RELIABILITY ANALYSIS
OF
EXCITATION SYSTEMS

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by

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CERTIFICATE

Certified that the dissertation entitled 'RELIABILITY ANALYSIS OF EXCITATION SYSTEMS' which is being submitted by Sri P. K. GOEL in partial fulfilment of the requirements for the award of the degree of Master of Engineering in Electrical Engineering (Power Apparatus and Electric Drives) of the University of Roorkee, Roorkee is the record of student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

It is further certified that he has worked for a period of 7 months from January 1980 to July 1980 for preparing this dissertation at this University.

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—P. K. GOEL

ABSTRACT

The classic arrangement of a direct driven d.c. exciter has proved, in general, a reliable, economic and satisfactory source of excitation supply for turbogenerators of moderate output. With increasing rating of individual units, the excitation power required exceeded that practicable for a direct coupled d.c. machine and gearing was introduced to permit operation at a lower speed. These two factors, higher output and lower speed, inevitably resulted in greater physical size, with problems of access for maintenance purposes. Economics dictate that larger base load units should operate for the maximum period between planned shut down and provide a stimulus to develop alternative sources of excitation power. The rotating field a.c. exciter with static rectifier has been extensively adopted. Other excitation schemes are in use only on smaller units or on special or prototype machines.

In this thesis, a critical uptodate literature review of the different excitation schemes has been done. Application of probability techniques is made for reliability assessment of different excitation systems. Different possible alternative designs have been considered and the reliability analysis of these design alternatives has also been done. At last, a comparison of the basic system and the different design configurations has been made from reliability point of view in a tabular form.

Further information presented in this thesis will aid in evaluating different excitation systems and assist in specifying and predicting generating system performance.

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CHAPTER 1

INTRODUCTION

The excitation system has been considered an important component of the large synchronous generators. So for each new generator rating, a careful reliability evaluation of alternative excitation systems should be made to assure that advantage of technical improvements would be obtained.

Historically the shaft-driven exciter has been the principal source of excitation for last many years. It is relatively simple and straight forward in that excitation power is generated physically close to the utilization point, the generator field. It does not rely upon the plant auxiliary systems for power and therefore, is not subject to electrical disturbances on other equipment or the system. The large inertia of the main generator rotor and the turbine provides power to allow field forcing during system transients. The shunt connected d.c. generator with commutator and carbon brushes [62] has been used for many years in this application.

After careful study of reliability and economic factors, the shaft driven d.c. exciter proved best each time. It is noted that as generator and exciter ratings increased, exciter speeds have been reduced by the use of speed reduction gears. Speed reduction was necessary because of practical design limits on 3000 RPM d.c. machines. The speed reduction gear friction losses result in about a one per cent reduction in exciter efficiency, also the physical size of the low speed exciter and gear became quite large in comparison to the main generator. The exciter rating pointed out the trend that as generator rating increased, the exciter size increased more than proportionally due to the lower speed. With the large speed reduction gears, the exciter required nearly as much space as the main generator.

Although, in general, performance, reliability and maintenance of rotating d.c. exciter have been excellent, there have been instances, especially in industrial plants, when maintenance has been quite troublesome [37]. Many of these plants have atmospheres contaminated by such gases as SO_2 , SO_3 and chlorine, which are detrimental to commutator films. These contribute to excessive sparking, short brush life, heavy carbon deposits in the exciter and brush rigging and excessive or uneven wear of the commutator. In many cases, a shut down of the synchronous generator has been necessary to correct these difficulties. Thus there is a need for an excitation system which can be maintained without shut down, and preferably one which completely eliminates rotating commutators.

In the last many years, large quantity procurement of commercial,military and aircraft generators has concentrated development activity on excitation systems for a.c. generators. This development experience, coupled with new components and materials has provided the excitation system designer with better tools to produce new circuits and advanced techniques which have been already widely applied to a variety of excitation systems for commercial generators.

The method used to convey current to and from generator rotors, namely carbon brushes running on a slip ring on the rotor shaft has changed during this century. Advances have been made in carbon brush materials and in on-load brush changing but on today's large generators some hundreds of brushes may need to be inspected and maintained at weekly intervals to ensure reliable operation. The system works well considering that we expect brushes to collect current from the metal slip ring surface moving at up to 200m.p.h. with a minute wear rate and good current division between brushes. Clearly it is better if such technical and maintenance problems may be avoided.

Upto approximately 1948, excitation for practically all externally regulated generators was provided by Rotating Exciters controlled by Mechanical Regulators. These regulators are still being used to-day in many applications. Around 1948, the development of square loop core materials and selenium rectifiers made it practical to use magnetic amplifiers in voltage regulators and excitation systems. The cost of this type of equipment was higher than mechanical regulators, and while magnetic-amplifier type regulators and exciters were used in military installations, air craft and electric utility applications, general purpose usage of these devices was slow in developing.

Following are the difficulties met with commutator exciters and directly mounted main and pilot exciters:

1. For vertical shaft generators, the constructional height of the shaft is more and therefore the cost for the construction of the Power House is appreciably increased.
2. For low speed generators, the size of the directly coupled exciter has to be larger and this results in their being more expensive.
3. Also the exciters of low speed generators, have large magnetic inertia, resulting in lower response ratio. This is particularly disadvantageous especially in the case of generators feeding into long distance transmission lines in which case high exciter response is an essential requirement.

The excitation and the regulation of large synchronous machines must comply with a certain number of purely technical requirements, apart from any question of technology, or whether we are dealing with thermal or hydraulic generators. The main qualities of the regulation system as stated in [40], which we must attempt to achieve, are the following:-

(a) Rapid Action of the Devices :- The high power alternators must give an effective contribution to the maintenance of system stability by their capability of supplying or absorbing very rapidly the active power.

(b) Independent Action of the Devices:- While independent starting of excitation systems is desirable in all cases, independence during operation is nearly always necessary, the potential over excitation of the alternator must in fact be maintained when there is a fault followed by a large drop in voltage in the system.

(c) Mamimum Safety in Operation:- Since the satisfactory behaviour in service of apparatus is a function of the degree of reliability given by each of the constituent elements, it is advisable to use, particularly for control circuits, elements which are intrinsically strong when subjected to electric stresses, and this can be achieved by adopting very large factors of safety or by limiting the stresses to which they may be subjected.

In order to obtain rapid action in the case of hydro-electric machines, we have replaced the shunt exciter at the end of the shaft, with low speed of response, successively by a main exciter which is excited separately by a pilot exciter combined with a mechanical regulator, then by systems with positive booster of high speed in series with the main exciter or in series with the field magnet of the main exciter. The positive booster was controlled by a regulator fitted with thyratrons, with vacuum tubes or magnetic amplifiers or by means of an amplidyne. Then the utilisation of mercury arc rectifiers, very wide spread in some countries, made it possible to achieve high speeds of response. Now a days silicon rectifiers and thyristors are used which eliminate the disadvantage due to auxiliary apparatus for the mercury arc rectifiers and all kinds of maintenance.

In the case of thermal machines, evolution has been parallel, however, it should be noted that while it has been easy to obtain high speeds of response with exciters at 3000RPM and this upto a power of the order of 70 MW, the increase in the powers of turboalternators to 125 MW, then to 250 MW and 500 MW, has resulted in a reduction of the speeds of exciters to 1000 RPM, then 750 RPM and this has reduced somewhat the performance of these machines. Further the presence of large pole pieces requires, during transient conditions, a pulse of excitation current which is much higher than that which is necessary in the case of machines with laminated poles, and this is even more so when the speed of excitation is high.

The design of control system hardware for electrical equipment has undergone radical changes over the past few years with the introduction of relatively inexpensive and reliable semiconductor circuits and power electric components. In the particular case of excitation systems for synchronous machines, the rotating d.c. generators have been replaced, almost entirely, by solid state controllers with thyristor power control elements. Redundancy of components and circuits has been used to meet the ever increasing demands for reliability of these systems. The relatively low costs of electronic components has made it possible to do this. Since so many alternative variations are possible with any basic system design, a consistent method is required to assess the relative merits of such alternatives from reliability and cost points of view.

In 1951, a static excitation system was developed by H.F. Storm [14] utilizing a.c. machine terminals, through current and potential transformers to provide excitation power to small generators on commercial and military air crafts as well as for marine service.

Recent technological advances have made large ratings of static excitation system attractive. These advances include improved semiconductor rectifiers, better steels for use in magnetic-amplifiers, saturable reactors and the introduction of silicon zener diode references for voltage regulators. The reliability of this system on military applications and the enthusiasm with which it has been received, has stimulated continuous study of this system for large ratings. In 1958, it was decided that the technology and economics of a machine terminal excited static exciter had reached the point where manufacture of an equipment for large generators should be undertaken.

