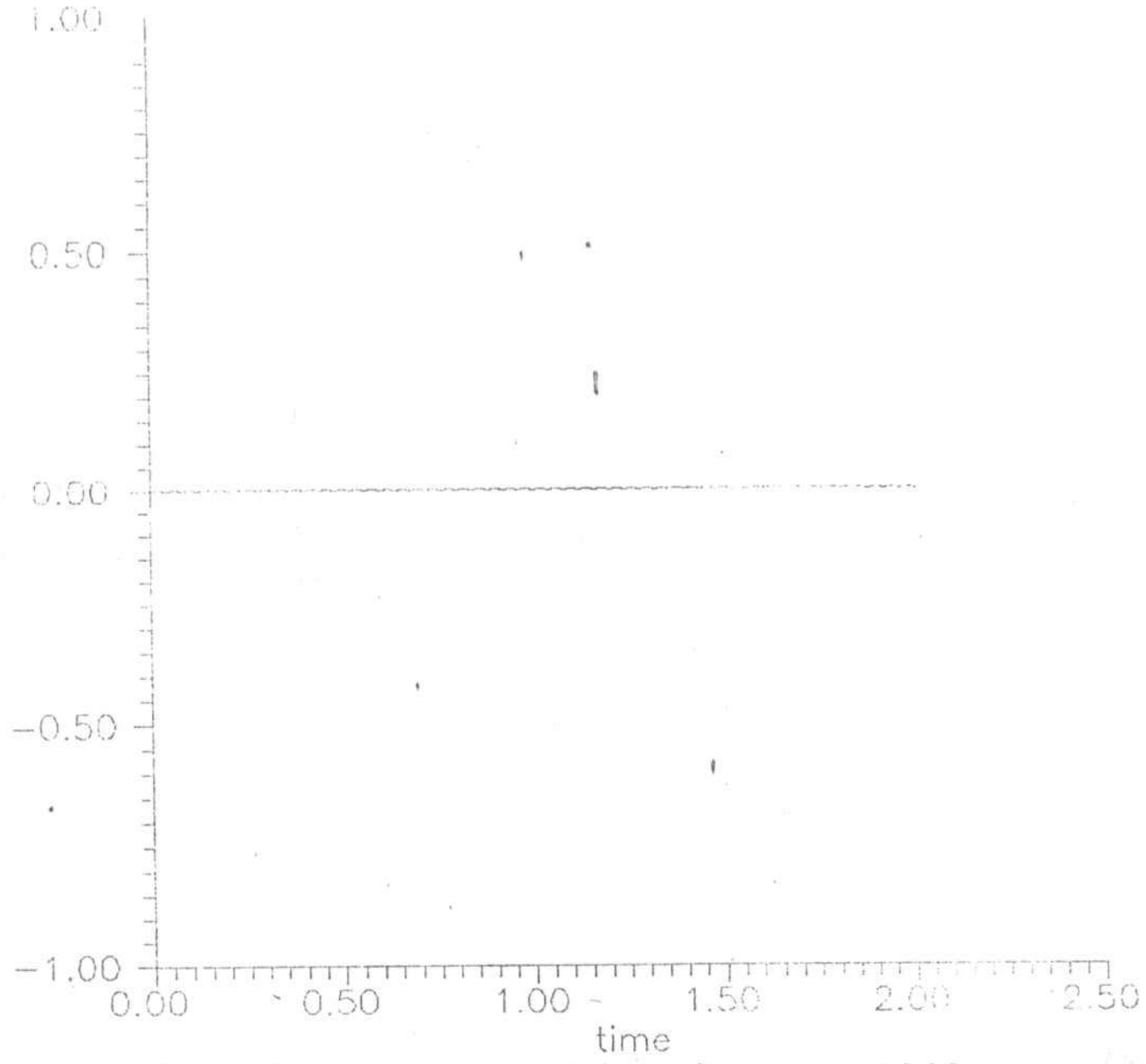


fig 4.1 c: build−up of iqr with ρ_{ro}=1.0025

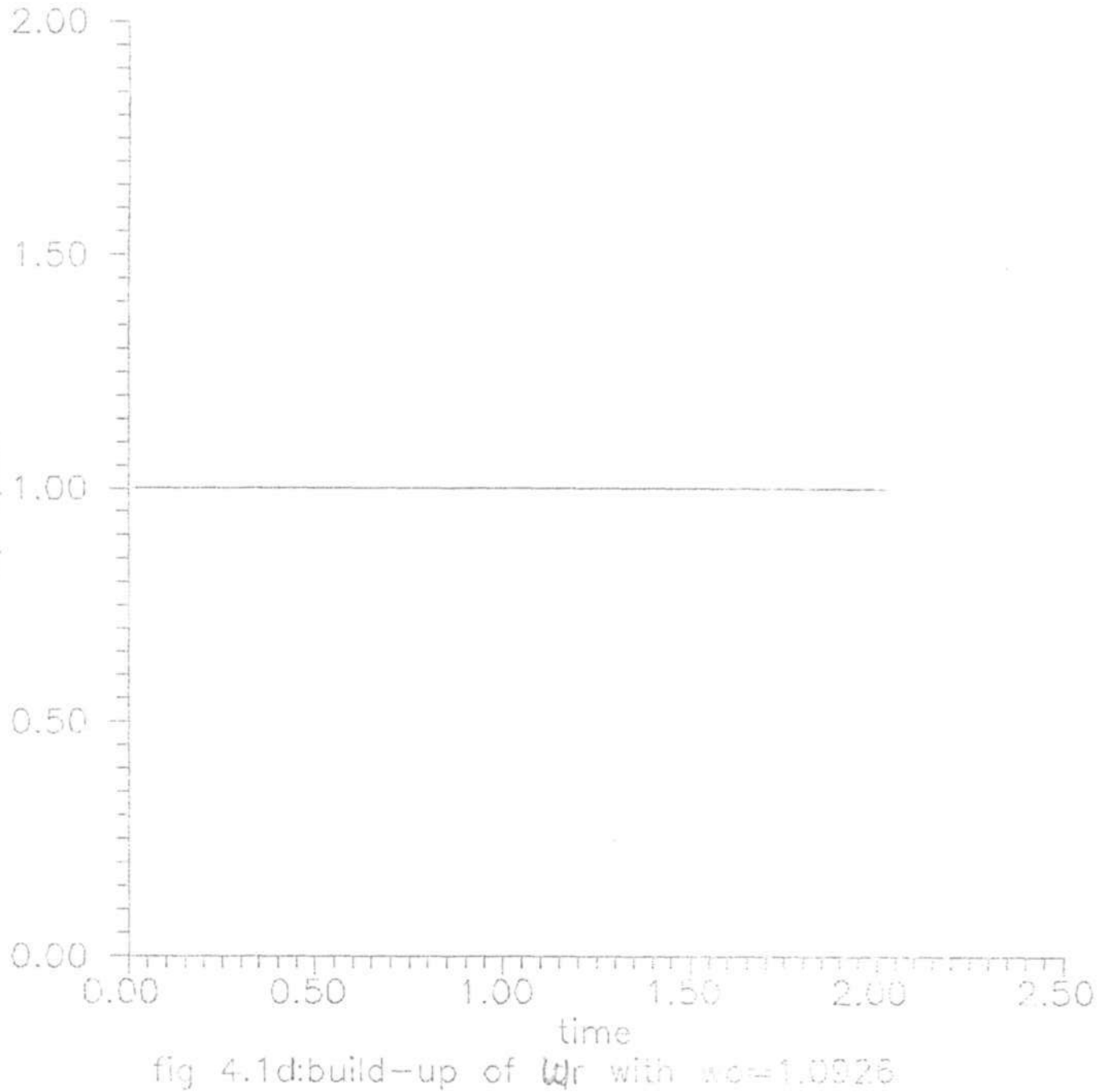


fig 4.1d:build-up of ωr with xc=1.0926

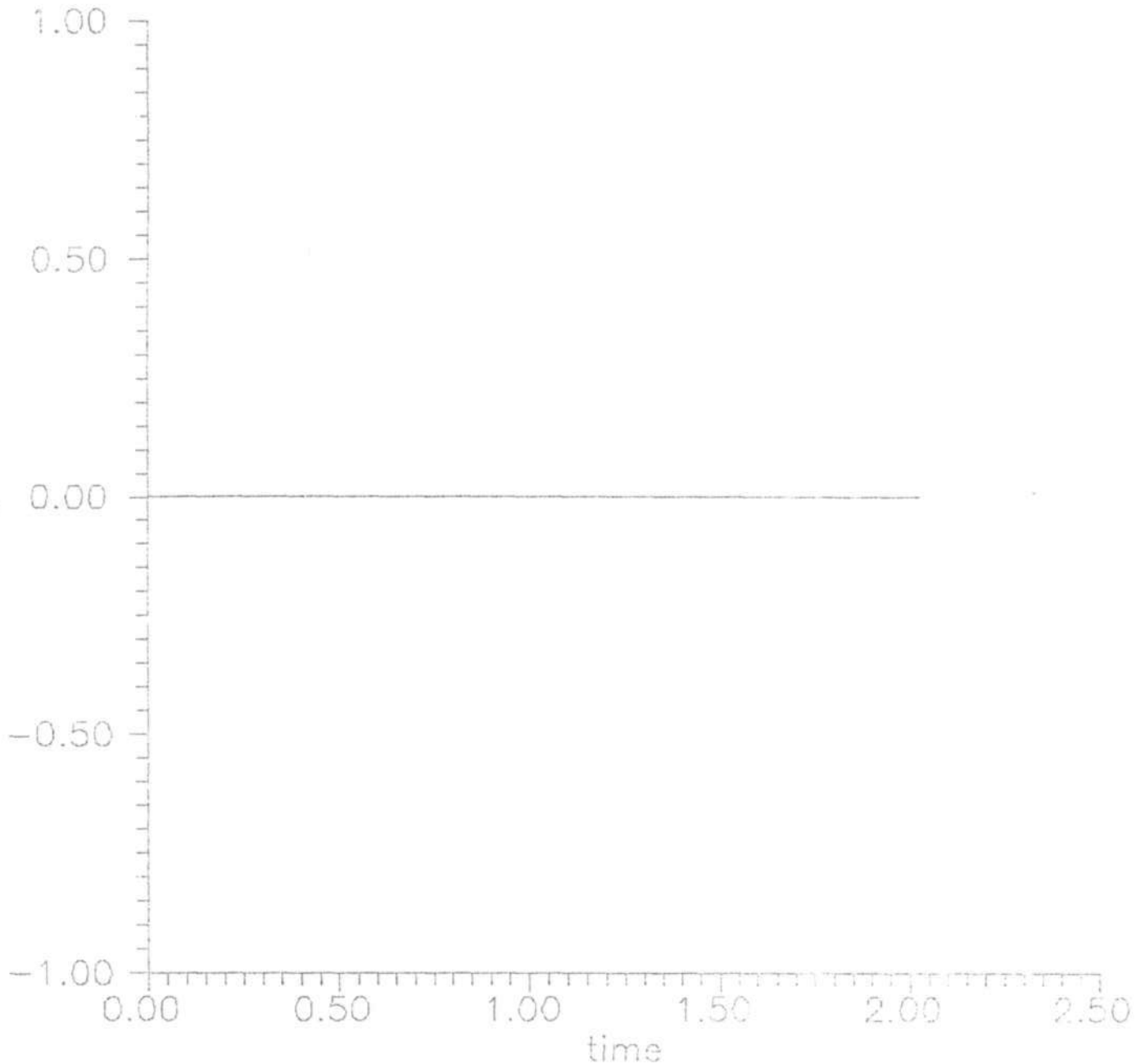


fig 4.1e: build-up of te with wo=1.0926

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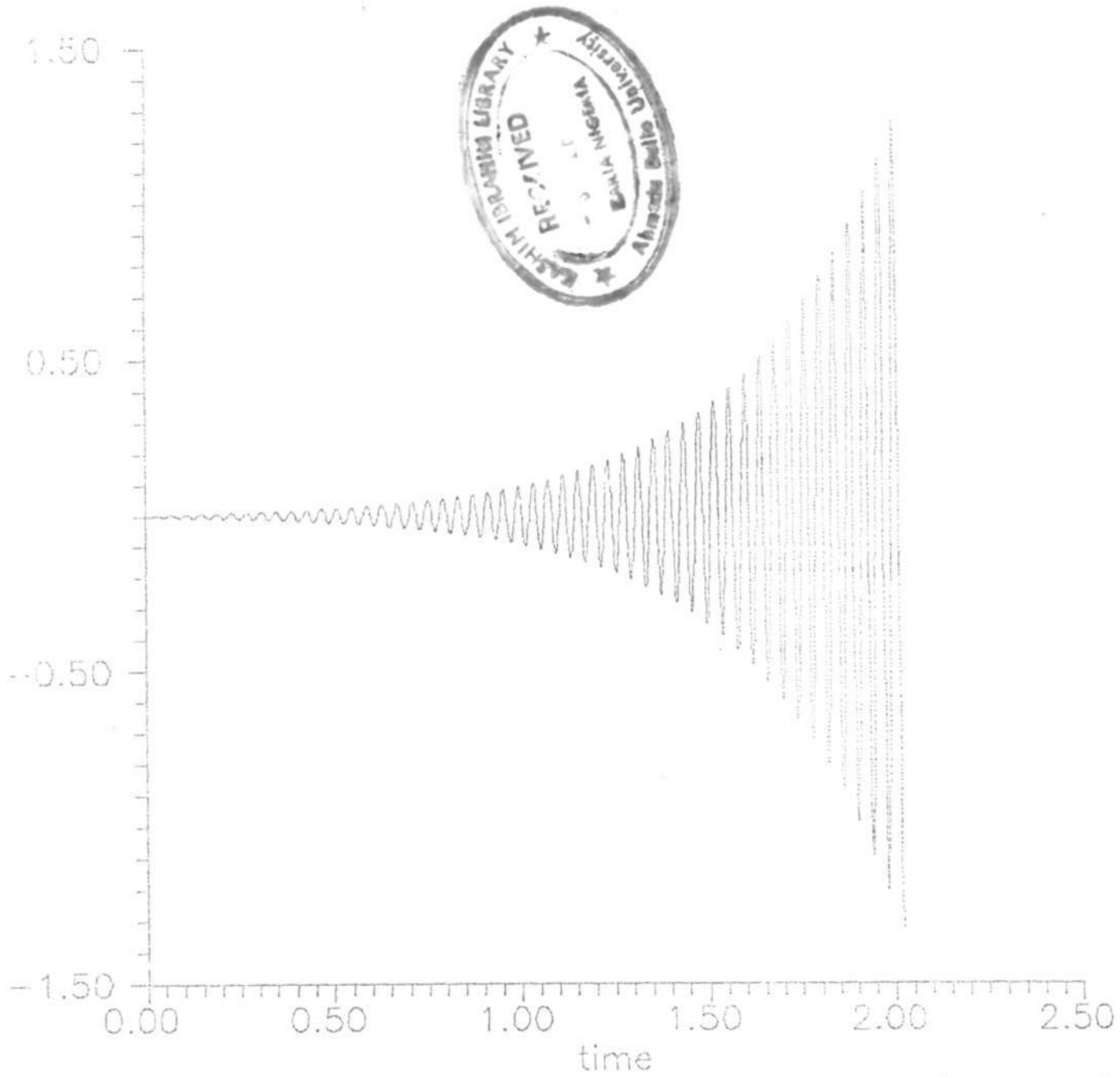


fig 4.2a:build-up of vqs with wo=0.7726 (XC =1.5)