Control circuitry of an exciter use thousands of electronic components like transistors, diodes, thyristors, resistors, capacitors and integrated circuits etc. Although electronic components are known for their unlimited capabilities but they fail to perform consistently and their failures are more and are almost always without advance warning. Also as the complexity of equipment in electronic systems increases, one can expect their reliabilities to decrease. Consequently, systems using electronic equipments are more susceptible to un-planned shut down which may have serious consequences in terms of cost, consumer confidence and safety. Static exciters also display this trait of random failures and low reliability when compared to conventional exciters. Conventional exciters provide a certain amount of warning to the experienced crew before break down occurs, which is not in case of static exciters.

Redundancy can be applied at any level in the system i.e. at component, subsystem or system level. It can be either active or standby redundancy. Therefore because of redundancy, a system operates successfully even though certain components have failed, thus increasing the reliability of operation. Hence redundancy provides more than one means for accomplishing a given task such that all means must fail before causing the system failure. Redundancy increases weight, size and cost of the system.

The major objective of system reliability analysis is to investigate means by which a reliability requirement or a goal can be achieved in the best possible way. This means a thorough analysis of the relationship of reliability with the other important parameters of the system. It means selecting a measure of system reliability effectiveness which may be quantitatively manipulated to describe the consequences of alternate system designs, developing a definition of failure which allows for reliability prediction and relating the level of system reliability to be achieved to the cost of system design. An important part of design is the studies which enumerate and identify the potential effects of component failure.

This thesis illustrates how a reliability assessment of an excitation control system can be carried out to provide an information about the relative merits of alternative hardware configurations. The approach commences with a basic block diagram for the system and then proceeds to the reliability analysis through a reliability block diagram, a set of reliability equations and finally the use of suitable failure rate data for the actual alternative system evaluations [88].

In Chapter II, description of different excitation systems has been presented. In Chapter III, the description of different static excitation schemes has been given. In Chapter IV, some idea about the basic reliability models e.g. series model, parallel redundant model and standby model has been given.

First actual system reliability equations are obtained in Chapter V and then reliability analysis is done of different static excitation systems according to the Computer Program given in Appendix II having some design modifications. While in Chapter VI, analysis of computer results is done.

At last in Chapter VII, some important conclusion are drawn from analysis of results and some suggestions have been given for further work in this field.

CHAPTER 2

DIFFERENT TYPES OF EXCITATION SYSTEM

When an alternator is connected to a passive load, its terminal voltage may be controlled by varying the field current-the excitation. In general, the excitation is adjusted in order to maintain constant terminal voltage as the load is varied. When an alternator is connected in parallel with a much larger power system, terminal voltage is determined by the system and the level of excitation now determines the power factor at which the machine operates. In this case, the excitation is normally adjusted to ensure that the alternator accepts a share of the total reactive load. Needless to say, there will be intermediate condition of operation in which the excitation will affect both voltage and power factor.

The excitation power required for present large turbo-generators is of the order of 0.4 % of the generator rated power and it approaches 1 % for a short time during field forcing [83].

The replacement of a d.c. exciter and gear box by an a.c. exciter and static rectifier involved a small cost increase but this was largely offset by reduced maintenance and the saving in cost of d.c. exciter brushes throughout the life of the plant. It was also essential that, in making the change, the highest reliability of the rectifier type of excitation was ensured. Experience in last decade has amply shown the reliability of this type of excitation with no generator outage due to rectifier failure.

A great variety of excitation systems for alternators have been developed during the last two decades. There were two factors which essentially affected these attempts to improve the reliability and therefore the availability of installation.

The rapid increase in unit outputs, particularly of turbogenerators, and the higher excitation requirements due to greater utilization, caused the classic excitation system using a directly-coupled or gear driven d.c. exciter to be discarded. On the other hand, developments in the semiconductor field led to simple, robust, efficient and reliable uncontrolled or controlled silicon rectifiers (diodes and thyristors) which have now become the basis for all modern excitation systems [61].

Disregarding their control characteristics for the moment, these novel excitation devices can be classified in three groups as far as their design is concerned —

1. Purely Static Systems, i.e.,transformer supply with transductor or thyristor regulating unit.
2. Combined Static and Rotating Systems, i.e., three phase a.c. exciters with static rectifier.
3. Rotating Systems, i.e., three-phase a.c. exciter with rotating armature and rectifier.

The one thing that all three have in common is the use of a static rectifier instead of a rectifier with mechanical sliding contacts (commutator). Although groups 1 and 2 still require slip rings to transmit the exciter current to the rotor field winding, group 3 does not as the semiconductor rectifier is mounted on the shaft and therefore rotates at the same speed. The principle of this brushless alternator with no slip rings has been known for a long time but it could not be put into practice until the advent of the silicon semiconductor rectifier.

The term "brushless excitation" encompasses a new type of excitation for alternators, with silicon diodes, rotating with the shaft, to replace the commutator of the directly coupled d.c. exciter used in the classic excitation system. This system dispenses with brushes or friction contacts of any kind and results in practically maintenance free, automatic operation.

Today exciters from the smallest to the largest ratings (4 MW and above) are being manufactured or designed without brushes or slip rings. The rectifier part is usually uncontrolled and fitted with semiconductor diodes. An additional condition for a controlled rotating rectifier system is a positive means of transmitting the control pulses to the rotating shaft.

The increasing importance of alternators with brushless excitation stems from the increased interest in automated installations where the main requirement is maintenance free operation.

Following are the reasons for increased applications of static exciters:-

1. Static excitation system is potentially more reliable than a rotating system.
2. Less maintenance is expected than on a rotating excitation system.
3. Maintenance under load can be accomplished for all components except for the power magnetic components (i.e. Power Potential Transformers, Saturable Current Transformers and linear reactors). This may permit elimination of the usual spare rotating exciter.
4. Generator rotor removal is simpler without a shaft driven exciter.
5. The basic circuit of the static exciter makes the alternator as much self regulating as possible.
6. The transient response is rapid and also well damped.
7. A short circuit on the alternator will not cause loss of excitation but during a short circuit, the excitation becomes several times normal, a feature desirable for selective tripping of protective devices.
8. Since the exciter is not attached with the generator, the length of the generator can be appreciably reduced compared with generator with integral exciters.

The static excitation system for a.c. generators is better than usual conventional or rotating exciters as it permits flexibility of installation, produces simplicity in the a.c. generator design and provides excellent reliability and performance.

The other type of static exciter is electronic main exciter. In this system, ignitron type of power rectifiers are used. Its use as main exciter for synchronous machines has been limited because it costs more than a conventional main exciter. Also it needs costly control, protective and regulating equipment. Further the ignitron and thyratron tubes in the electronic exciter are subject to deterioration and eventual failure and replacement.

Modern a.c. generators are capable of continuous operation over long periods without being shut down for maintenance. It is necessary, therefore that excitation system be capable of similar operation and that wearing parts be replaceable without requiring shut down or even unloading. The static exciters possess the special advantage of being absolutely self contained and independent of separate energy sources, which in starting requires neither switching nor any special attention from the operator, which containing only static components, which needs no maintenance, which has an almost unlimited life and easily understandable circuit design.

One objection to the static exciter circuit is due to high rectifier reverse voltage, which can be caused by a lightning stroke, on out of synchronism condition or a sudden short circuit on the alternator terminals. However each diode is shunted by a resistor and a capacitor to protect against excessive voltage.

Further, the other reason for the choice of the static excitation system is the transient performance. When a sudden load surge occurs, a magnetic flux component proportional to the load current is also produced at the first instant, thus causing a voltage of ample magnitude to build up the field without any delay. This voltage forces the current in the pole wheel to increase rapidly. The exciter current reaches its new steady state value within a few cycles. The exciter response achieved by this arrangement can not be obtained by normal exciter equipment using mechanical or magnetic regulators. Recent technological advances made in the field of improved semi conductor rectifiers, better steels for use in magnetic amplifiers saturable reactors and the introduction of the silicon zenerdiode references for voltage regulators shall further improve the performance and increase the application of static exciters.

2.1. Amplidyne Main Exciter Excitation System

The initial objective in developing this system was for application to generators of large rating, especially for cases of unusually high voltage response requirements. Recent developments in control circuits and components and in conventional exciter design have extended the application of the more conventional commutator exciters with amplidyne type voltage regulators. These conventional systems can be applied to all generators, including the largest anticipated in the near future.

The amplidyne main exciter system, therefore will be reserved for special applications requiring its characteristics.

2.1.1 Features of Excitation System

The amplidyne exciter resembles a conventional exciter of similar rating in physical size and general appearance [31]. The present exciter is gear driven and rated 400 KW, 375 volts, 1200 RPM. The exciter also may be motor-driven.

A.C. Voltage Regulator: The main automatic voltage regulator controlling the a.c. generator voltage consists of two stages of magnetic amplifiers, a magnetic reference, and a rectifier comparison circuit.

D.C. Voltage Regulator (Manual Control Means): Manual Control of amplidyne exciter direct voltage is by means of a d.c. voltage regulator, similar to the main a.c. voltage regulator. This regulator will permit adjustment as well as maintenance of direct voltage for which it is set during system and station disturbances if the a.c. voltage regulator is not in operation.

2.1.2 Other Features

A voltage droop circuit aids in paralleling with other direct voltage sources such as a spare exciter. An alternative means of control, utilizing the station battery, is provided in case, both a-c and d-c voltage regulator become inoperative. This feature requires a low battery current of about 1 ampere. The accessories, controls and instrumentation to operate the amplidyne exciter are similar to these required for a conventional rotating exciter and amplidyne voltage regulator.

2.1.3 Advantages: Because of the high power gain of the amplidyne exciter, control power is materially decreased, resulting in a simpler and smaller voltage regulator.

Although the system was designed to meet present industry requirements, it is easier to provide increased accuracy, higher exciter voltage response, and better dynamic and steady state stability than with a conventional system.

Reduction in maintenance is expected with the static magnetic voltage regulator.

The exciter field rheostat, as we now know it, is eliminated, providing reduction in losses and a saving in space. Also, with the new manual control of the exciter voltage, it is relatively simple to obtain low exciter voltage, necessary for generator synchronizing and line charging. Zero exciter voltage can be obtained.

The adjustable direct voltage droop permits safer and easier transfer of excitation to and from a spare exciter.

Since power requirements of exciter control fields are small, consideration can be given to providing special features. Fast reduction of generator field excitation can be accomplished with a generator zero field current or exciter zero armature voltage regulator. A degenerative field current or exciter voltage signal is applied to an amplidyne control field. If a spare exciter is not used, this may permit elimination of generator field breaker. The main field discharge resistor, as we now know it, thus may be eliminated. The high voltage impulse, which is applied across the machine field winding by use of a discharge resistor, may be avoided, and more reliable protection of the generator field results. Similarly, exciter field breakers, where normally used, are not necessary.

Better commutation and less flashover also may be expected with the system described. The laminated magnet frame improves commutating ability under transient conditions, when load current is changing rapidly, by allowing commutating flux to be proportional to the commutating current in magnitude and phase.

The amplidyne exciter is less susceptible to flashover from over voltage because the voltage between commutator segments is near zero at the quadrature axis brushes. This tends to discourage the establishment of an arc, caused by severe sparking under the direct axis brushes.

2.1.4 <u>Description of Amplidyne Exciter</u>: The amplidyne exciter is an armature excited machine having a conventional rotor winding. There are two effective flux paths in quadrature on the stator, identified as the direct and quadrature axis. The control flux in the d-axis produces a current in the q-axis winding which includes the rotor winding and a q-axis series field on the stator. The q-axis current is carried from the rotor to the q-axis winding on the stator by a set of q-axis brushes on the commutator. A q-axis commutating field on the stator is included to allow commutation of the q-axis current.

The flux produced by the q-axis current generates d-axis voltage which appears at the d-axis brushes. The mmf produced by the d-axis load current in the rotor is in the same axis as the control mmf. Compensating fields on the stator, therefore are required to produce an opposing mmf. This will prevent the load current from influencing the control flux, d-axis commutating fields on the stator are included to allow commutation of the d-axis current.

Of particular interest is the commutator brush rigging in the assembled exciter. The commutator design and size does not differ from a standard d-c machine of the same rating.The smaller brush rigging is the q-axis brush assembly.

Three features of the exciter affect maintenance and size —

(1) Additional maintenance is required because of the extra set of brushes.

(2) The extra brushes, interpolar space required for q-axis commutating poles and the poles themselves result in reduced utilization of the machines periphery for useful flux.

(3) Both axes use the same magnetic circuit and output voltage is subjected to saturation in each axis. Therefore amplidyne must be designed for lower flux densities than a conventional machine.

Because of the factors presented in the last two points, the amplidyne exciter size (D^2L) is from 5 % to 10 % larger than a conventional exciter of the same rating.

2.1.5 Operating Experience: The amplidyne main exciter is gear driven from the shaft on the high pressure turbine generator, while a conventional exciter of equal rating and speed is gear driven from the shaft of the low pressure turbine generator. An amplidyne voltage regulator provides automatic control. This arrangement provides a unique opportunity to compare maintenance requirements, reliability, performance and compatibility of the two excitation systems.

Operating experience with the amplidyne exciter system has been most acceptable. Performance has been excellent, judged by criteria such as transient response, accuracy and stable operation. Operator reports indicate ease and fine adjustment of manual direct voltage control, and ease and assurance in transferring excitation between a spare excitation source.

2.2 Alternator-Rectifier (Alterrex) Excitation System

The alternator-rectifier excitation system concept [62] is a shaft driven excitation system, which consists of a conventional solid rotor alternator driven from the main generator shaft with stationary silicon diode rectifier banks to accomplish the a.c. to d.c. conversion. The combination has good efficiency, approximately 95 % for the alternator and 98 % for the rectifier. Voltage regulator control is accomplished by controlling the field of the alternator in a manner similar to a commutator exciter.

Furthermore, the system is adaptable to any future rating of turbine generator because of the use of a solid rotor alternator. Preliminary layouts indicated a reduction of 8 inches in the overall length of the cardinal unit as compared to the length when using a commutator exciter. While experience with large rated units did not exist at the time of evaluation, each of the components of the system has had considerable operating experience. The alternator is of the type that has been used for normal, industrial, municipal and station service application, having accumulated over 3500 machine years of service since 1946. The amplidyne voltage regulator has been used on over 750 turbine generators. The rectifier section had considerable experience in excitation service on smaller rated generators.

After weighing all these consierations, the basic system had been accepted as a standard by the Central Electricity Generating Board of the United Kingdom for nineteen 500 MW units. Since this excitation system was adopted by Cardinal, 25 Alterrex system have been ordered by other users. The normal evolution of a new concept in excitation system consists of progression of the system from smaller to larger ratings. This is generally done to prove the concept to the higher risks associated with the larger units. In this case, because of the sound engineering principles involved and the substantial component experience accumulated, this prototype step was deemed unnecessary, particularly since the first unit was to be extensively tested at the factory.

2.2.1 Development of the Alterrex System: While the components of the system have been used individually in other applications, they have not been used together in an excitation system in this country. Therefore the major work in development has been of the system rather than of the components. To coordinate this development and to assure each party that the system would meet his requirements, close cooperation between manufacturer and user was required during the design stage.

1. Ratings of components
2. need for a main field breaker
3. protection of alternator and rectifiers
4. spare excitation.

2.2.2 Ratings and Description of Components: Fig.(2.1) shows a schematic of the basic components of the Alterrex excitation system.

Alternator Exciter: The direct driven alternator exciter contains a solid forging alternator rotor with a low voltage armature. The alternator is air cooled and includes a completely enclosed frame with a top mounted air to water heat exchanger for alternator cooling. The bearing are mounted as part of the end shields in a construction similar to the main generator. The rotor for the exciter is designed for rectifier duty. Calculation indicate that the harmonics generated by the rectifier will cause two loss components which are not normally present in the alternator, an additional armature load loss and an additional pole face loss in the rotor. Together these amount to about 3 % of the exciter rating.

Power Rectifier: The ac-to-dc conversion is accomplished by an assembly of silicon diode rectifiers, consisting of 10 double 3-phase full wave rectifier bridges. Each double bridge can be isolated electrically by a disconnect switch while maintenance and inspection are performed. The equipment is designed to allow turbine-generator operation with one double bridge removed from service. The switch can be operated while the main generator field is energized, since the current carried by the switch transfers to the remaining parallel circuits.

Fig.(2.2) illustrates the complement of rectifier diodes in each double bridge. There are three diodes in series in each leg. In the event of a short circuited diode, the remaining two diodes can withstand the circuit peak reverse voltage with normal design margins. In the event that all three diodes fail, the fuse will open and protect the nonshort-circuited diodes in the other leg of the rectifier bridge.

The diodes are water cooled using the water system of the hydrogen coolers. The diodes are mounted on a heat sink which is insulated from the extrusion which carries the water. Thus the water need not be of high purity. The water to each double bridge can be shut off and drained for servicing. The water system is monitored by thermostate located on the heat sinks.