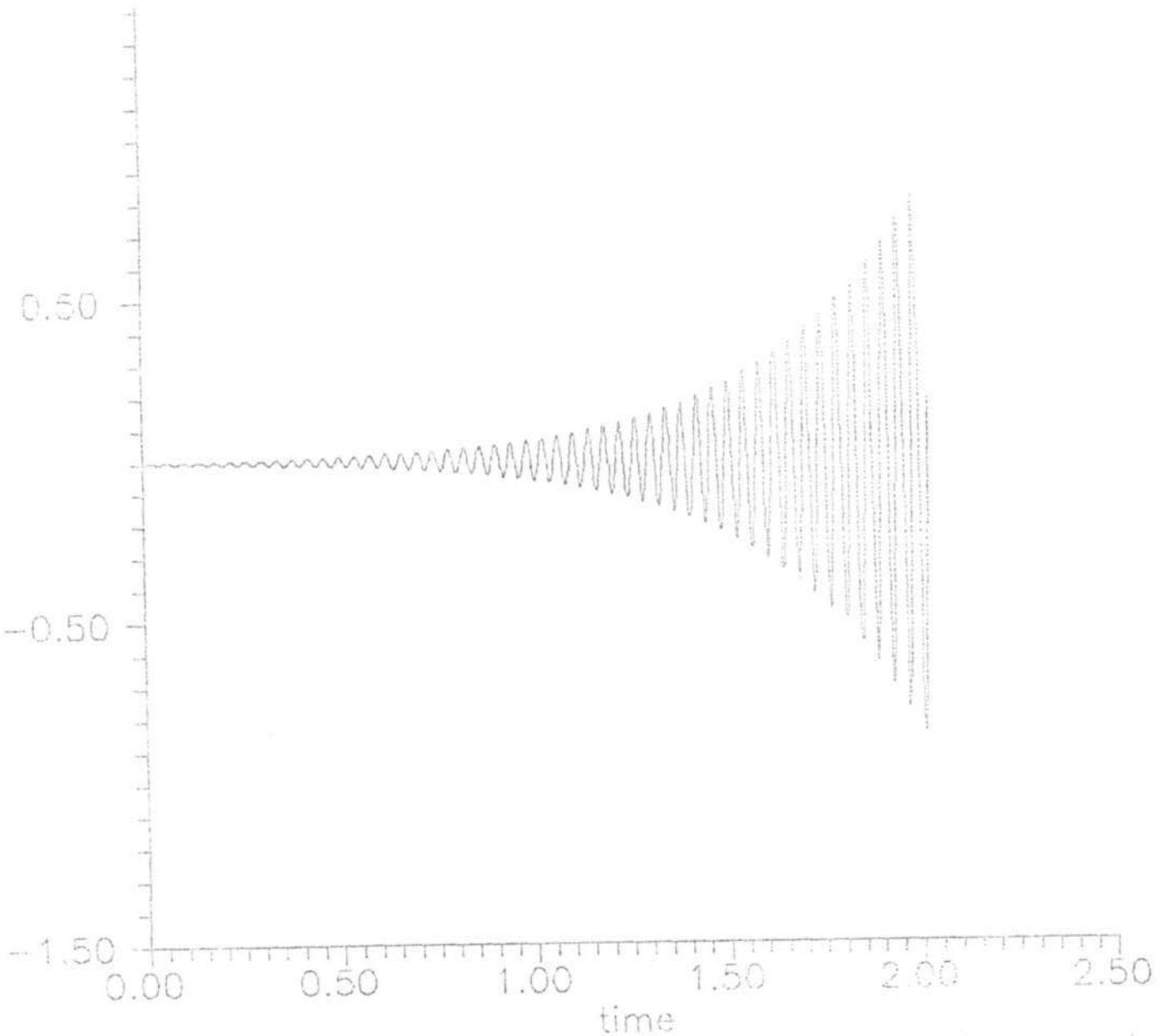


fig 4.2b:build-up of iqs with wo=0.7726 (XC =1.5)

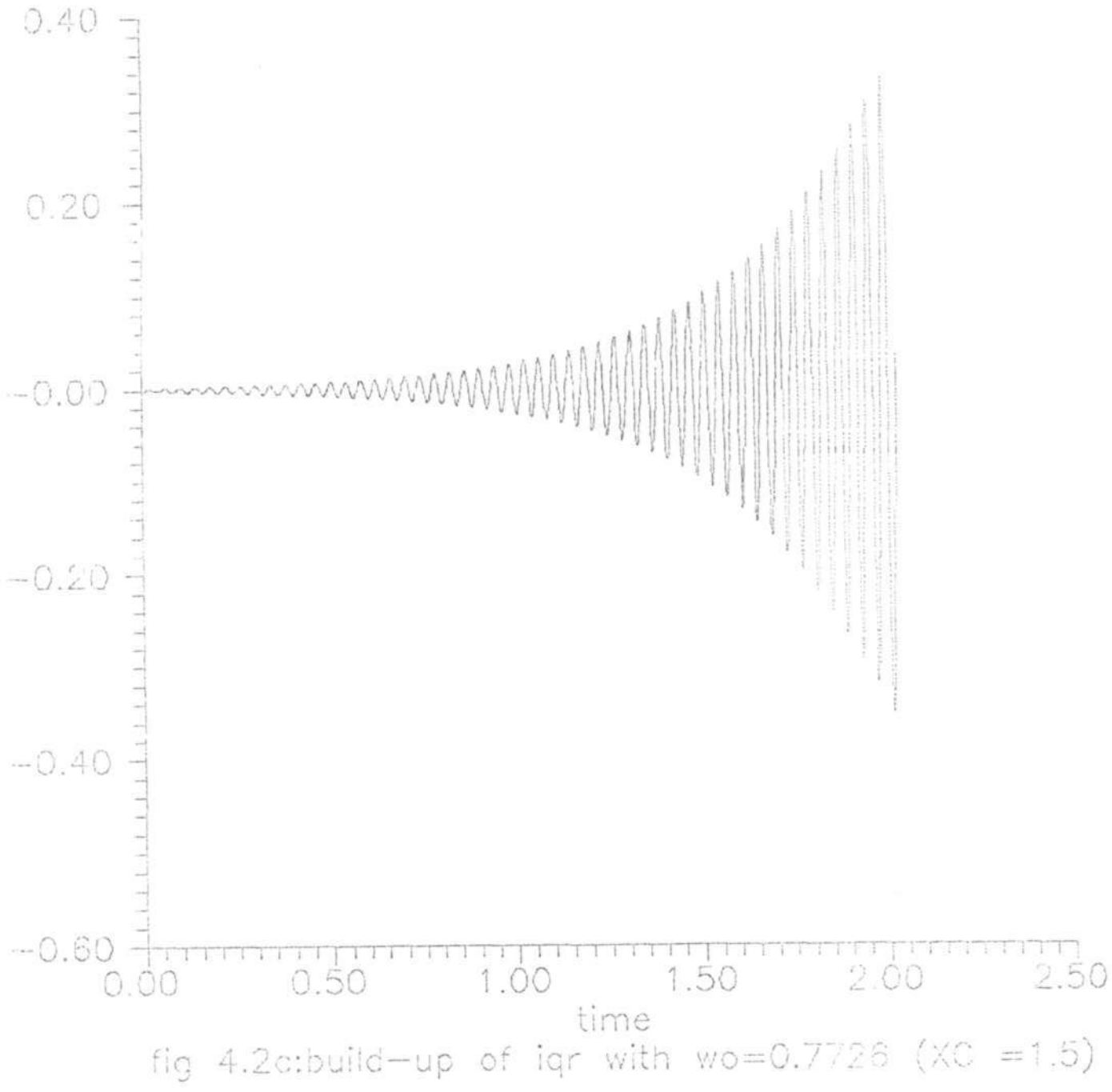


fig 4.2c:build-up of iqr with wo=0.7726 (XC =1.5)

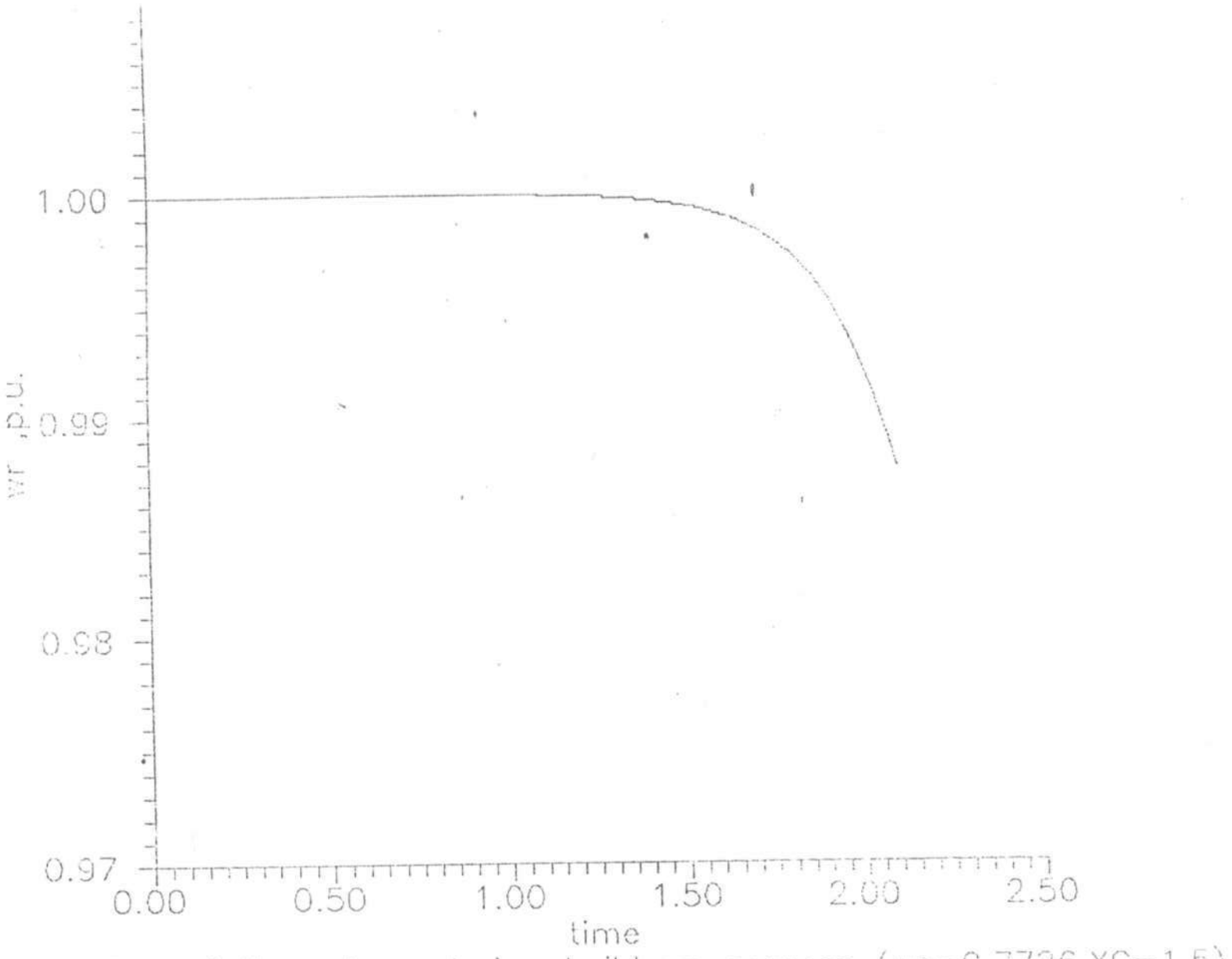


fig 4.2d:variation of wr during build up process (wc=0.7726,XC=1.5)