In the rectifier assembly, four double bridges are located in the centre cubicle, and three double bridges in each of the outside cubicles. Suitable barriers have been used to allow safe servicing under load. The lights on the

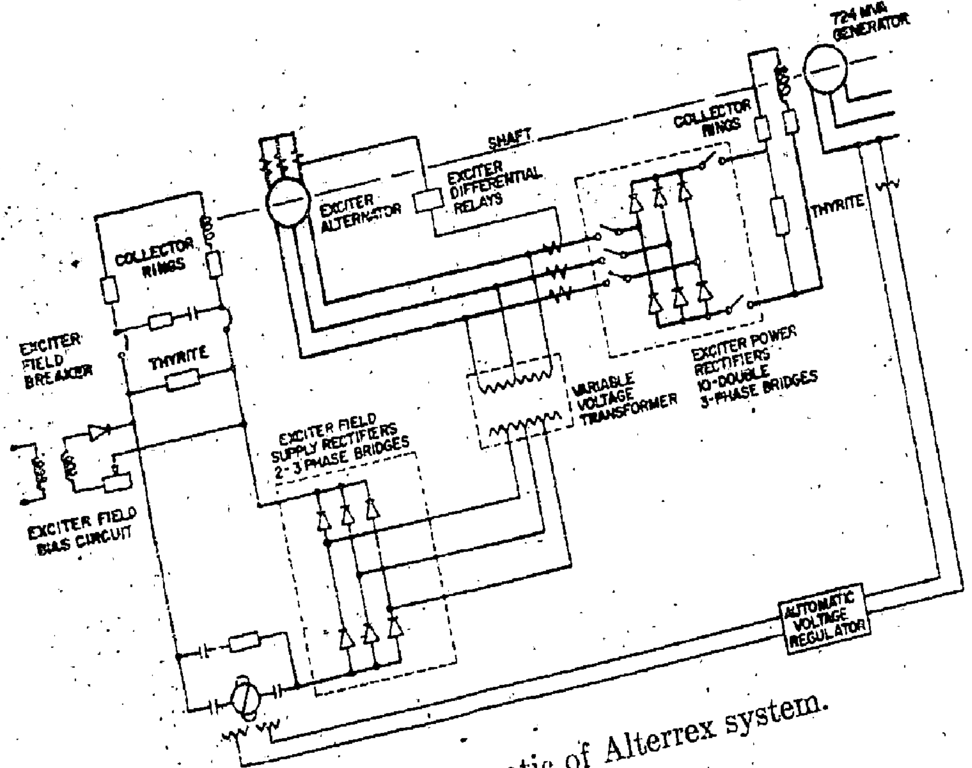


Fig. 2.1 Schematic of Alterrex system.

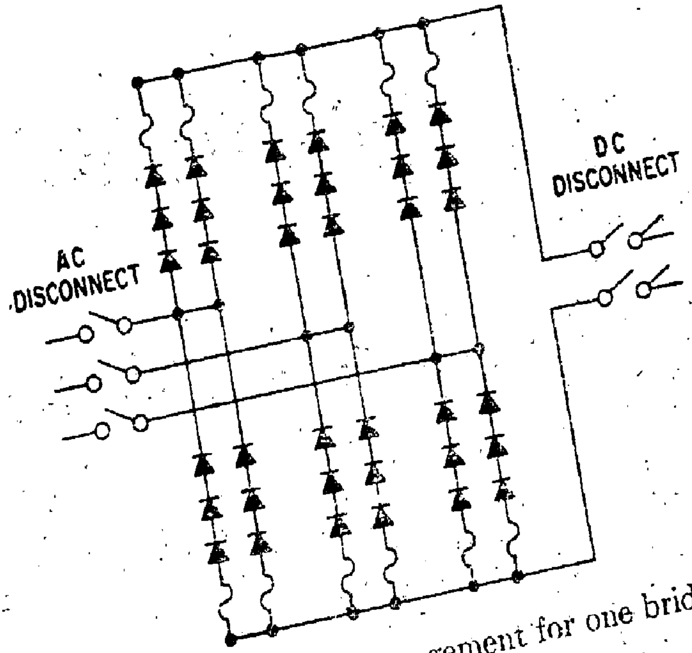


Fig.2.2 Rectifier arrangement for one bridge.

front of the cubicle indicate and identify open fuses. In addition, each double bridge is provided with an accessible terminal board for checking each diode in service.

Spare Excitation Source: While a standby spare exciter which could be switched into service by operation of a main generator field breaker was deemed unnecessary, consideration of a back up for the alternator was studied. The use of stationary rectifiers in the excitation circuit would allow the connection of a spare source of a.c. excitation in place of the alternator. It appeared that such a spare excitation source could be obtained for very little additional investment. After considering the cost of the alternative transformer supplies, the connections to auxiliary switch gear and the extra bearing that would be necessary if the machine were to be operated with the alternator removed, AEP decided not to obtain a spare excitation source.

With no commutator and gear, it was felt that the alternator would be more reliable than the conventional exciter.

2.3 An Electric Utility Brushless Excitation System

In the evolution of power generation another major step has been taken, the development of a brushless excitation system. Excitation current is furnished to the field of the synchronous generator through a rotating rectifier from an a.c. exciter, all of which components are coupled to the generator shaft. With a permanent magnet generator (PMG) overhung from the a.c. exciter, the total excitation power requirements including that for regulation is obtained directly from the generator shaft. This excitation system also offers the advantages of (1) improved reliability, (2) improved maintenance and (3) improved performance.

Electric utility a.c. generator field excitation requirements have been rapidly increasing during the past few years. Larger ratings of a.c. generators have been made possible by the engineering development of more efficient cooling methods and by the use of better materials. As a result the excitation requirements have increased from a maximum of approximate 1000 amperes a few years ago, to nearly 4000 amperes at the present time [29]. The excitation voltage has increased from 250 volts to 500 volts during this period. Exciters of a 2000 KW rating will be required in the near future if the increase in a.c. generator sizes continues.

Various types of exciters have been used to furnish these requirements, d.c. rotating exciters, electronic excitation and in a few cases external dry type rectifiers have been used. In any of these cases the power must be transferred from the device to the field of the a.c. generator. This requires collector rings and brushes. The design of large capacity collector rings becomes more difficult as the power transmitted becomes larger, since the rings must be designed to cool properly and brush life must be kept to a resonable figure . Commutation and brushes are required if the rotating d.c. exciter is employed. The commutator design and brush life problems have been resolved by the use of slow-speed-geared exciters or motor-generator set exciters, but this does not solve the collector problems.

Consequently, the greatest improvement in reliability of this excitation system is the elimination of the commutator, the slip rings, and the associated brushes, which is, indeed, a major step. The system is free of carbon dust and the maintenance of insulated parts is materially improved. The brushless excitation system has been in service on small application such as air craft for some years. The smaller applications have been quite successful up to the present, however, this idea has not been applied to the electric utility excitation system which require large quantities of d.c. power for excitation. The system consists of an a.c. exciter and a rotating rectifier mounted on the same shaft as the turbine generator field. Overhung from the a.c. exciter is a small PMG whose stator output furnishes excitation energy, as controlled by the regulating system, into the stationary field of the a.c. exciter. The a.c. exciter has a rotating armature whose output is fed along the shaft to the rotating rectifiers. The output of the rectifier is then fed along the shaft to the field of the a.c. generator. Thus, an ultimate degree of reliability is obtained by deriving all excitation power including that for regulator control directly from the machine shaft. The advantages of the previously used self excited exciter are retained.

The brushless excitation system utilizes components of such promising reliability and with such margin that it should eliminate the need for reserve (or spare) excitation. It would therefore eliminate the requirement of the generator field breaker, which was heretofore utilized primarily for the transfer of excitation sources. It also would eliminate the previously required exciter field rheostat with its mechanically operated contacts and space requirements.

Six years of development work on the brushless excitation system have proved that the system is reliable and may be applied to electric utility a.c. generators. Selemium rectifiers were first tried and found not suitable for operation at 3600 RPM. Silicon diode rectifiers were then tested and found to be ideal for the application. Rotation of the silicon diode at 3600 rpm did not impair its operation in any way. This was further proved by actual silicon diode applications on high speed air craft generators.

The brushless excitation system provides good reliability because each of its components is reliable. The silicon diode has proved its ability as an efficient rectifiers that may be rotated at high speed without sacrificing its operating characteristics. It is a sealed unit that is not affected by moisture or chemical atmosphere contaminants. The diodes are applied on a very conservative rating basis so that with approximately one third of the diodes out of service the rating of the diodes is not exceeded. The peak inverse voltage requirements of the application are determined and the type of diode is selected on a conservative basis. Overload and fault conditions must be considered before the number and arrangement of the diodes are determined.

The a-c exciter is also a reliable component since it is similar to many previous designs. The whole rotating mass is studied for lateral and torsional vibration and is designed to withstand 20 % overspeed. The regulator is a static device. Similar components of the regulator have been proved on many previous regulator applications. It can therefore be seen that the brushless excitation system possesses the qualities of reliability which are desirable in an electric utility application.

The need for extensive maintenance, as may be seen, has been greatly reduced by the elimination of mechanical and auxiliary parts, the little maintenance still needed must be easy to accomplish. A side from the normal maintenance of sleeve-bearings and insulation, the only parts of the system requiring it one diodes and fuses, which demands occasional replacement, and which are so designed that they may be replaced quickly upon shut down. The necessity of cleaning is minimized since there is no conducting carbon dust to collect on the rotor or stator parts.

The ventilation of the brushless exciter presents no unusual problems, it is similar to the present design of d-c rotating exciters. The diodes are mounted in aluminium heat sinks which are cooled by the ventilating air for the a-c exciter and rectifier. There is a possibility that in later applications, the units may be cooled by the a.c. generator hydrogen system.

The exciter rating is based on the d.c. output of the rectifier, which in turn is determined by the requirements of the a-c generator field. Silver quartz fuses are used since then action is fast and dependable.

The a-c exciter which supplies the rotating rectifiers must naturally have the a-c winding on the rotor and the field winding on the stationary outer member as in a d-c machine without commutator. To fulfill the requirements of a good excitation system,the generator must operate over the same voltage range as have precious exciters and have a field time constant low enough for a good speed of response. As the time constant is reduced, the a.c. generator time delay becomes the only major delay of the excitation system.