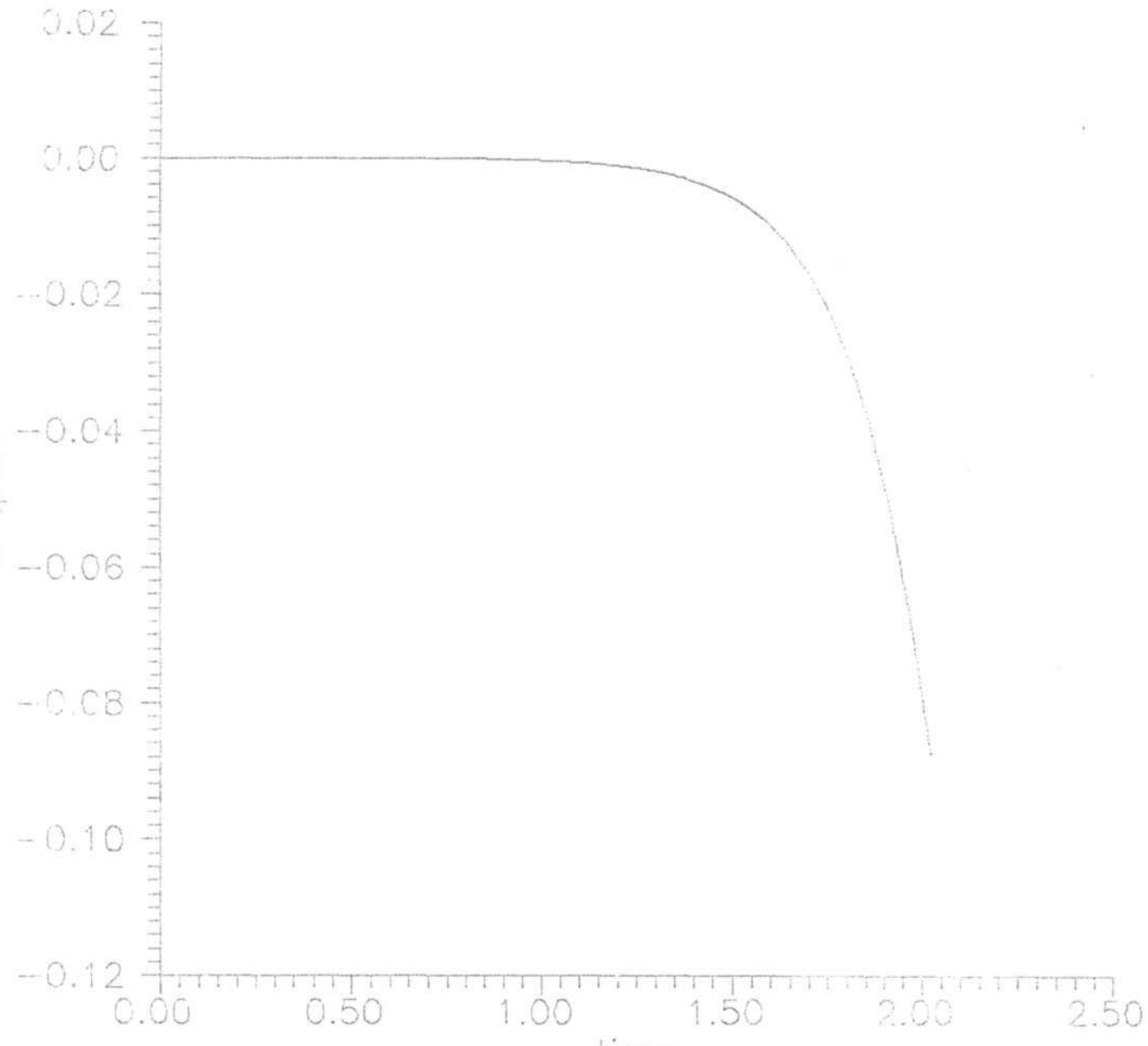


fig 4.2e:build-up of Te with wo=0.7723 (XC = 1.5)

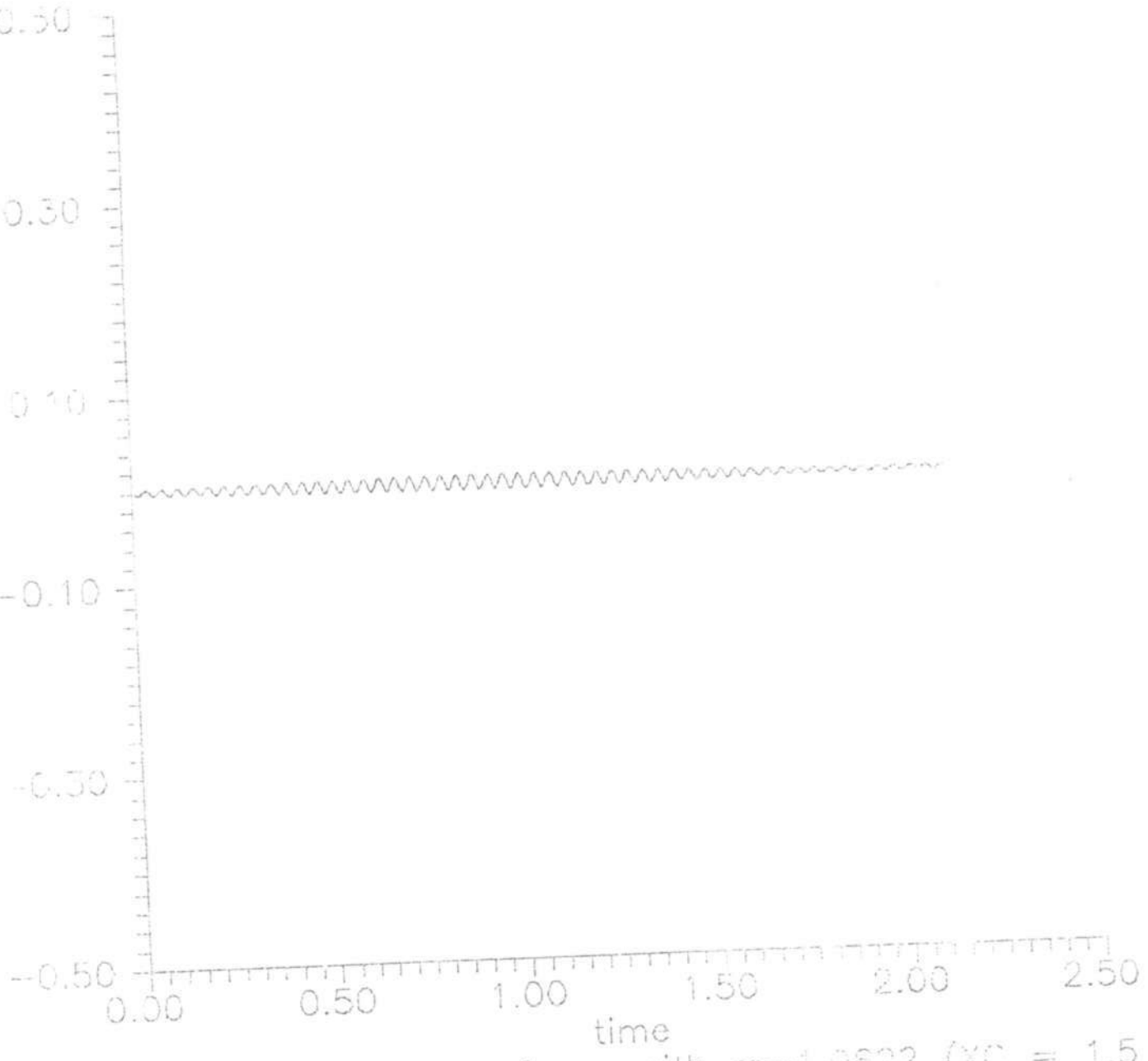


fig 4.3a:build-up of vqs with rs=1.0622 (XC = 1.5)

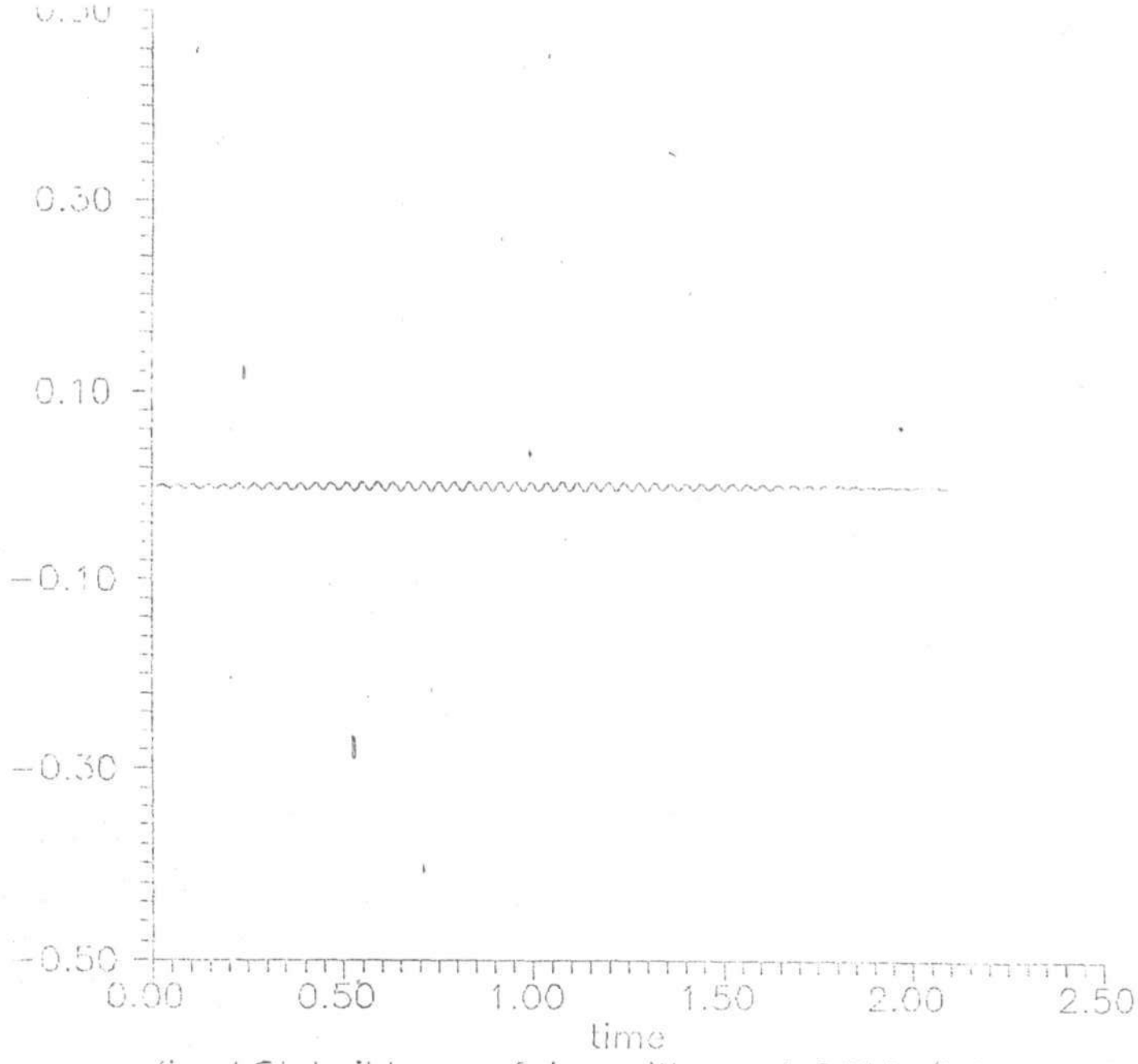


fig 4.3b:build-up of iqs with rs=1.0622 (XC = 1.5)

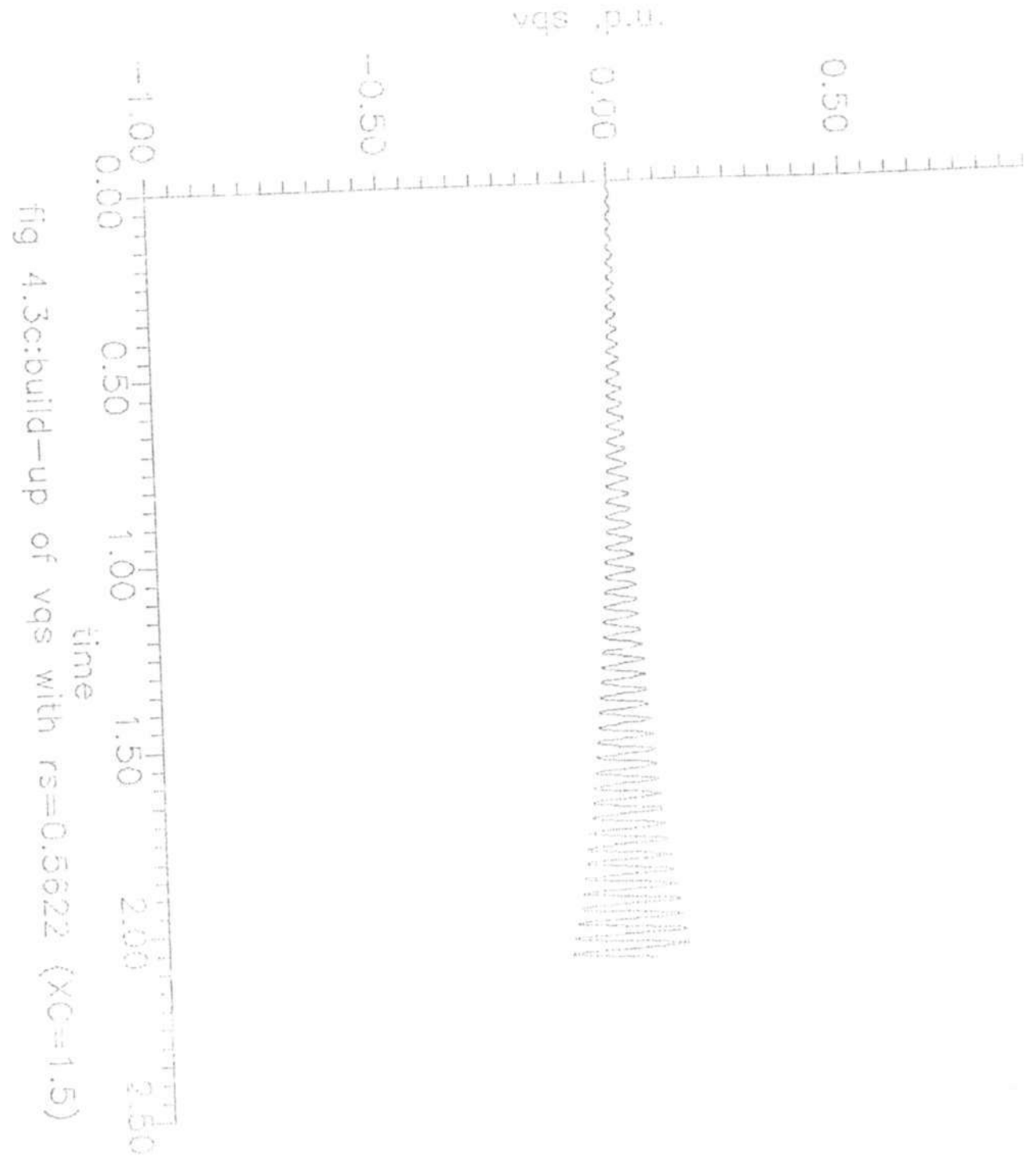


fig 4.3c:build-up of vqs with rs=0.5622 (XC=1.5)