Improved reliability and improved maintenance were achieved without sacrifice in excitation system performance. The performance of the brushless exciter is related directly to its controls. To match the improvements of the brushless exciter, the excitation regulating equipment must likewise have the same high degree of reliability, the same freedom from maintenance and the same high degree of performance.

Five principles of regulator design have been followed in the development of this excitation system. The system must (1) be continuously acting (2) have fast response (3) be easy to stabilize (4) have reliable components (5) have a good excitation limiter.

CHAPTER 3

STATIC EXCITATION SYSTEMS

3.1 Introduction

Large turbogenerators comprise those machines producing 200 MW and more from a single shaft. Maximum unit outputs of two pole machines are between 1300 and 1600 MVA, depending on speed and type of cooling. With 4-pole machines, these values can be increased by a factor of 1.5 to 1.7 [80].

The power supply to the exciter windings of such large machines can reach quite large proportions because the field current can be several thousand amperes. In the interests of economy, every effort must be made to keep this outlay as low as possible and make the power supply equipment to the simplest possible design. At the same time, the main aim must be to ensure that the heavy current source, together with an efficient voltage regulator contributes towards full utilization of the generator capacity under any operating conditions, including unfavourable network conditions.

These considerations led to a general preference to supply the field windings through controlled rectifiers. A simple and reliable excitation system is achieved with a rectifier transformer and an electronic voltage regulator.

Such excitation systems have been produced for a number of years. Until recently, controlled mercury arc rectifiers have been used as static converters, but today over 80 % of large turbogenerator sets are equipped with thyristorized excitation equipment as a result of their excellent service record.

For the excitation of large turbo-generators, it is now common to find a.c. machines followed by diodes or completely static systems employing mercury-arc rectifiers or thyristors [60].

Although the use of rectifiers has only been used on any scale during the past few years for the excitation of large turbo-generators, the principle itself is quite old. In view of the remarkable speed of excitation which can be achieved, however, it has hitherto only been used for generators that are required to cope with very steep load surges, such as are encountered in networks supplying rolling mills. Subsequently hydroelectric generators that have to cope with difficult stability requirements, were equipped with controlled rectifiers, a notable example being a Power Plant in Canada. The excellent results obtained with such installations, as well as the increasing demands for excitation power made by large turbogenerators, resulted in this system of excitation being adopted in thermal power stations. Many of turbogenerators are being supplied with controlled rectifiers.

3.2 Arrangement of Reserve Capacity

According to published statistics [68], the probability of failure of rectifiers used for exciters is $p = 0.2\ \%$ per annum. Using this figure, the probability of failure can be calculated for an assembly of 2q groups (in bridge connection) of $(n+1)$ units, each group containing one spare unit —

$$P = 2qn(n+1)p^2$$

e.g. if $q = 3$ and $n = 5$, the probability is

$$P = 2.3.5.6.\ 0.04\ .\ 10^{-4} = 0.072\ \%\ \text{per annum}$$

This result shows that in general a single spare unit per group gives a completely satisfactory safety margin.

Current practice in Belgium is however to provide at least 30 % of spare. In the case of a design having a large number of phases, the reserve can be provided by the neighbouring phases provided that dissymetry on different poles is not introduced.

3.3 Static Excitation System No.1

This system is used for industrial and utility steam turbogenerators. Fig.(3.1) illustrates the essential elements of the static exciter [37]. The excitation equipment consists of a twin rectifier which receives a.c. power from the a.c. machine terminals. The a.c. power to the rectifier is derived from three single phase potential transformers (PPT's), three linear reactors, and three saturable current transformers (SCT's) which include d.c. control windings to modify saturation of the cores.

These components are coordinated to utilize generator terminal voltage and current and approximately provide the required excitation to maintain generator terminals voltage constant for all steady state generator loadings. Basically, the PPT's and linear reactors provide no load excitation for the generator, while the SCT's provide excitation for load

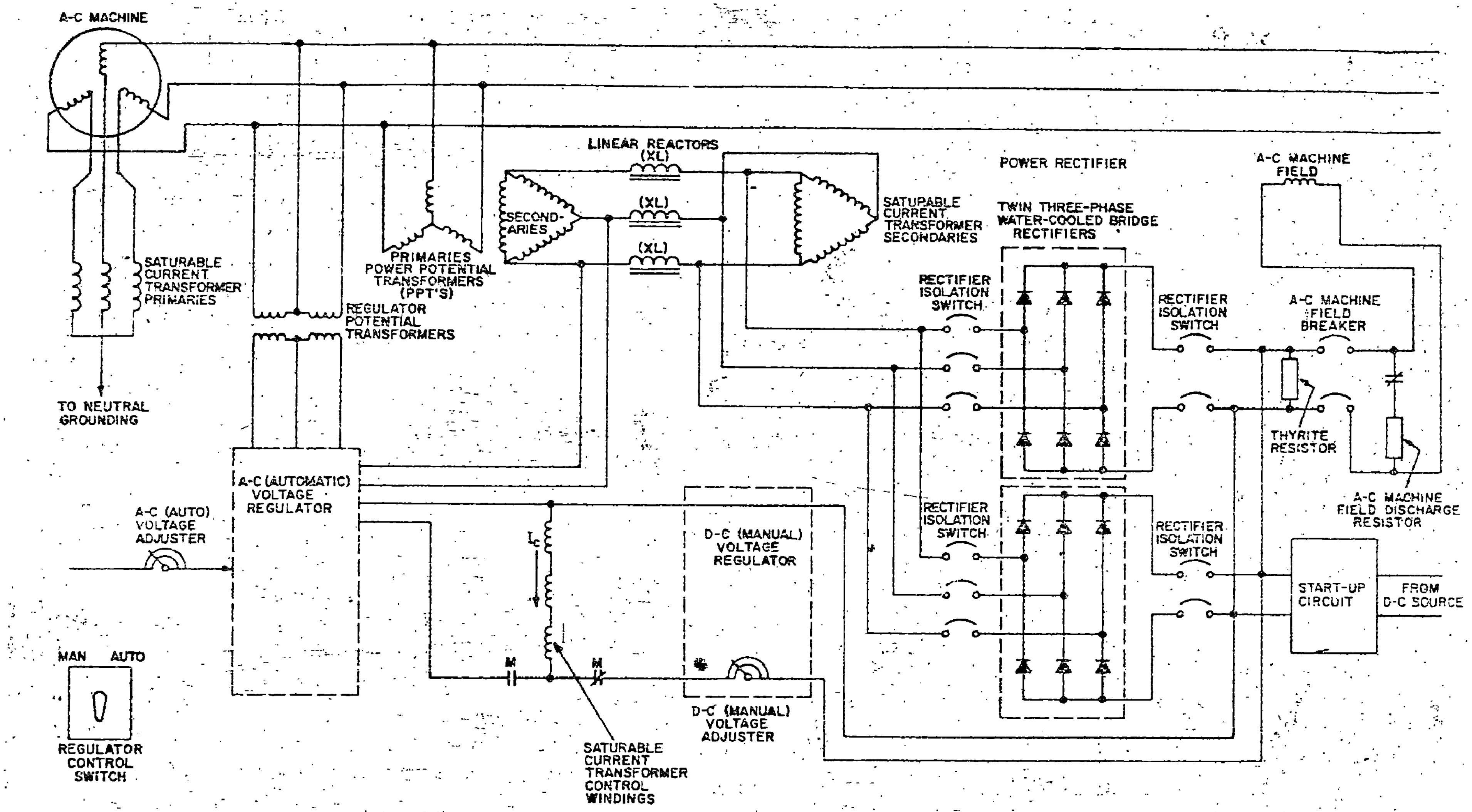


Fig.3.1 Schematic diagram of static excitation system

changes on the generator. A valuable feature of this system is its ability to produce ceiling excitation for an extreme fault condition such as a 3-Ø short circuit at the generator terminals.

It is necessary to trim the action of the power-potential transformers and saturable current transformers to provide exact compensation for load changes and for generator field heating and saturation. This is accomplished by varying the magnitude of the direct current flowing in the saturable current transformer control winding. This control the magnetizing impedance of the saturable-current-transformer and therefore controls the SCT secondary current. Increase in SCT control winding current will result in less secondary current of the saturable current transformer and ,thus, less current in the generator field. Decrease in SCT control current will result in an increase in secondary current of the SCT, and, thereby, an increase in generator field current.

The SCT control winding current is determined in one of two ways —

(i) By an a-c automatic voltage regulator

(ii) By a d-c manual voltage regulator

Under control of the a-c voltage regulator, the SCT control winding direct current is automatically varied in order to maintain constant a.c. voltage of the generator. The a.c. regulator consists of two stages of magnetic amplifiers and a comparison circuit utilizing a zener diode reference. If the a.c. generator voltage rises above normal, a.c.

regulator output is increased to increase the SCT control current and therefore decrease the excitation voltage and current. If the a-c generator terminal voltage drops below normal, the regulator will decrease the SCT control current. This will increase the output of the SCT and increase excitation.