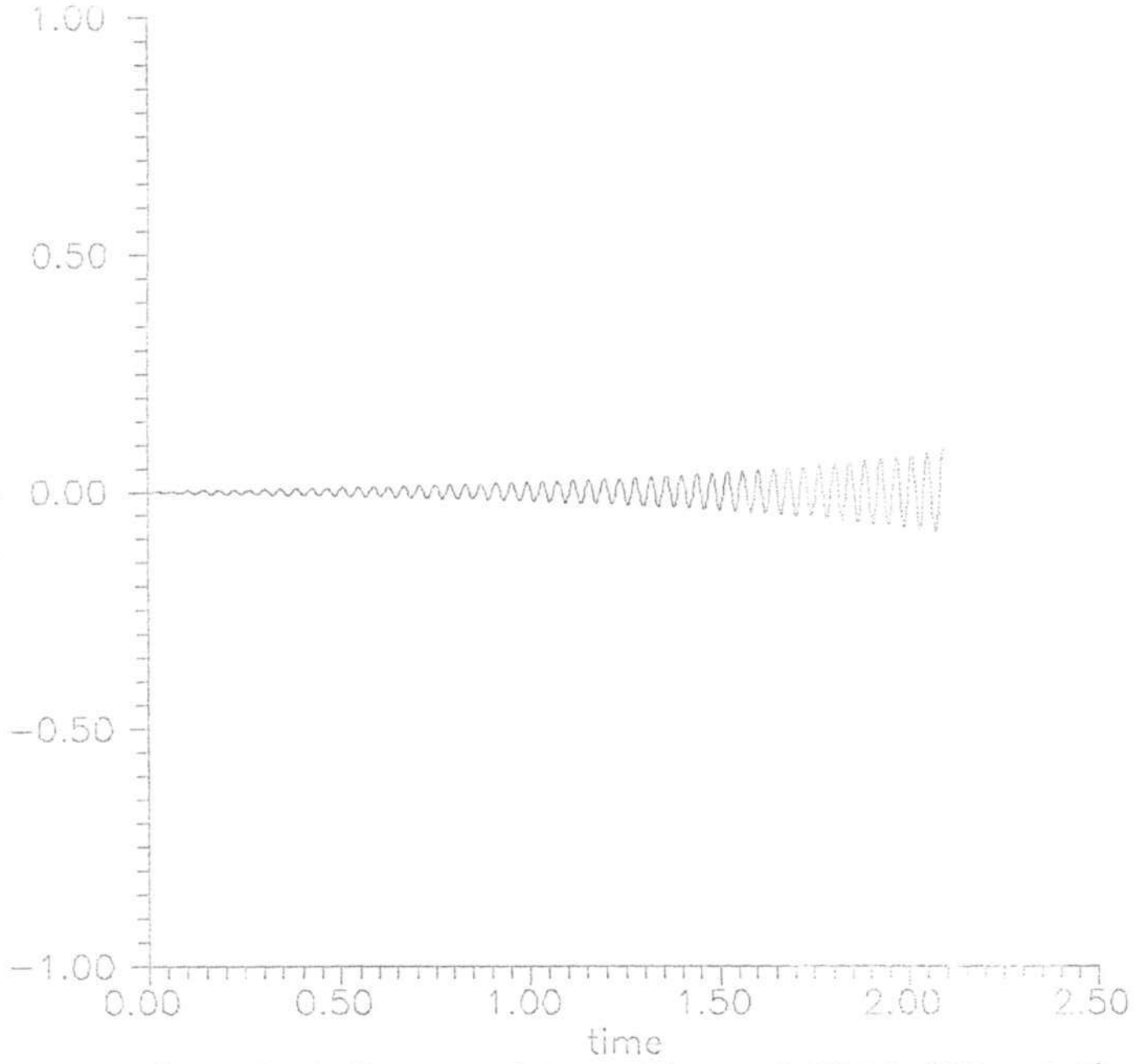


fig 4.3d:build-up of iqs with rs=0.5022 (XC =1.5)

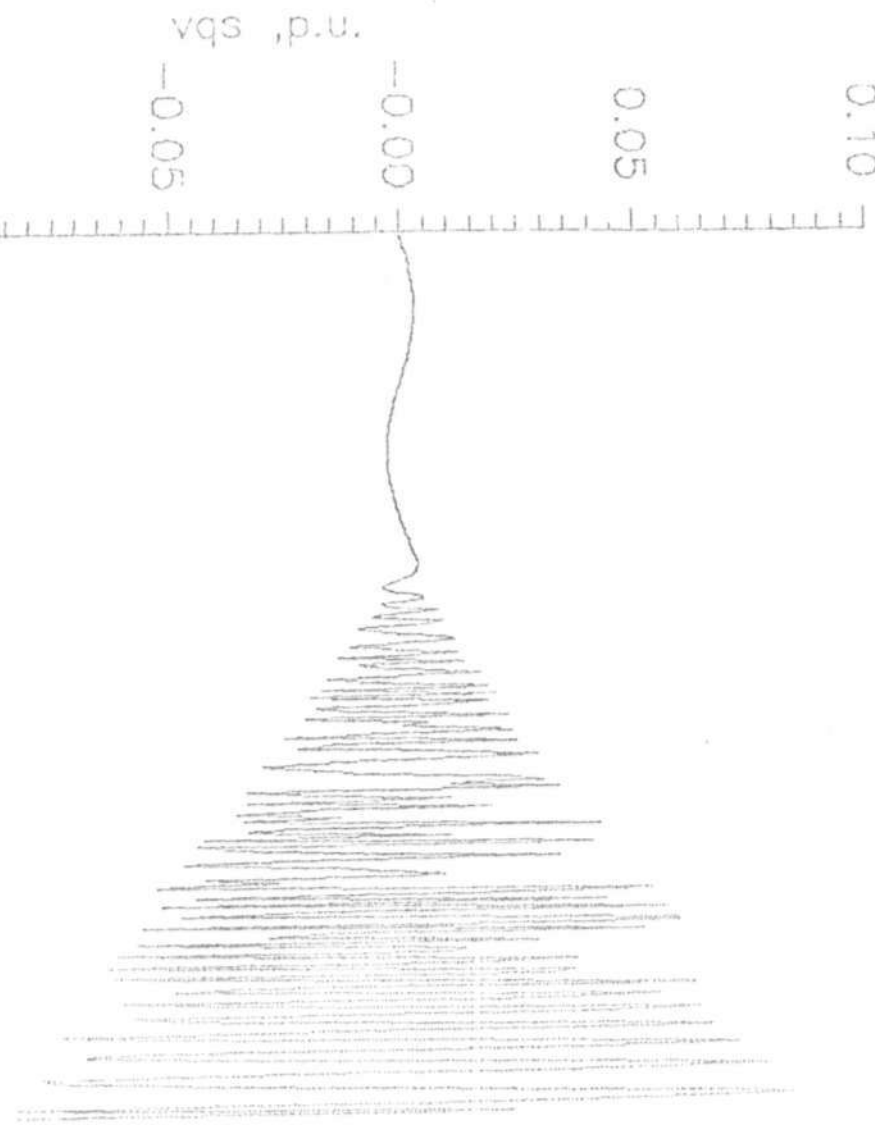


fig 4.4a:build-up of v_{qs} for rotor excitation ;stator open (XC =1.0)

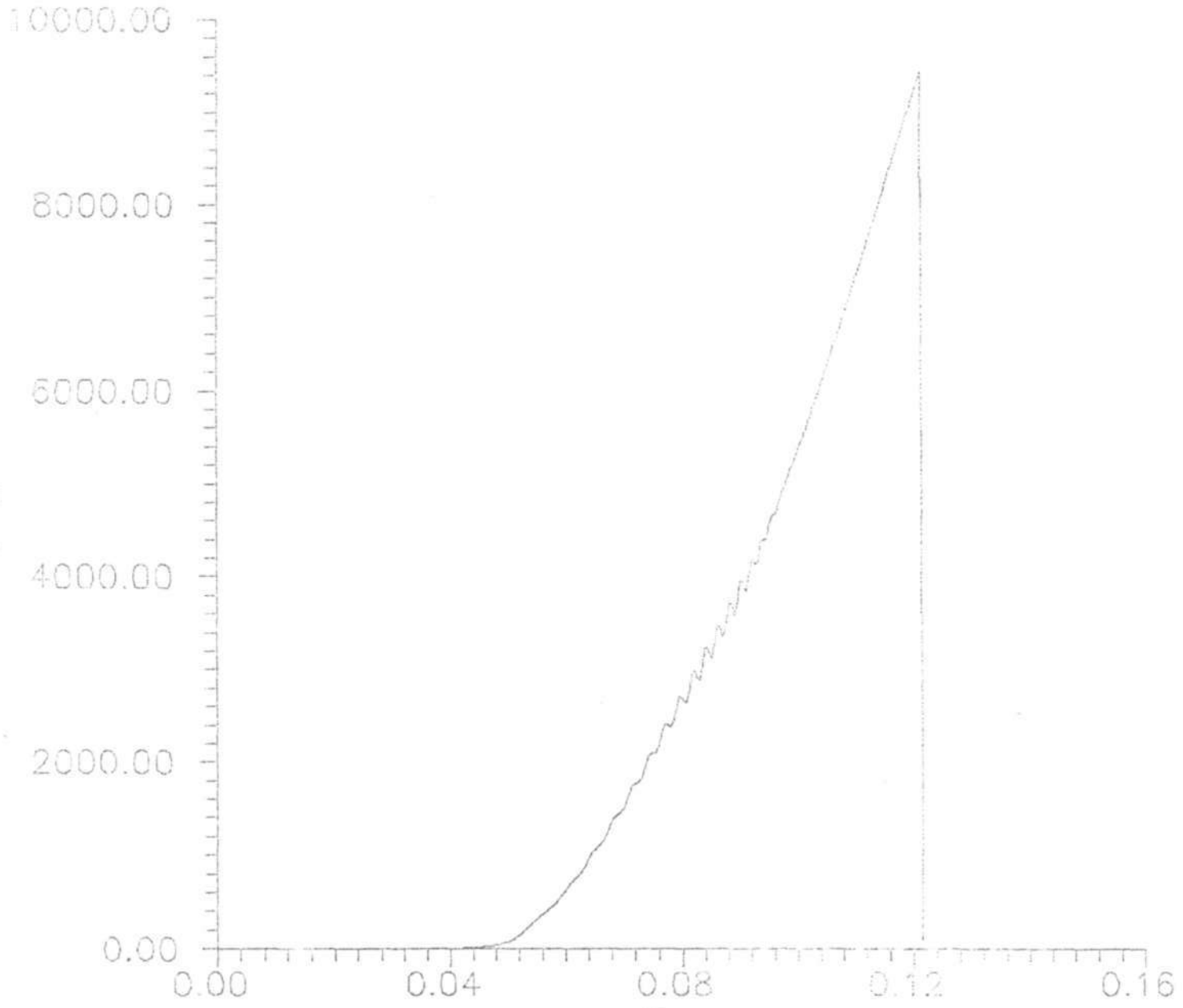


fig 4.4b:build-up of iqr for rotor excitation ;stator open (XC =1.5)

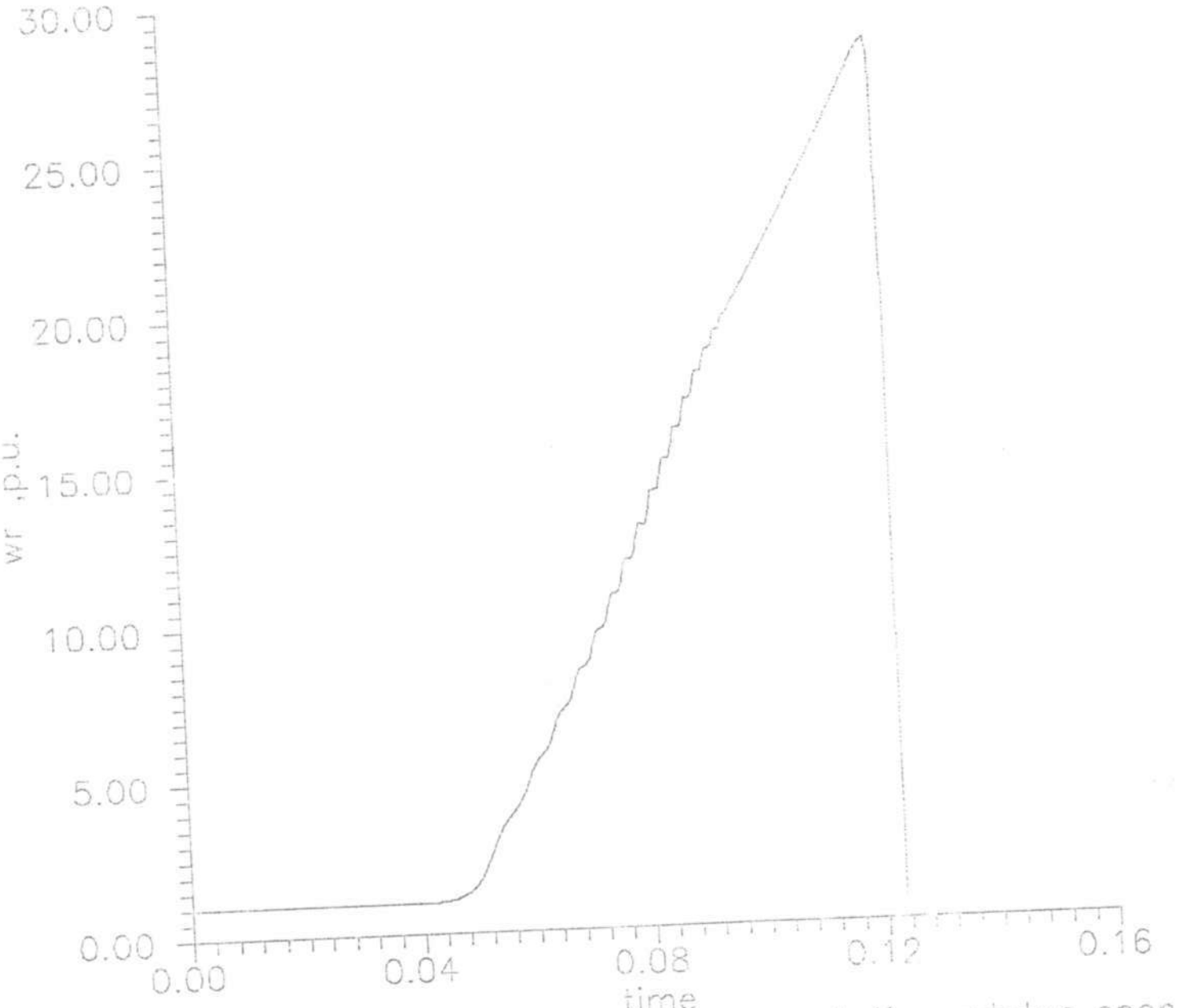


fig 4.4c:build-up of wr for rotor excitation ;stator open (XC =1.5)

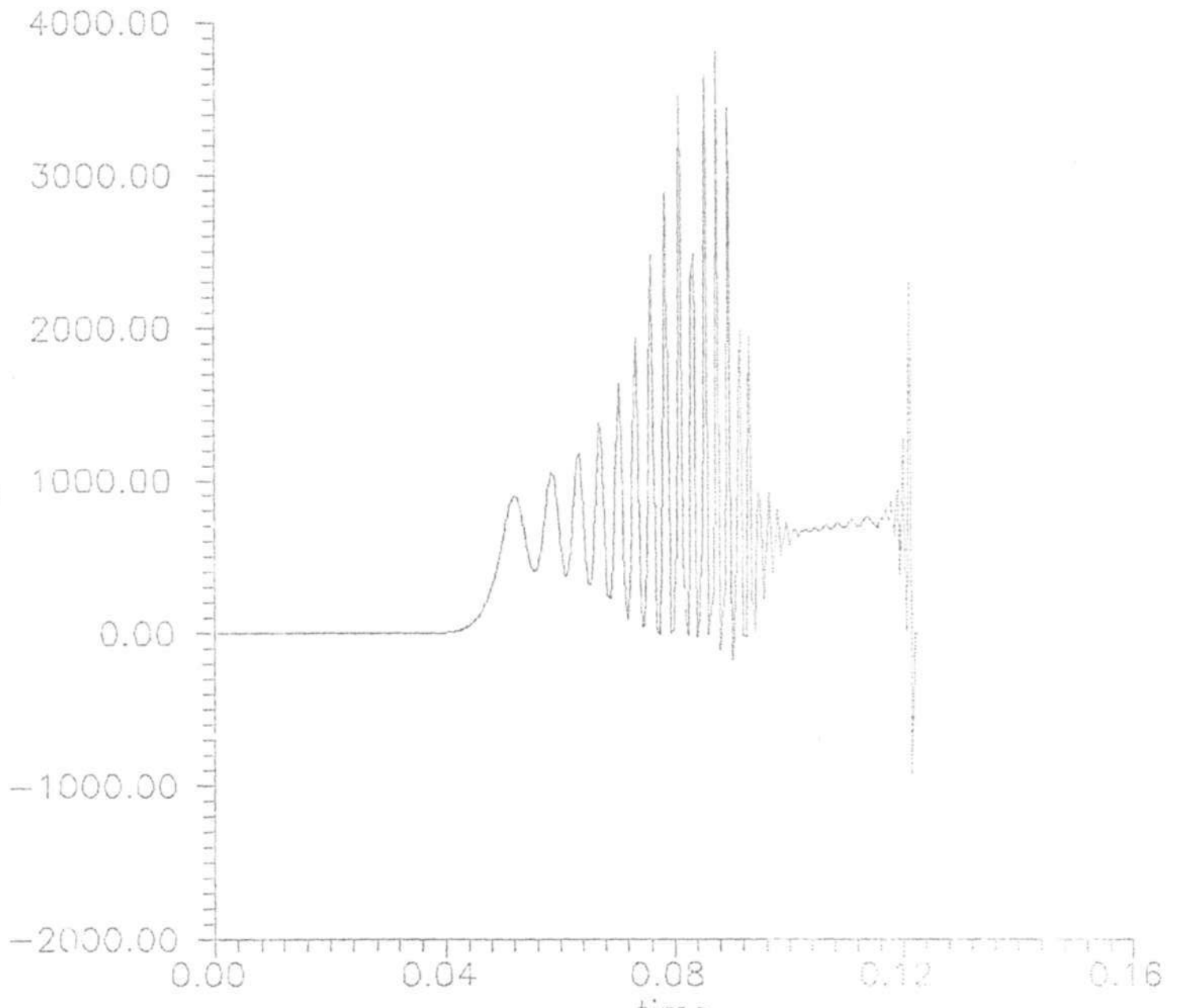


fig 4.4d:build−up of te for rotor excitation ;stator open (XC =1.5)

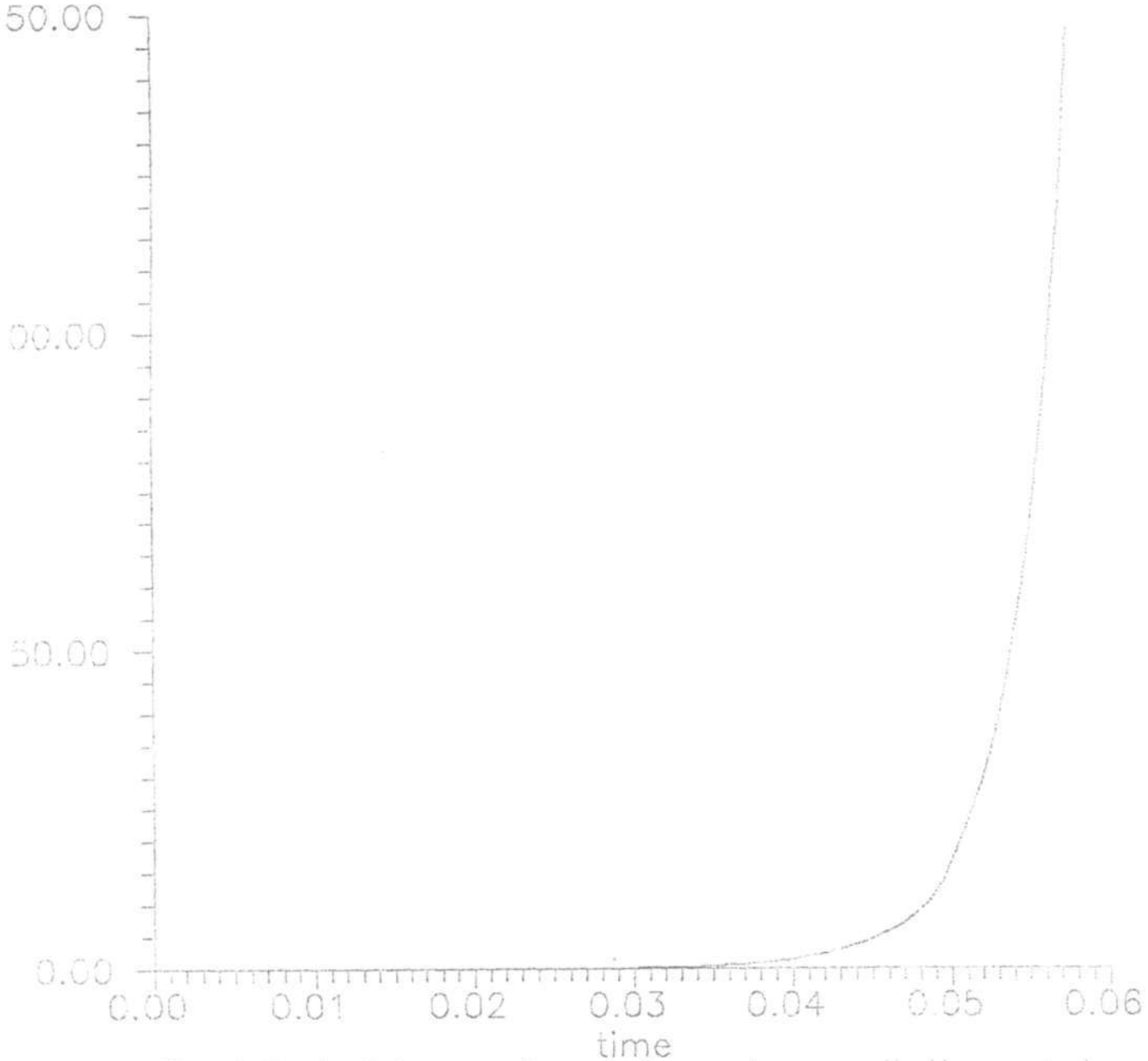


fig 4.5a:build-up of vqs for rotor excitation ;stator has a resistive load connected(XC =1.5)

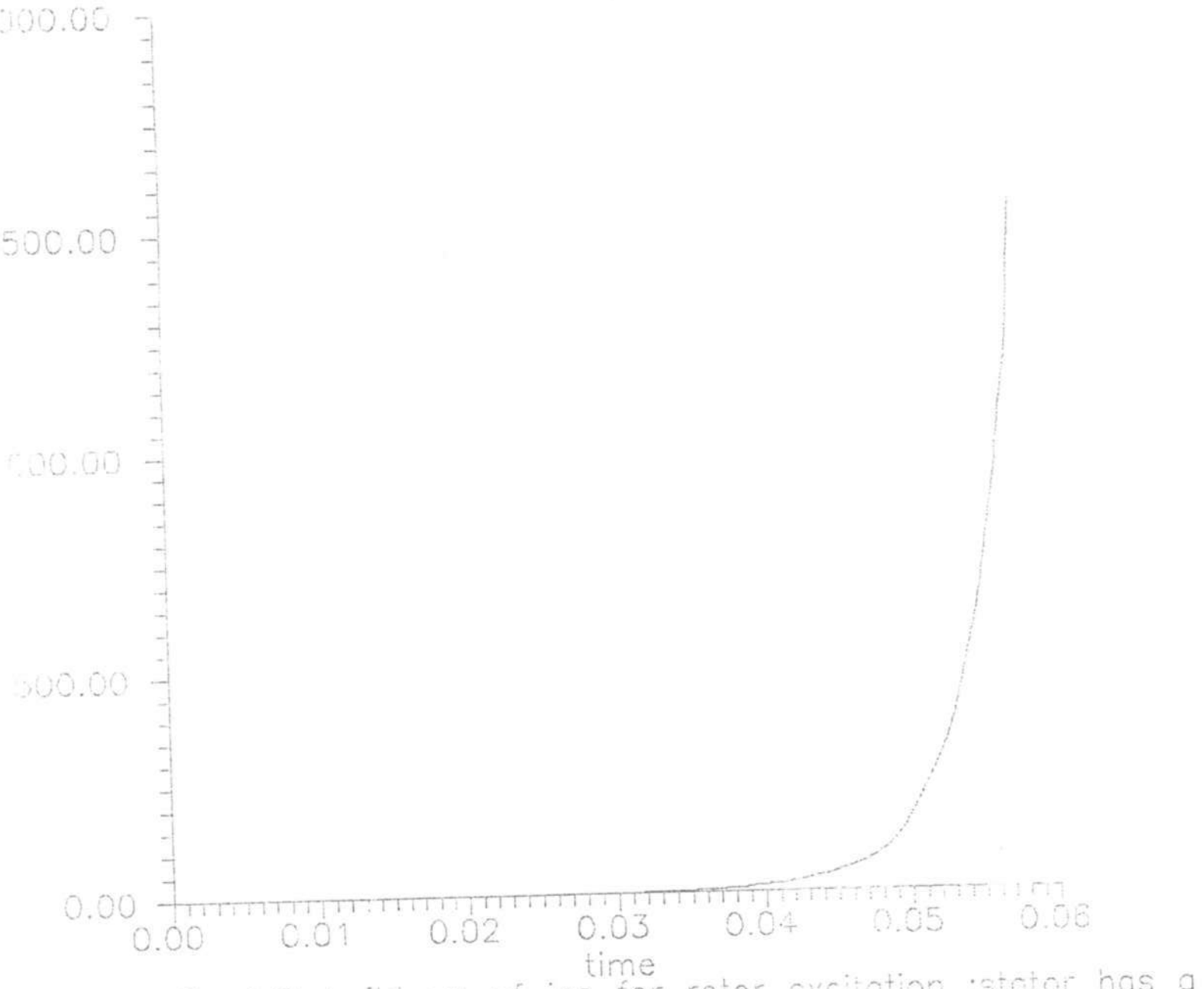


fig 4.5b:build-up of iqs for rotor excitation ;stator has a resistive load connected(XC =1.5)

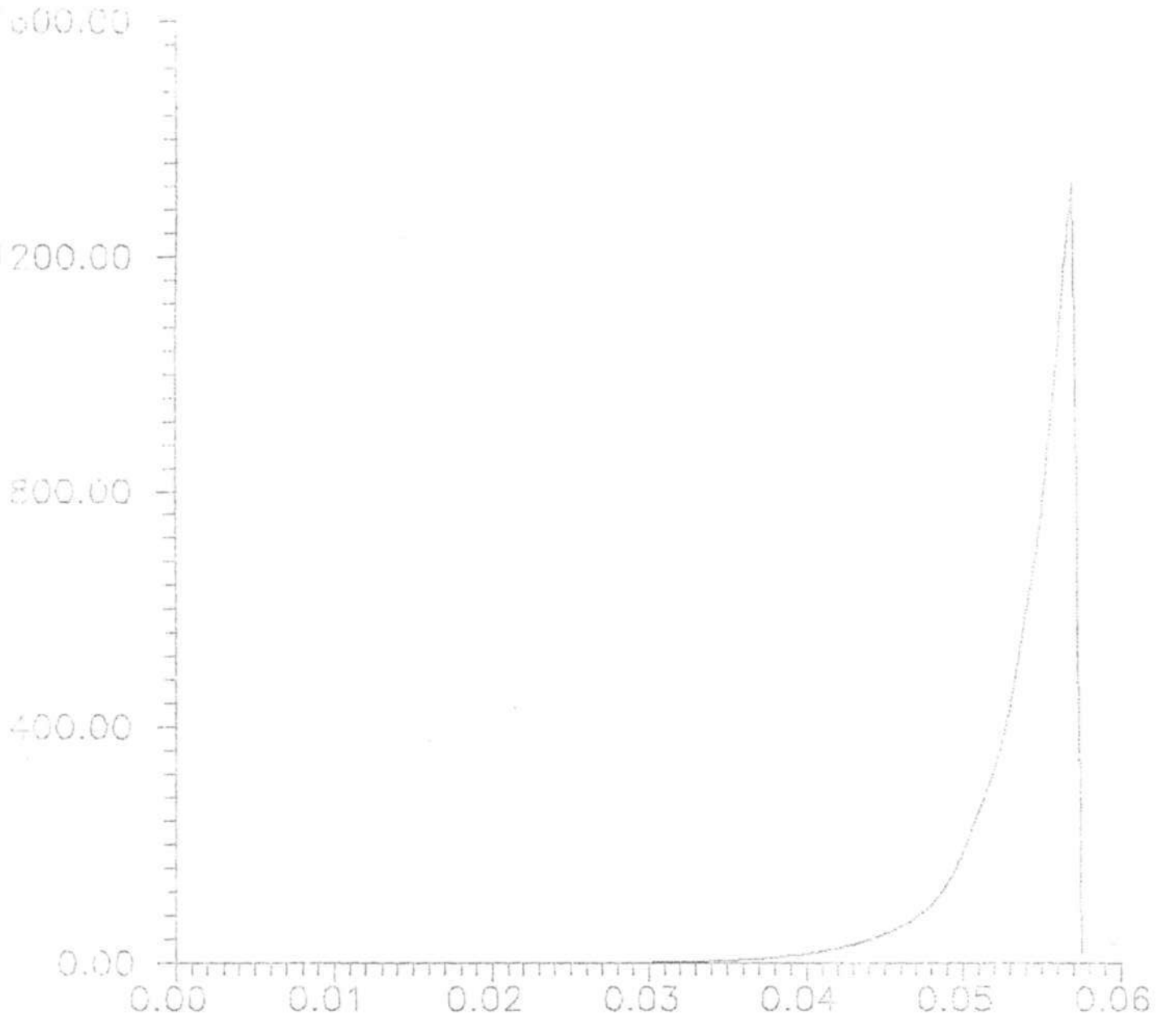


fig 4.5c:build-up of iqr for rotor excitation ;stator has a resistive load connected(X0 =1.5)