The d-c voltage regulator operates in a manner similar to manual control of a conventional rotating exciter excitation system. The d-c regulator consists of a rheostat connected in series with the SCT control winding. This rheostat and the control winding are energized from the exciter voltage.

Fig.(3.1) shows schematically one rectifier diode for each leg of each bridge. Each rectifier of the twin rectifier combination actually consists of a 3-Ø bridge connection of 24 silicon rectifier diodes with four rectifier diodes in series for each leg of the bridge. The equipment is designed to provide for maintenance under load by isolation of one of the twin rectifiers. The rectifier diodes are also protected from transients by thyrite resistors and transient suppression-resistance-capacitance circuit. The rectifiers are water cooled with the water path insulated from the rectifier diodes. This permits a normal supply of water to generator cooling systems.

A start-up circuit is required to supply a small amount of power to the field for a few seconds in order to build up generator voltage.

Features and Advantages:

(1) This static excitation system is potentially more reliable than a rotating system.

(2) The generator shaft is free from the possible mechanical difficulties of a shaft driven rotating exciter.

(3) Less maintenance is expected than on a rotating excitation system.

(4) Maintenance under load can be accomplished for all components except for the power magnetic components (PPT's, SCT's and linear reactors). This may permit elimination of the usual spare rotating exciters.

(5) The overall length of the turbine-generator is decreased. For the initial application, the length was reduced approximate 6 feet.

(6) A foundation for support of a shaft-driven exciter is not required.

(7) Air ducts in the foundation for exciter ventilation are not required.

(8) Oil piping for shaft driven exciters is not required.

(9) Generator rotor removal is simpler without a shaft driven exciter.

(10) The excitation system components can be arranged in various combinations to provide flexibility of power house arrangement.

Recent years have seen increased application of fast response, high performance excitation systems to improve the transient stability of synchronous machines. Many of these installation are at hydro plants where typically, long transmission circuits connect the plant to the system and stability is an important design consideration. Electronic Exciters have become nearly the standard for hydro installations. Today, solid-state, controlled rectifiers have replaced the mercury arc rectifier for such applications.

The short time constants of electronic exciters have made it possible to apply very effective positive damping of machine oscillations with suitable supplemental signal. Such supplemental signals can provide positive damping with conventional rotating exciters, but more effective damping can be obtained with the faster responding, low time constant excitation systems.

The application of faster excitation systems to steam turbine generators has developed at a slower pace. Traditionally, steam turbine generators have derived excitation energy from the shaft with a direct connected rotating exciter. The Westinghouse brushless excitation system employs a shaft driven alternator-rectifier exciter with rotating rectifiers directly connected to the generator field. This scheme retains the concept of a shaft power source, independent of power system disturbances, and provides improved reliability and reduced maintenance by eliminating all commutators and collector rings and associated brushes.

3.4 The Static Excitation System No.2

The system [88] chosen for the case study to illustrate the application of probability techniques is a modern static exciter used by Calgary Power Ltd. on Sundance Unit 3. It is illustrated in Fig.(3.2).

The basic system as installed (Fig3.2) consists of a main avr with a standby avr which will switch in automatically if the main one fails; a power stabilizer; electronic control circuitry and firing pulse generators; the three phase thyristor bridges which supply the d.c. field power; the associated transformers and switching equipment.

The main and standby avrs are identical (Fig3.3) and both contain a number of functional units, each of which contains a number of semiconductor devices and static electronic components. Manual input points are identified specifically since the components associated with them are subject to failure. The manual inputs of reference voltage level, manual voltage adjustment (for operation in the non-feedback mode), generator mvar and current limit settings are indicated in Fig.(3.3). The generator terminal voltage measurement for the main avr comes from a potential transformer connected directly to the generator while the standby avr samples the voltage indirectly through the excitation transformer and an auxiliary potential transformer. The power stabilizer obtains a generator power signal from the mvar circuit of the appropriate avr as selected by the change over switch 83A. The output of the stabilizer is fed back into the main signal

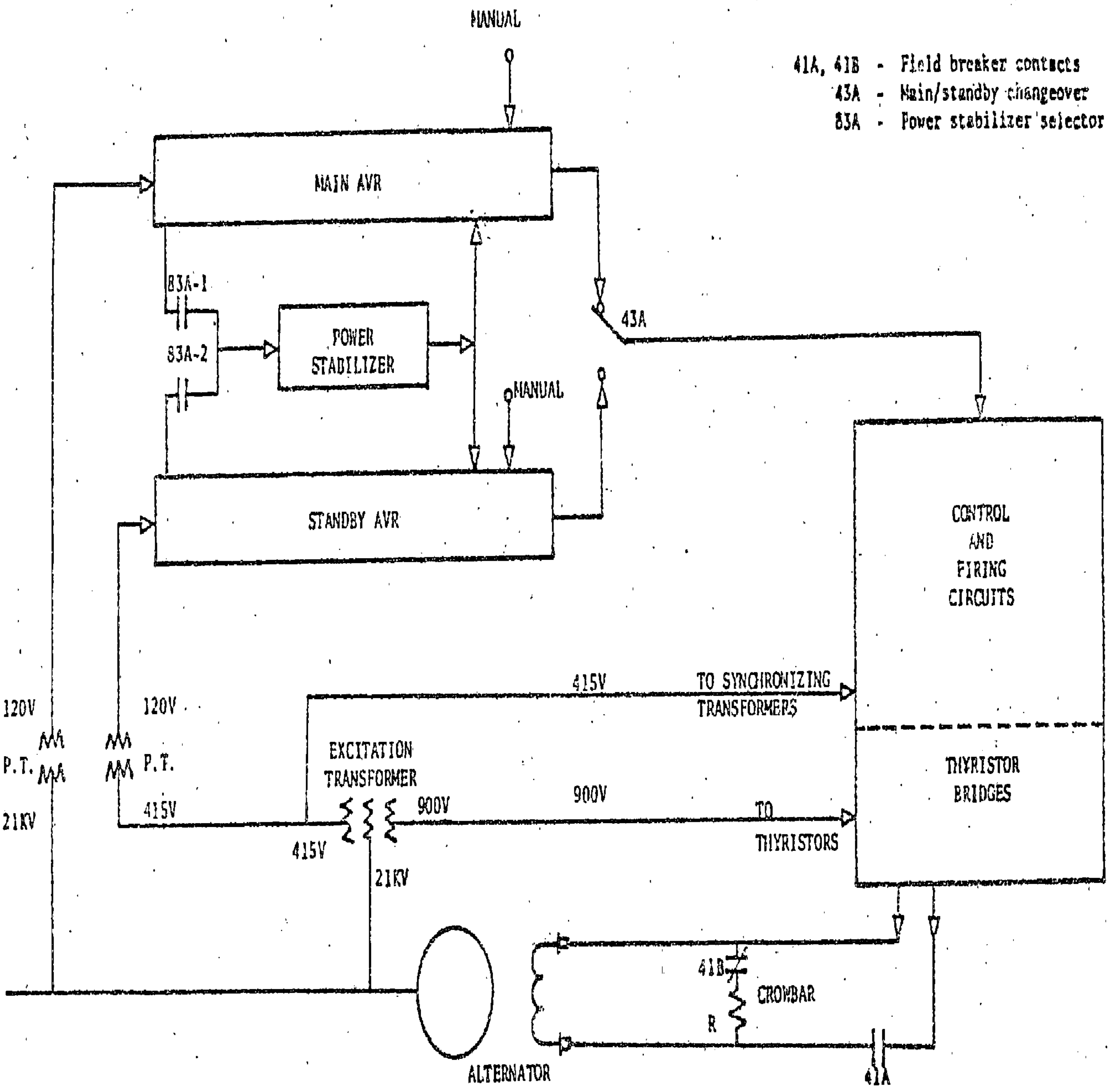


Figure 3.2 Simplified block diagram of excitation system for CPL Sundance Unit #3.