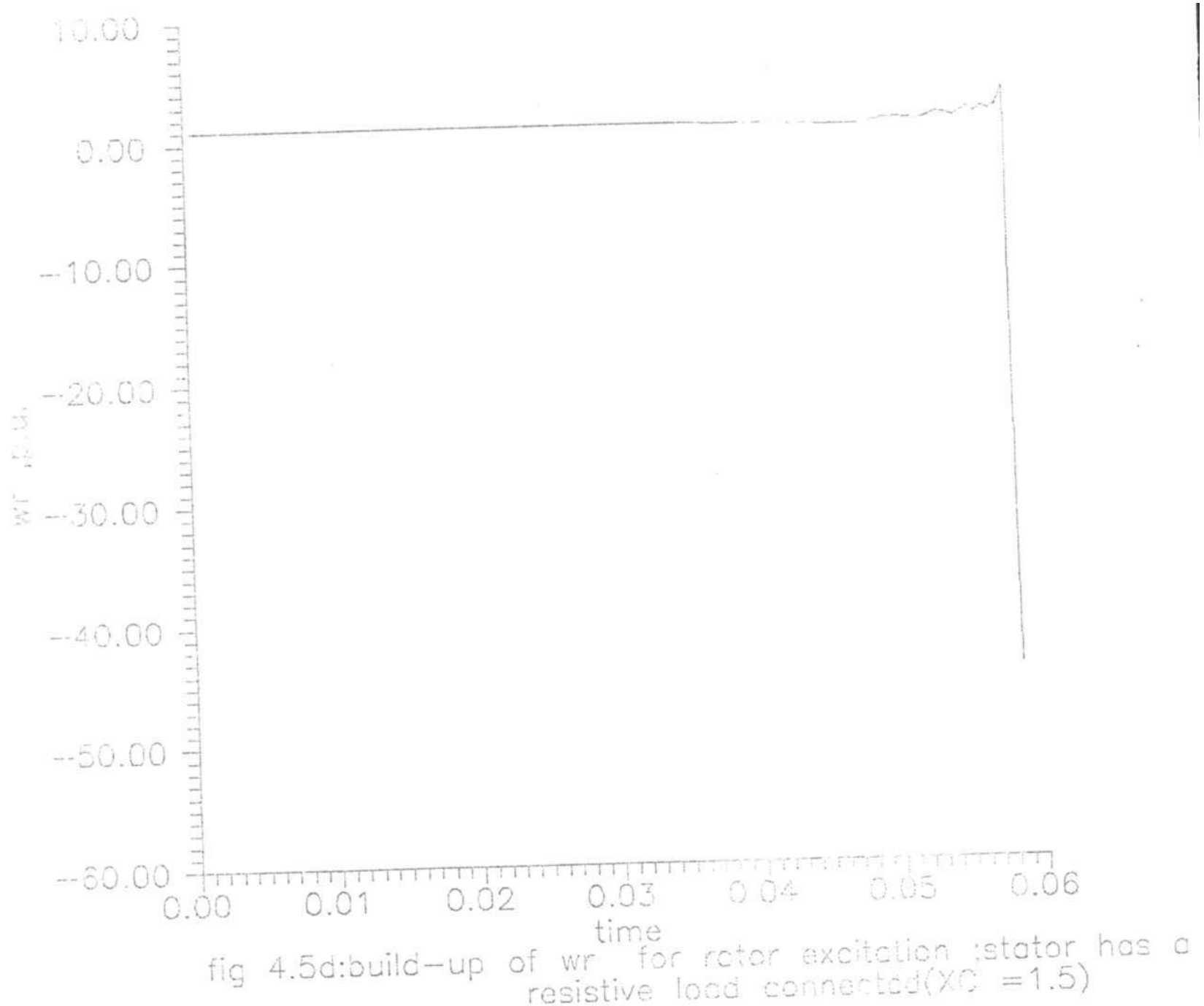


fig 4.5d:build-up of wr for rotor excitation ;stator has a resistive load connected(XC =1.5)

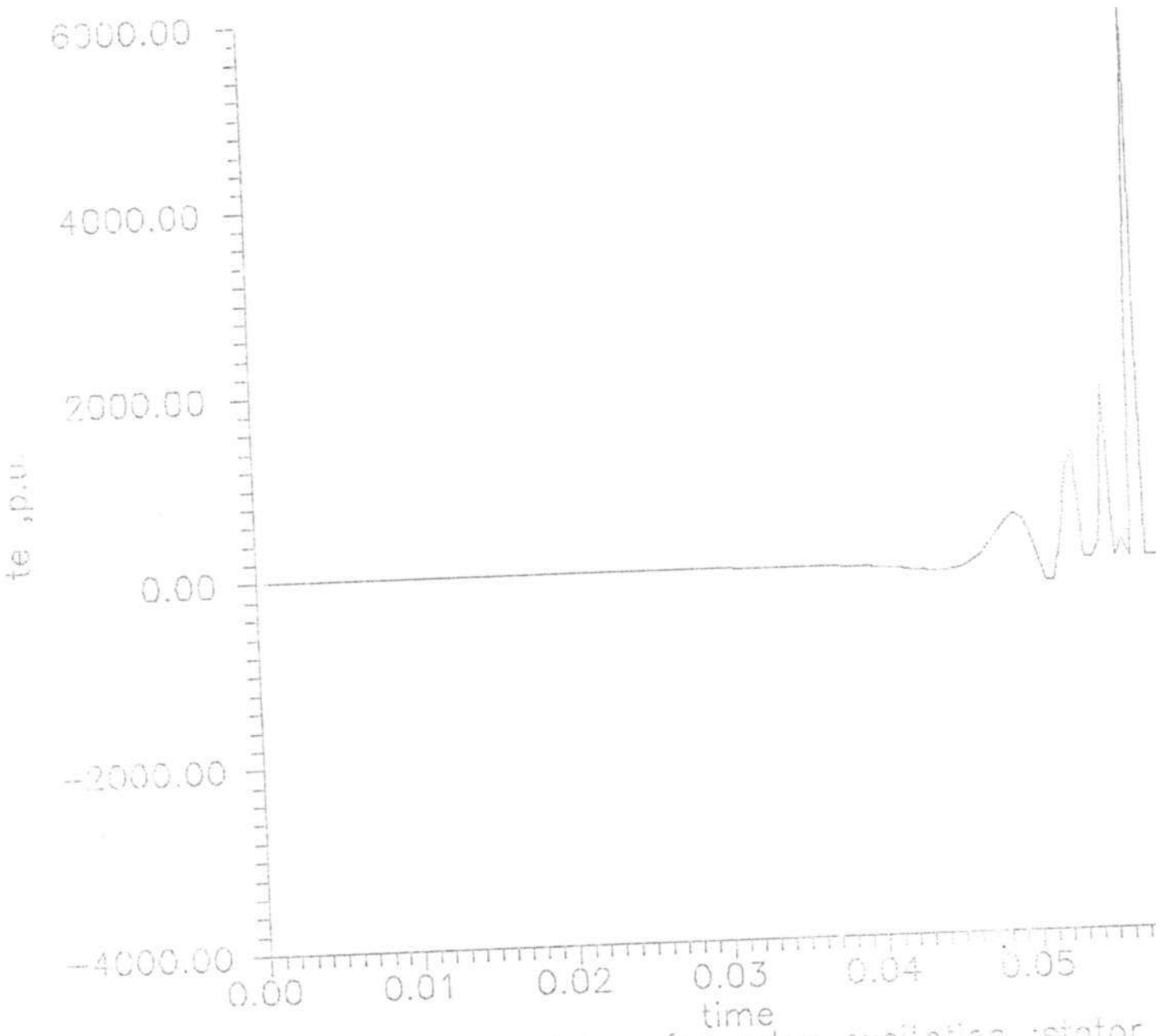


fig 4.5e:build-up of te for rotor excitation ;stator resistive load connected(XC =1.5

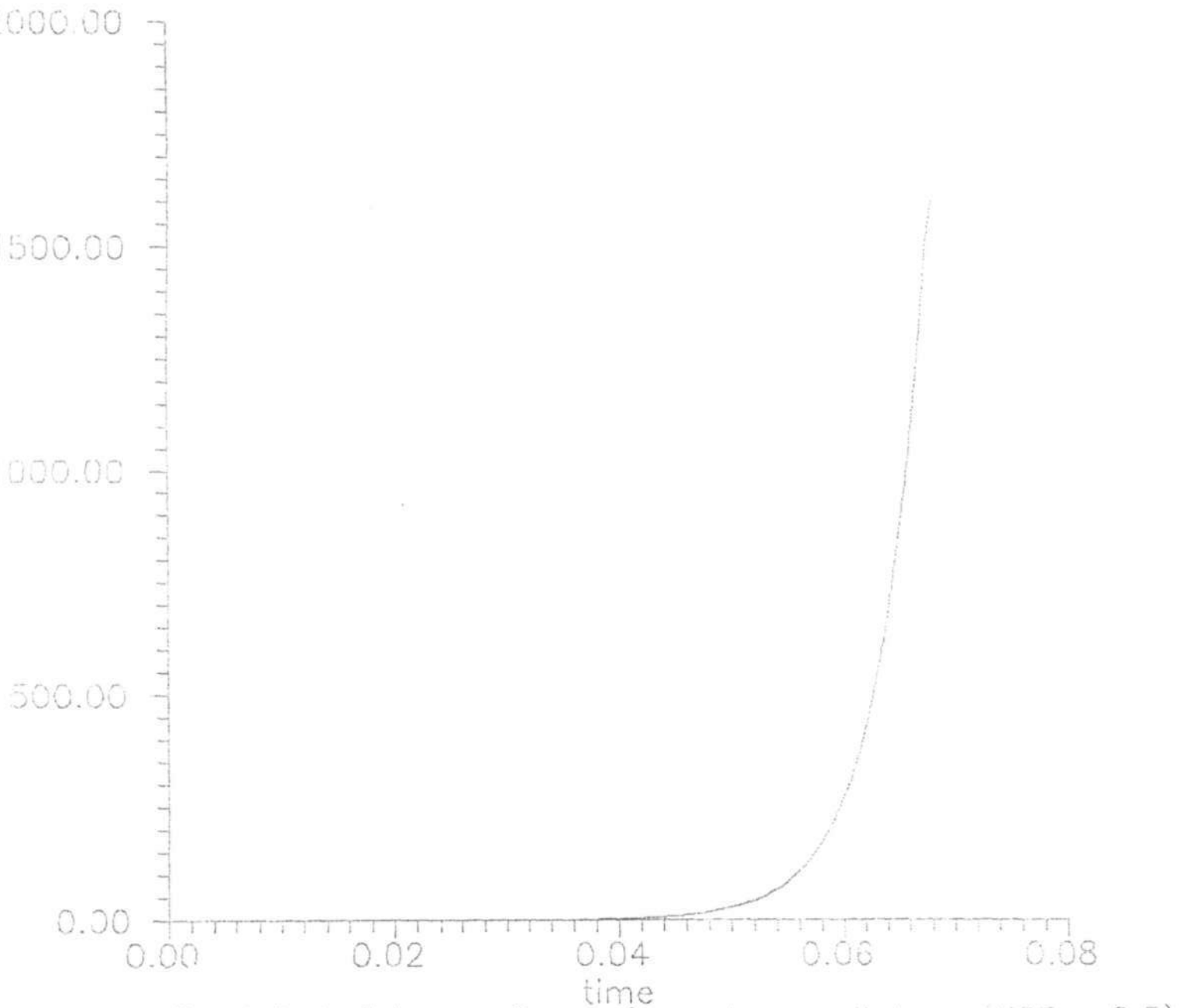


fig 4.6a:build-up of vqs for rotor excitation (XCR =0.5)
stator has terminal capacitors(XC =1.5)

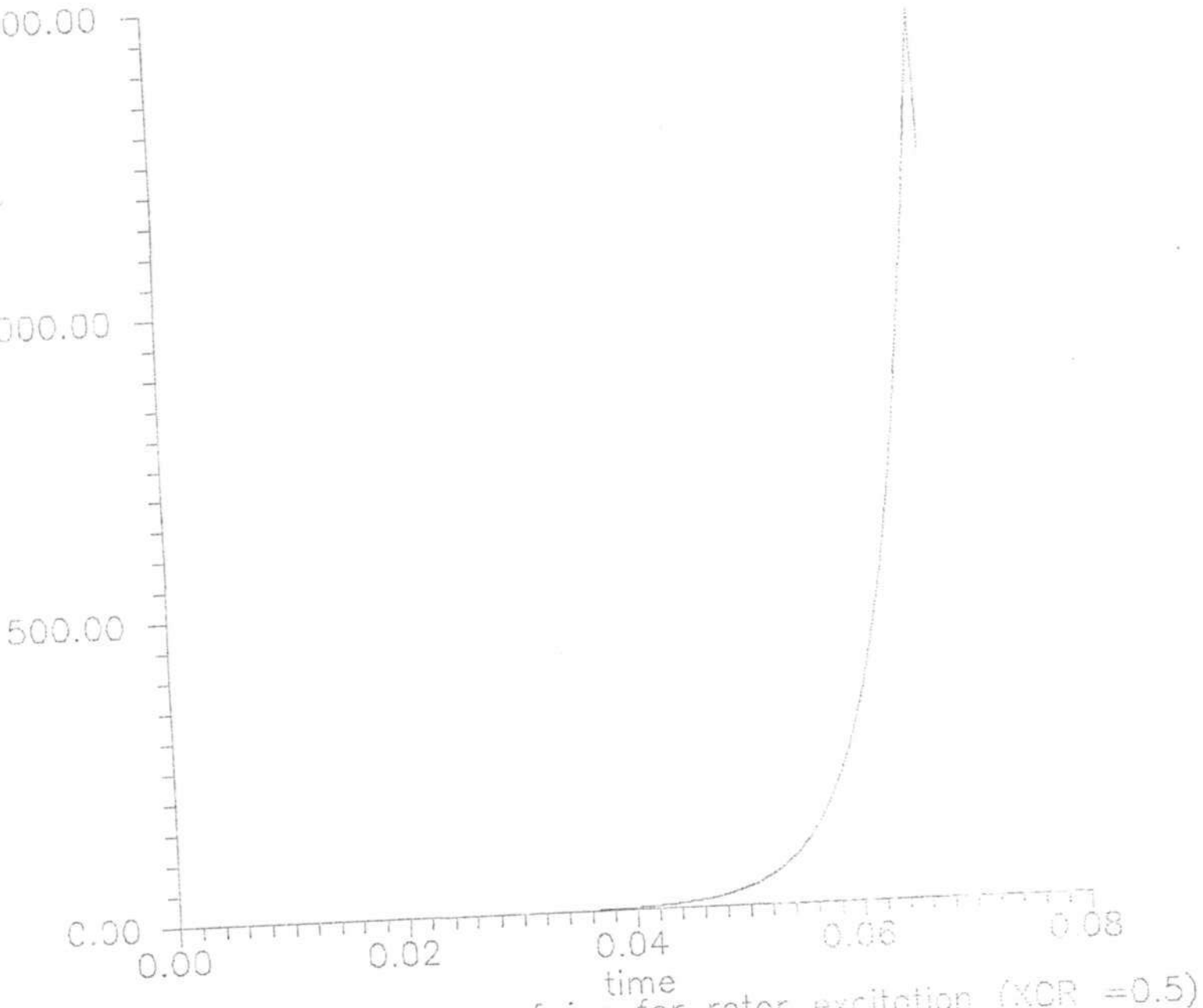


fig 4.6b:build-up of iqs for rotor excitation (XCR =0.5)
stator has terminal capacitors(XC =1.5)

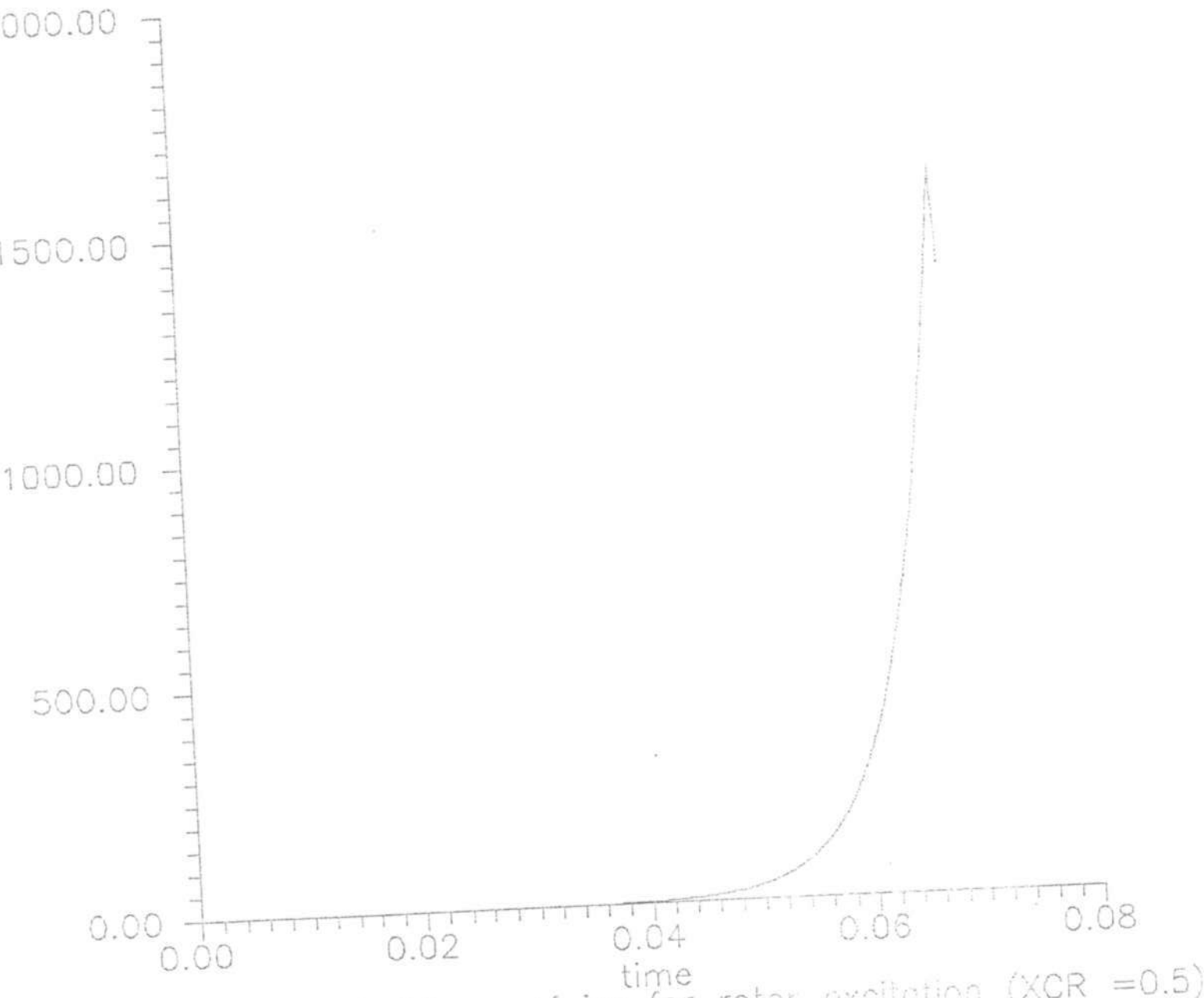


fig 4.6c:build-up of iqr for rotor excitation (XCR =0.5)
stator has terminal capacitors(XC =1.5)

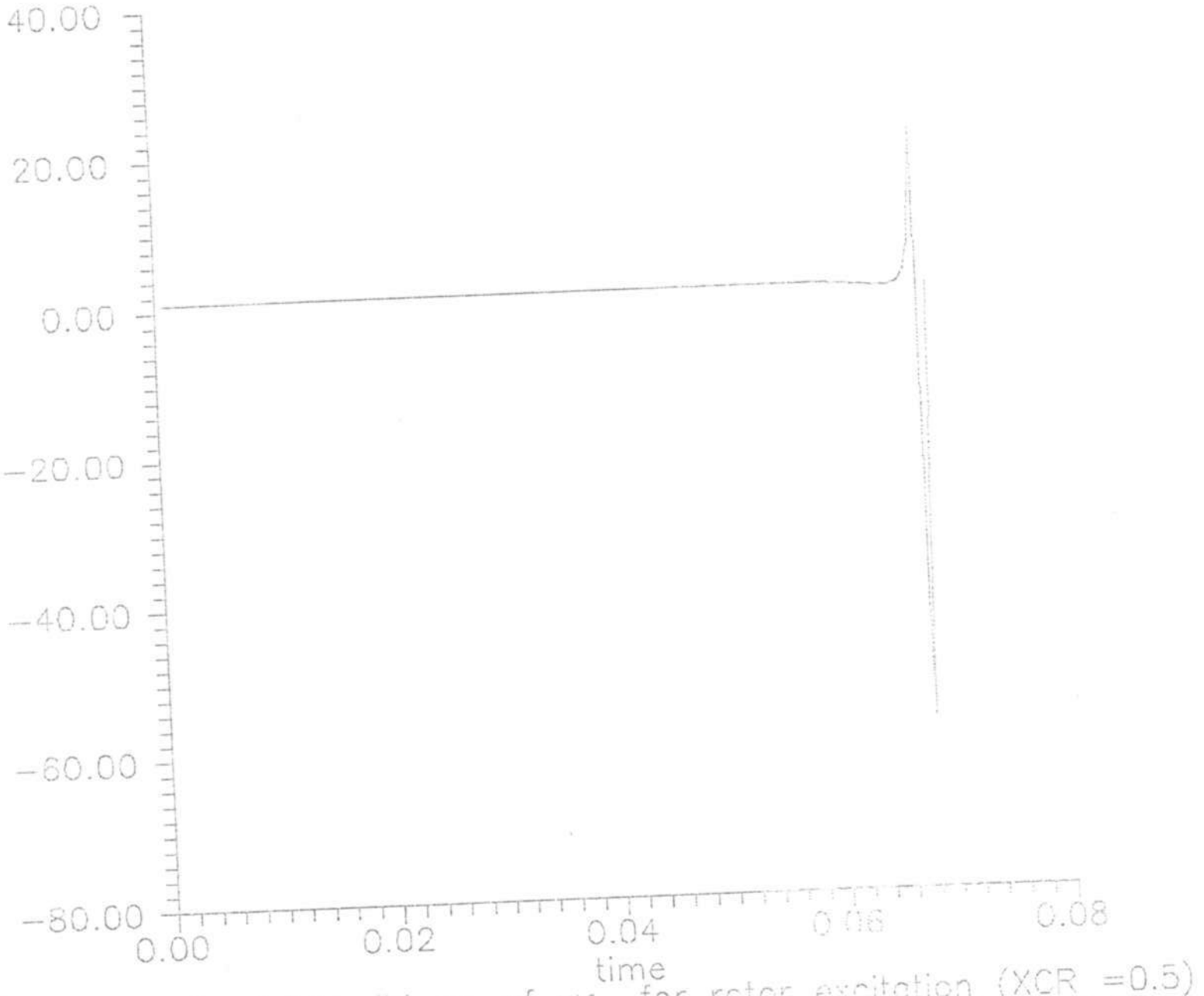


fig 4.6d:build−up of wr for rotor excitation (XCR =0.5)
stator has terminal capacitors(XC =1.5)

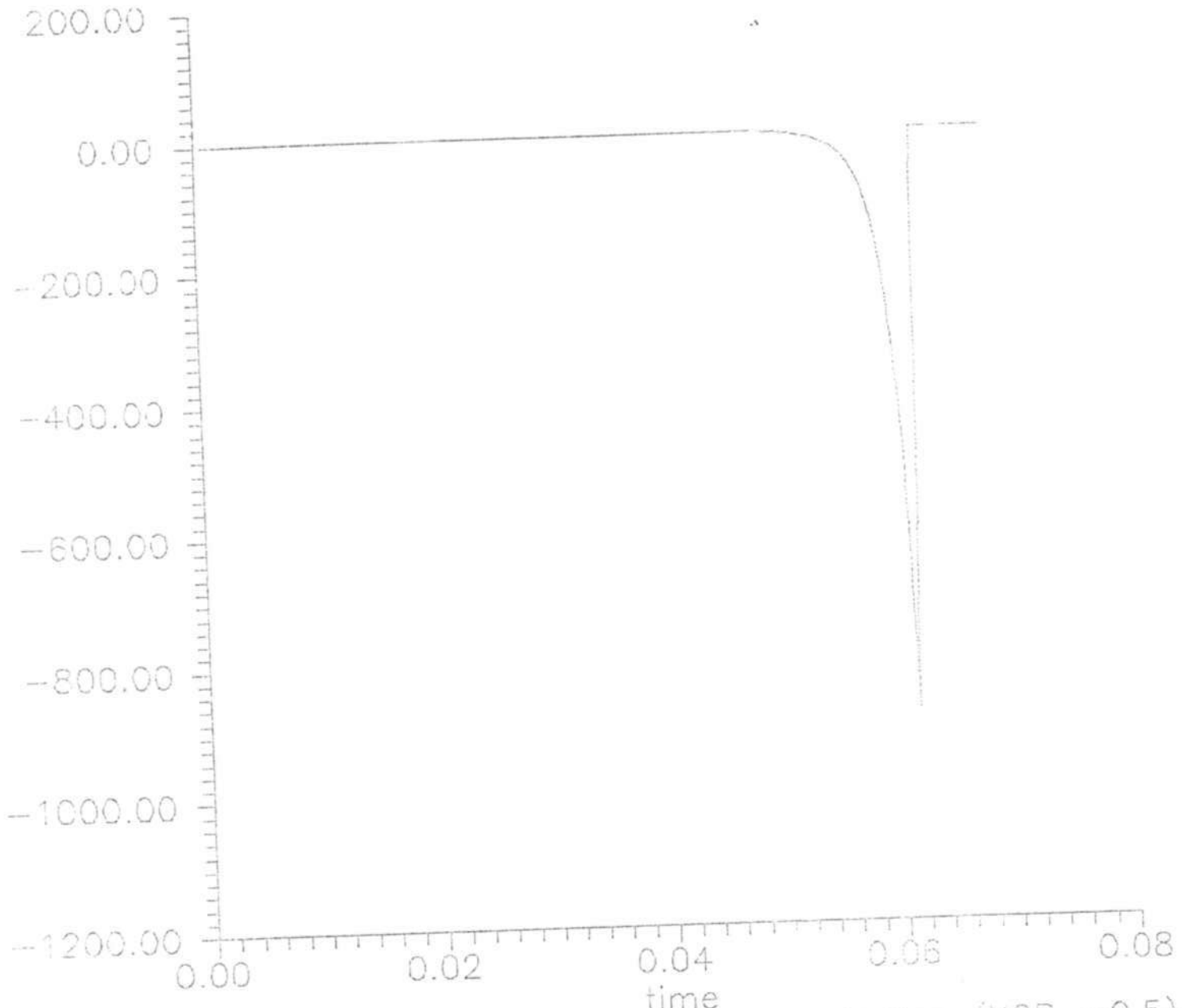


fig 4.6e:build-up of te for rotor excitation (XCR =0.5)
stator has terminal capacitors(XC =1.5)