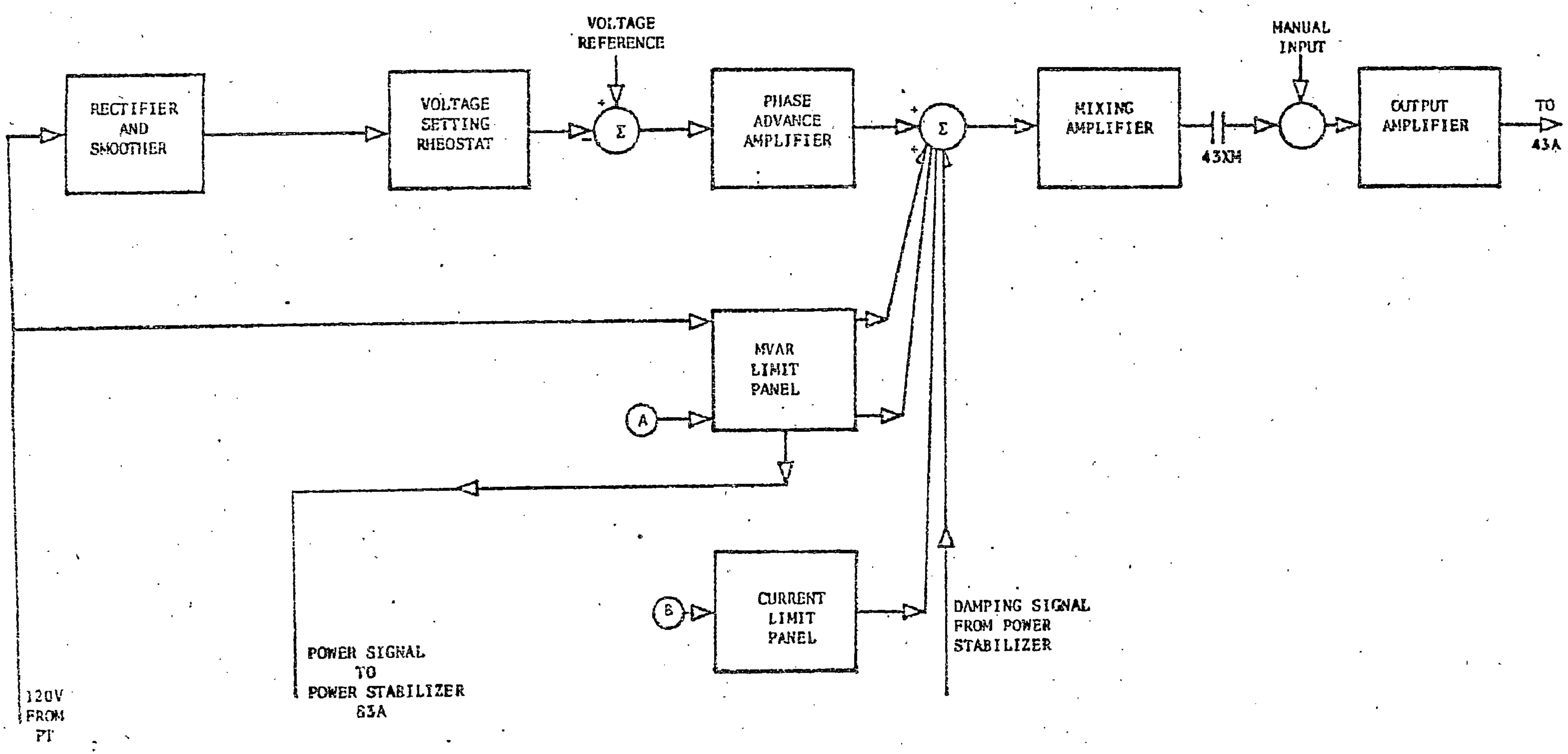


Figure 3.3 Main and standby avrs.

summation amplifier in each avr. The outputs of the avrs go to the selector switch 43A which selects the appropriate avr to be used for control. The logic of the avr selection is based on signal loads. A loss of signal from the main avr results in automatic switch over to the standby avr.

Two electronic power supplies (not shown in Fig. 3.2 or 3.3) are used to provide operating power for all of the electronic circuits in the avrs and in the control and firing circuits. Either one of these two supplies has adequate capacity to supply all of the power needs of the excitation system.

There are four separate three phase thyristor bridge rectifiers and each bridge is supplied by its own individual control and firing circuitry. Synchronization signals for the firing pulses are obtained by transformers energized from the excitation transformer. A separate electric motor driven cooling fan is provided for each of the four thyristor channels. Redundancy is inherent in the thyristor bridges in that each bridge arm contains five parallel thyristors, any four of which will carry the full rated current for that bridge. In addition the ratings are such that any three of the four separate bridges are adequate for the full rated output. The dc rectifier outputs are paralleled and fed directly to the generator field. A crowbar circuit consisting of a discharge resistor and a back contact of the field breaker (41b) is used for field protection.

Seven transformers are essential to the satisfactory closed loop operation of the excitation system. These are the 3 winding excitation transformer, the two potential transformers feeding terminal voltage measurements to the avrs, and the four potential transformers which supply synchronizing signals to the firing circuits for the thyristor bridges.

For the purposes of this study, any component malfunction which results in a need to revert to "manual" control is considered to contribute a failure of the system. The system is assumed to be in its useful life period of operation in which component failures occur purely by chance.

3.5 Brushless Thyristor Excitation System (Static Excitation System No.3)

The static thyristor excitation system has attracted attention because of the speed with which generator excitation voltage can be changed. The term 'static' however is slightly misleading as the excitation current must still be fed into the generator rotor, involving an interface between the static and rotating components of the system. Current collection at this interface is likely to become an even more difficult problem on the larger output generators of the future, employing, perhaps, water cooled or divided winding rotors.

The idea of combining a brushless concept with direct thyristor control of excitation is therefore attractive deleting as it does the problem of current collection whilst at the same time giving a system that can change the excitation voltage rapidly. The approach [81] adopted is aimed at reducing the essential electronic components on the rotor shaft to a minimum whilst at the same time using the experience gained with brushless diode systems to the fullest extent.

3.5.1 <u>Brushless Diode Excitation Systems</u>: Service experience using static diodes was very good and because the silicon diode is mechanically very robust, and capable of withstanding high 'g' forces, it became entirely practical to produce, as an alternative system, an exciter consisting of a stationary field system and a rotating armature diode rectifier assembly solidly coupled to the main generator rotor. This approach results in a "brushless" excitation system.

The most commonly used rectifier configuration is that of the three-phase bridge which, in the ideal case, requires a supply capacity of only 1.05 kVA for each kW of d.c. produced. In the case of a 3600 r.p.m., six pole exciter the rectified output voltage carries a basic ripple frequency of 1080 Hz which, when applied to the highly inductive generator rotor, causes a negligible ripple current to flow therein. Thus the quality of d.c. produced is acceptably good. The inservice life of a silicon diode is many years but statistically a very low failure rate is still a possibility thus each diode is usually connected in series with a fuse which will disconnect a failed diode without interruption of excitation. Each bridge arm consists of several diode paths in parallel and at least 20 % redundant rectifying capacity is built in so that generator full load can be maintained until a planned shut-down allows diode and fuse replacement.

The design of the rotating armature and field system follows well established machine design principles. The choice of diode and fuse, and the overall design of the rotating rectifier must meet the following conditions —

(1) Maintain rated current, with the minimum number of arm paths, within acceptable temperature limits.

(2) Survive surge currents induced in generator field as a result of faults in or nearto the generator.

(3) Survive fault current until fuse operation connects the failed diode.

(4) Withstand the high inverse voltages that arise due to the combination of pole-slipiing induced rotor voltage and exciter armature voltage.

(5) Withstand centrifugal forces of at least 5500 g.

Brushless exciters incorporating these principles are already in service, or on order, for generators of rating from 15 to 660 MW. The in-service reliability has been excellent and the reduction in maintenance is valued by Station Operators.

Modern automatic voltage regulators (AVR), using solid state components, are very fast acting and the only important restraint on the rate at which the voltage of such an exciter can be changed is that due to the time constant of the exciter itself. Economic consideration set a limit to how short this time constant may be made, but thyristor-operation also removes this constraint hence the more recent interest in static thyristor excitation even though it necessitates the use of brushes and slip rings.

3.5.2 Direct Control of Excitation Using Thyristors: If silicon diodes are replaced by thyristors and suitable arrangements made to apply firing pulses to their gates, with the firing angle under control of the operator, then it becomes possible to change the excitation voltage over the whole range in 10 mS or less. The input voltage to the thyristor converter has a constant value equivalent to the ceiling excitation voltage required by the generator. The thyristor converter performs the dual functions of rectification and control of the mean voltage supplied to the generator field. This voltage can usually be varied from full positive ceiling to a substantial negative ceiling. The voltage, by its very nature, has a high harmonic content but this is not detrimental to its use for this purpose.

Static thyristor excitation systems are now in service, usually drawing excitation power from the generator terminals via a step-down transformer. The excitation voltage is dependent on system voltage and will be reduced during system faults. An alternative arrangement uses a generator coupled ac exciter as an excitation source to overcome this disadvantage.

Static thyristor excitation systems are now being supplied giving output powers suitable for the largest generators. A necessary corollary of the use of such systems is that some form of rotor current collection system is necessary and in a sense this is a retrograde step from the brushless concept, which should be retained if at all possible.

It is possible to combine brushless and thyristor excitation principles to give direct control of generator field current supplied from a shaft mounted exciter. This supply is independent of system disturbances and is automatically available when the generator is run upto speed.

The brushless thyristor system is still under development and it is not yet possible to refer to operational experience or costs. There can be no doubt that solid state devices and techniques are finding increasing use on rotating machines and will play a more important role in the future.

3.5.3 Brushless Thyristor System: Developments are well advanced towards combining the principles of thyristor control and brushless excitation and thus also providing an excitation supply which is independent of main power system voltage fluctuations.