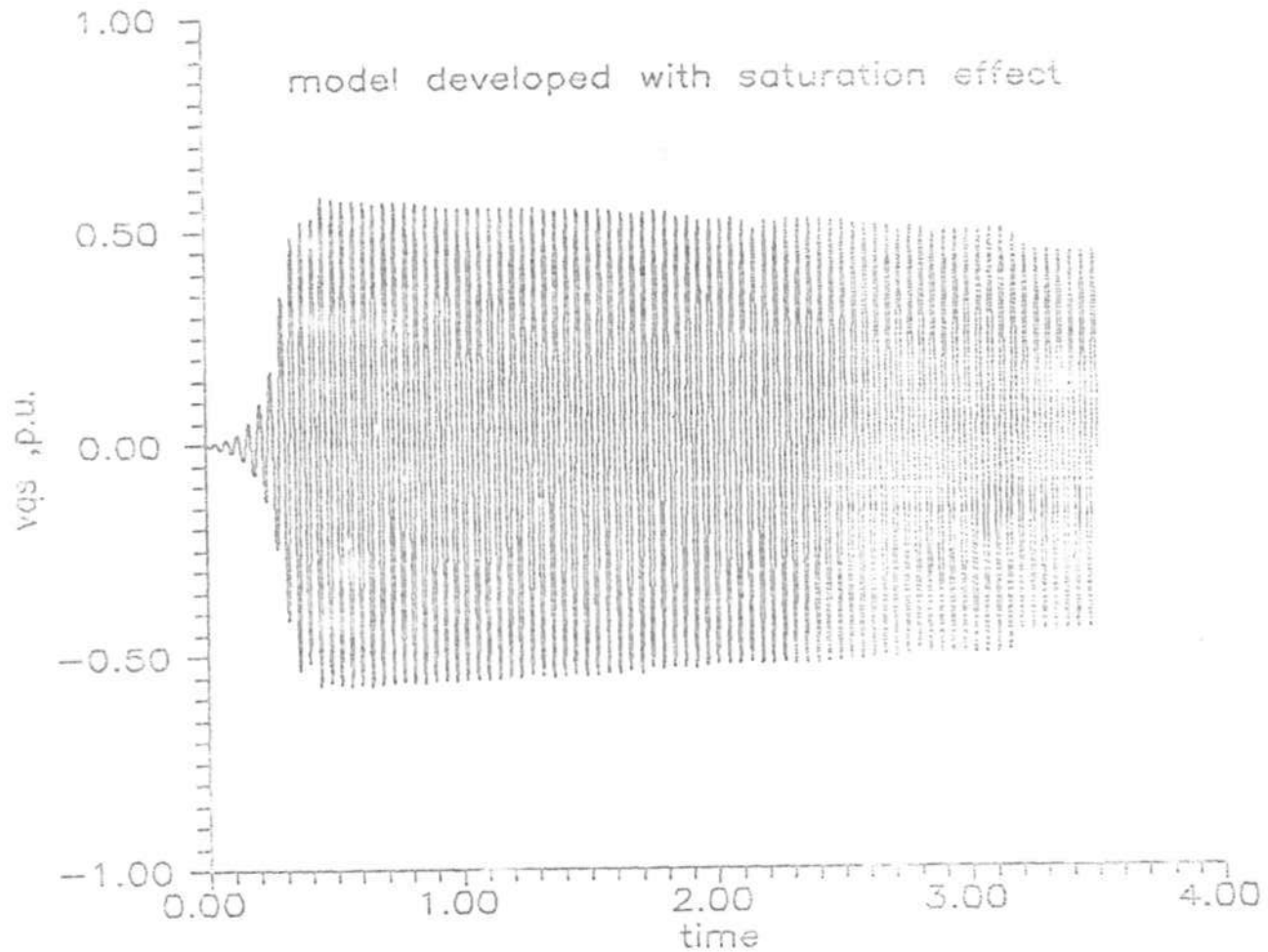


fig 4.7a:build−up of vqs with wo=0.7726 (XC=1.5)

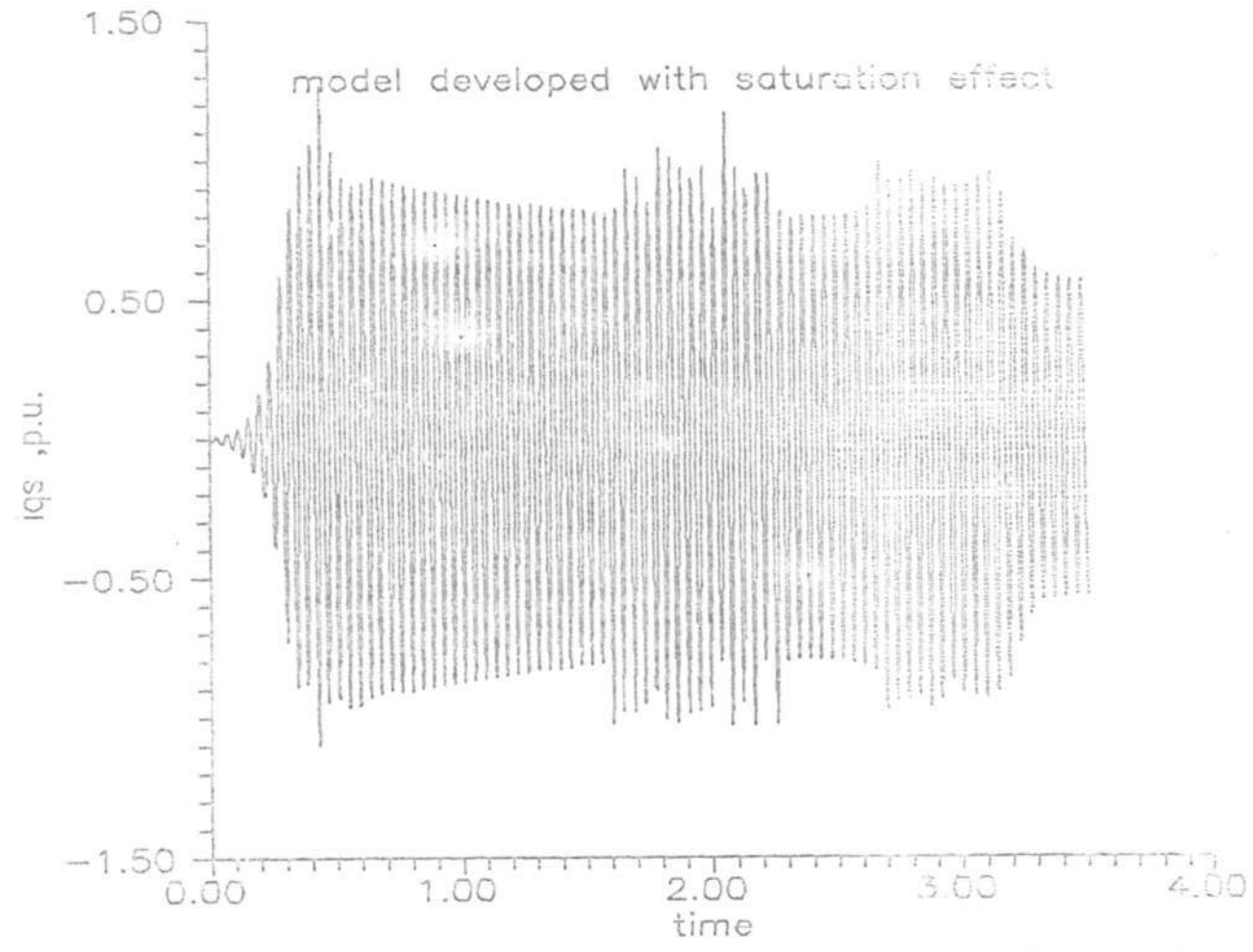


fig 4.7b:build-up of iqs with wo=0.7726(XC=1.5)

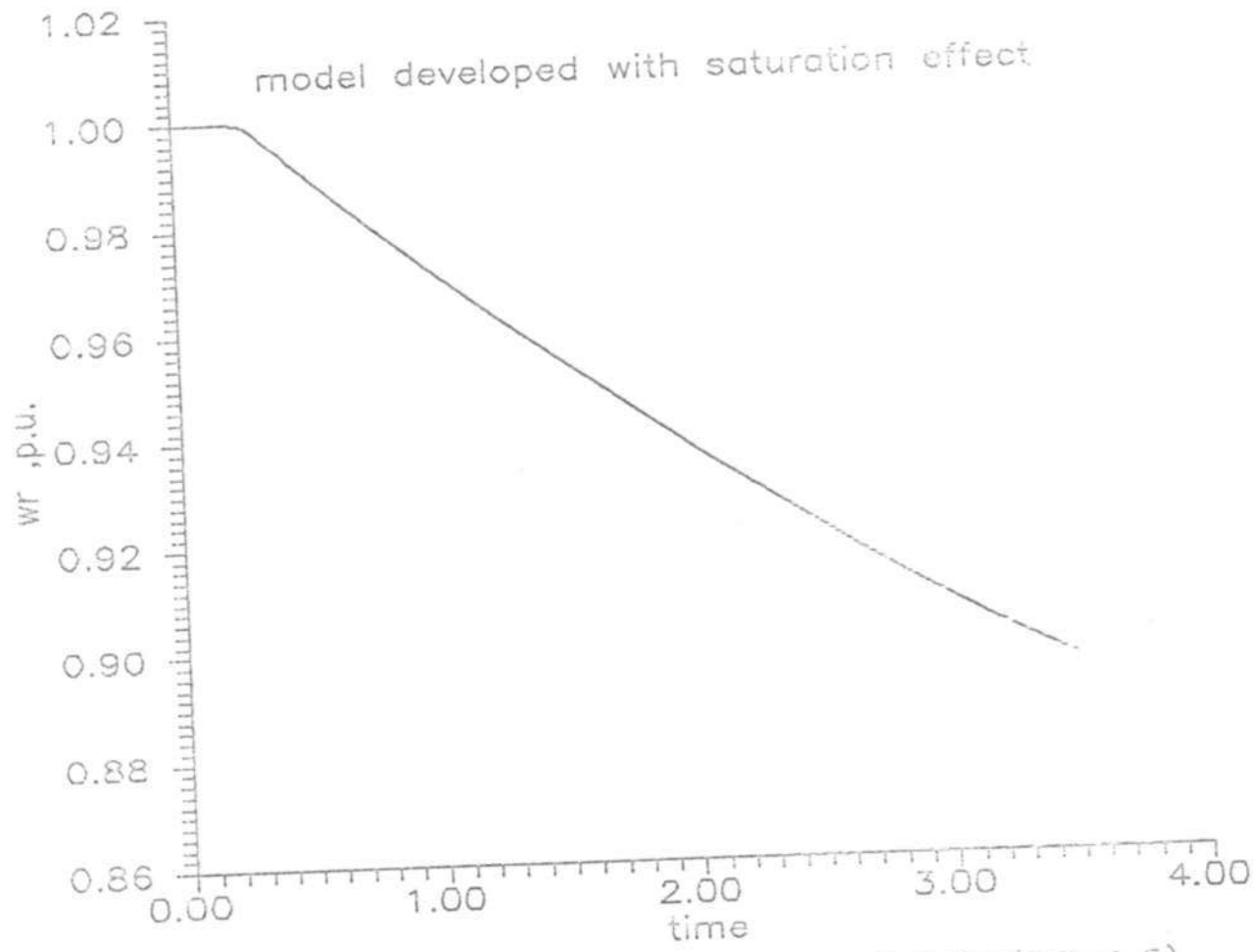


fig 4.7c:build-up of wr with wo=0.7726(XC=1.5)

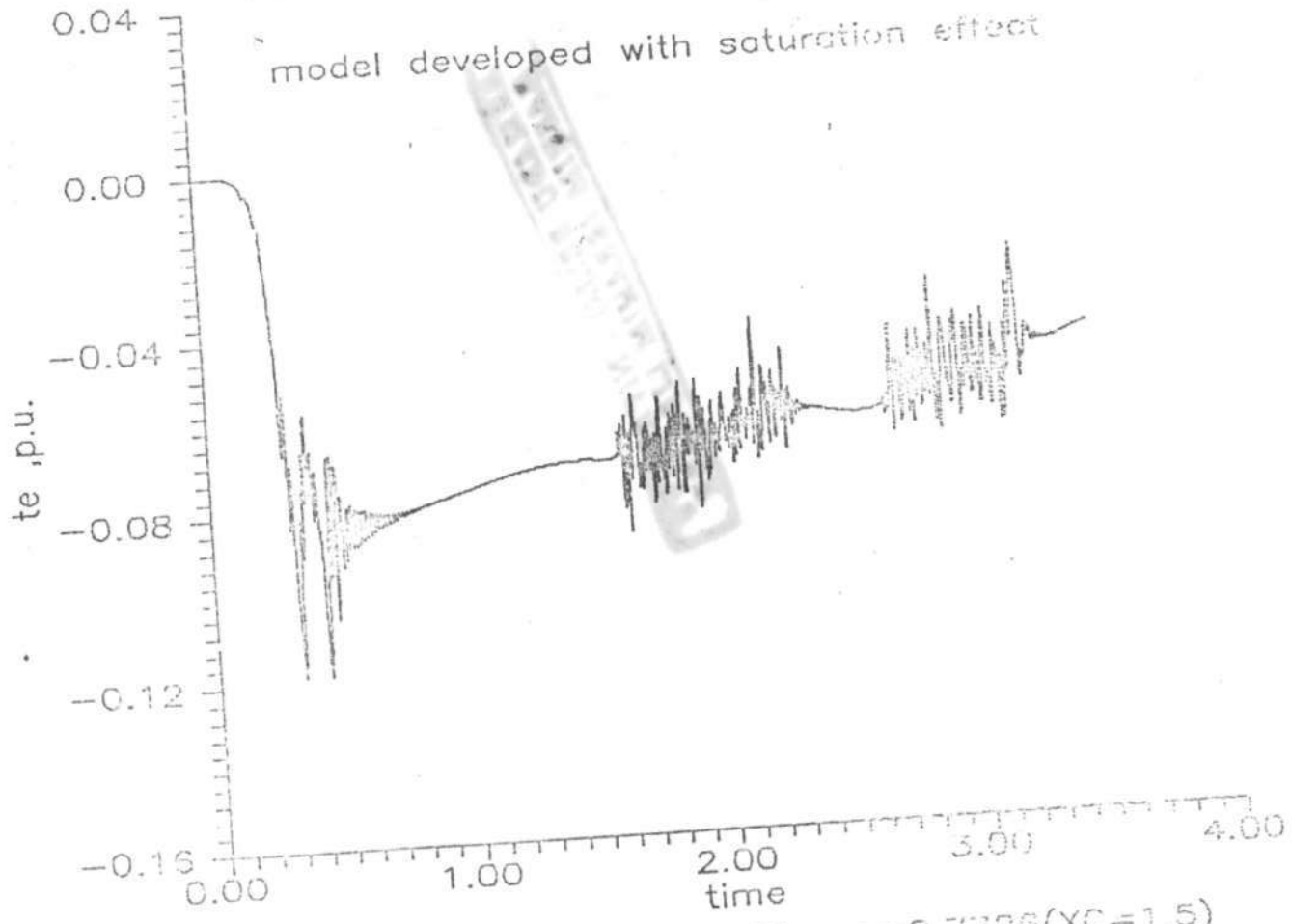


fig 4.7d:build−up of te with wo=0.7726(XC=1.5)