The technical problems are more difficult than those which have been overcome in the case of the rotating diode system. This is because of the need to apply firing pulses to the rotating thyristor gates whilst at the same time allowing control of pulse timing and thereby exciter voltage, to remain in the operators hands. A control link between stationary and rotating parts is therefore necessary and one method of achieving this is as follows —

At the simplest level, a brushless main exciter has power thyristors substituted for diodes and a small rotating armature generator having the same number of poles as the main exciter, is mounted on the shaft. This is called the

Control Exciter and its armature phase ends are connected to the thyristor gates thus providing firing pulses in synchronism with the main exciter armature voltage waves. The phase displacement between the control and main exciter voltages is determined by the physical angle between the stationary field systems of the main and control exciters, which in turn determines the average value of the exciter output voltage.

In fact the control exciter field systems contain field windings on both the direct and quadrature axes. These windings, are supplied independently with current automatically controlled and proportioned, so that the net field mmf resulting from both windings is constant but its position in space can be changed, thus varying the thyristor firing angle. A range of control of main exciter voltage from a positive ceiling to a negative ceiling of substantial amount is thus achieved. The design of the control exciter allows it to operate with an effective time constant of less than 10 mS and it thus imposes only a slight additional time lag on the control loop.

A further important refinement is that the control exciter output voltage is not applied directly to the power thyristor gates but is shaped to a waveform which gives the necessary rate of rise.

Fig.(34) shown in schematic form, an arrangement basically as discussed, having a control exciter with double the number of phases of the main exciter. A pilot exciter, not shown supplies a constant current to the main exciter field which therefore operates with a substantially constant

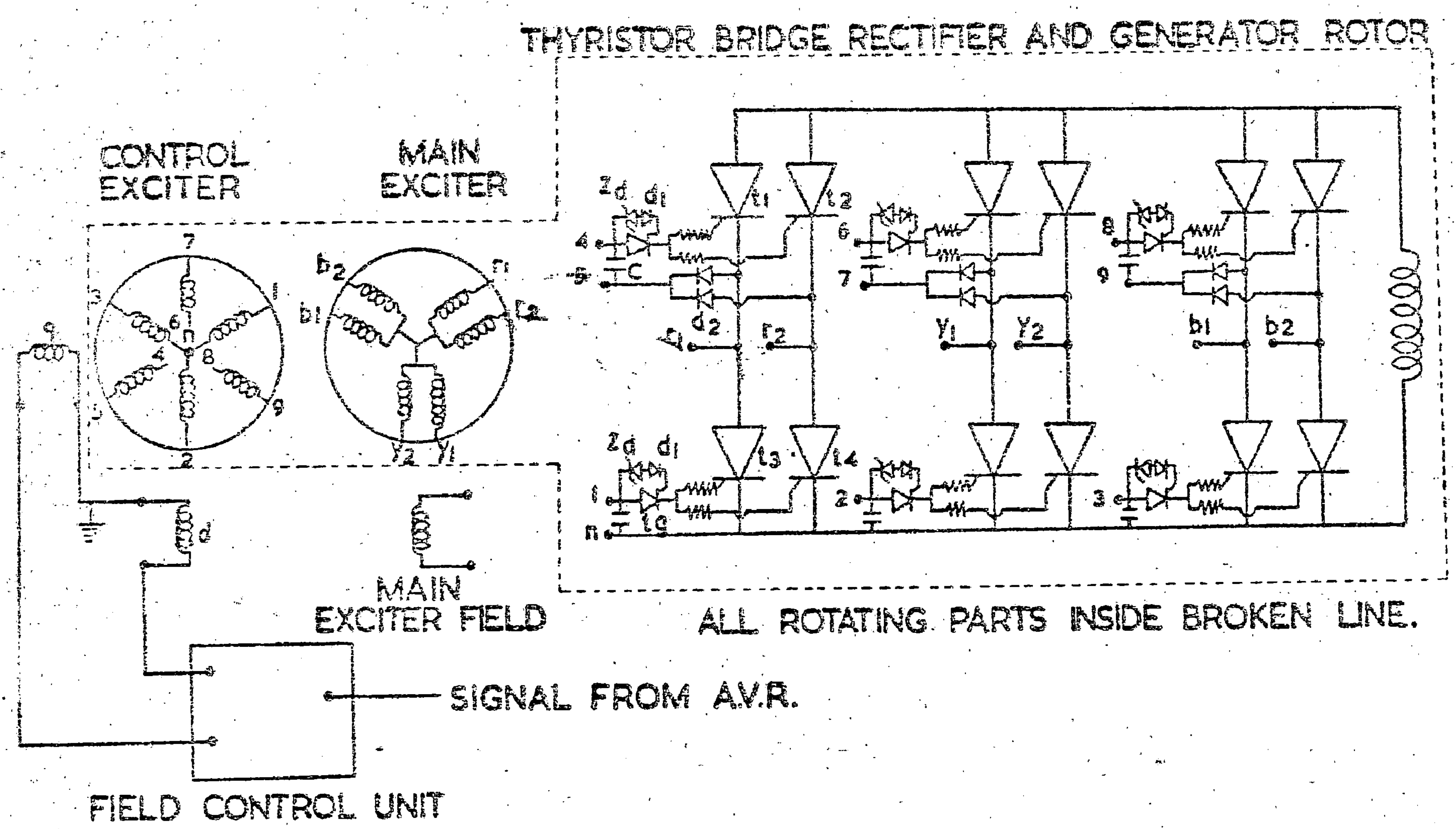


Figure 3.4 Brushless thyristor excitation system.

flux. Electrical connections are made from the numbered terminals on the control and main exciters to the corresponding numbers on the thyristor bridge rectifier. The number of paralleled thyristors per phase could be greater than the two shown without altering the principle of operation.

3.5.4 Operation: As all phases operate in a similar manner, it is necessary to consider only one phase, say the red phase thyristors t_1 to t_4. The windings 4-5 and 1-4 on the control exciter are used to supply gate current to thyristors t_1, t_2 and t_3, t_4 respectively in the following manner :-

When the sinusoidal voltage across terminals 1-4 reaches a certain value, with such a polarity that thyristor t_g is forward biased, the zener diode Z_d breaks over allowing current to flow into the gate of the thyristor t_g turning it on. This then allows current to flow from the control exciter winding 1-4 into the gates of thyristors t_3 and t_4 turning them on. Thyristors t_1 and t_2 are turned on 180° later in time because windings 1-n and 4-5 are arranged in antiphase. Then other phase thyristors are similarly fired in the correct sequence. Gate current continues to flow until thyristor t_g is reverse biased by the control exciter voltage and thus returns to the blocking state. Diode d_1 protects against reverse current in the gates of both main and gate thyristors t_g. Diode d_2 allow for a common return from the cathodes of a parallel set of thyristors to the control exciter whilst keeping the parallel phases isolated. Capacitor C charges up during the time, thyristor t_g is forward biased and before it fires.

Therefore when t_g is turned on, capacitor C rapidly discharges into the gates of the main parallel thyristor sets. This ensures fast rising gate currents, the rise time of which is only limited by the turn on time of the thyristors t_g, which can be in the region of 1 μ sec. The gate current flows for at least 90° of each cycle, thus ensuring positive firing and simultaneous conduction of a positive and negative bridge arm, without which it would not be possible for current to build up in the generator field initially.

3.6 A Rotating Thyristor Excitation System for Hydroelectric Generators (Excitation System No.4)

Excitation system in service on hydroelectric generators have been extremely reliable. Generator outages due to failure of elements of the excitation system are rare. Reliability is due to —

(1) Conservative rating of elements, exciters, etc.

(2) Low generator speed, minimizing maintenance of brushes.

(3) Short direct connection of exciter output to the field collector rings, minimizing exposure of the excitation power connections and eliminating mechanical switching devices.

(4) Voltage control element employing mangnetic amplifiers.

(5) Isolation of excitation system from voltage variation and transients in the A.C. power systems.

(6) Transfer to manual operation on failure of automatic control, avoiding loss of excitation for such reason.

The use of solid state power components for rectification, amplification and control now affords opportunity to further improve reliability and contribution to power system performance by increased speed and more sophisticated control. The design objective for the system described is to retain the proven functional features of the present direct-connected excitation system, improving these as possible, and to better provide for supplementary stabilising signals to improve power system performance through excitation control. Recently, improvements have been made on a piecemeal basis, a solid state regulator to replace the amplidyne or magnetic amplifier control, a supplementary stabilising control for addition as a separate package, and a solid state exciter to replace the rotating exciter.

3.6.1 System Operation : A block diagram of the excitation system is shown in Fig.(3.5). The section enclosed by dashed lines is the rotating portion of the system. The remainders is divided into 2 independent regulating systems.

The exciter regulator maintains the exciter ac terminal voltage at a nearly constant level corresponding to ceiling voltage. The exciter output is then used to power the entire excitation system effectively isolating its operation from outside disturbances. Voltage build up can be accomplished using only the residual exciter flux. For convenience and to shorten the build up time, flashing from the station battery supply is also incorporated.

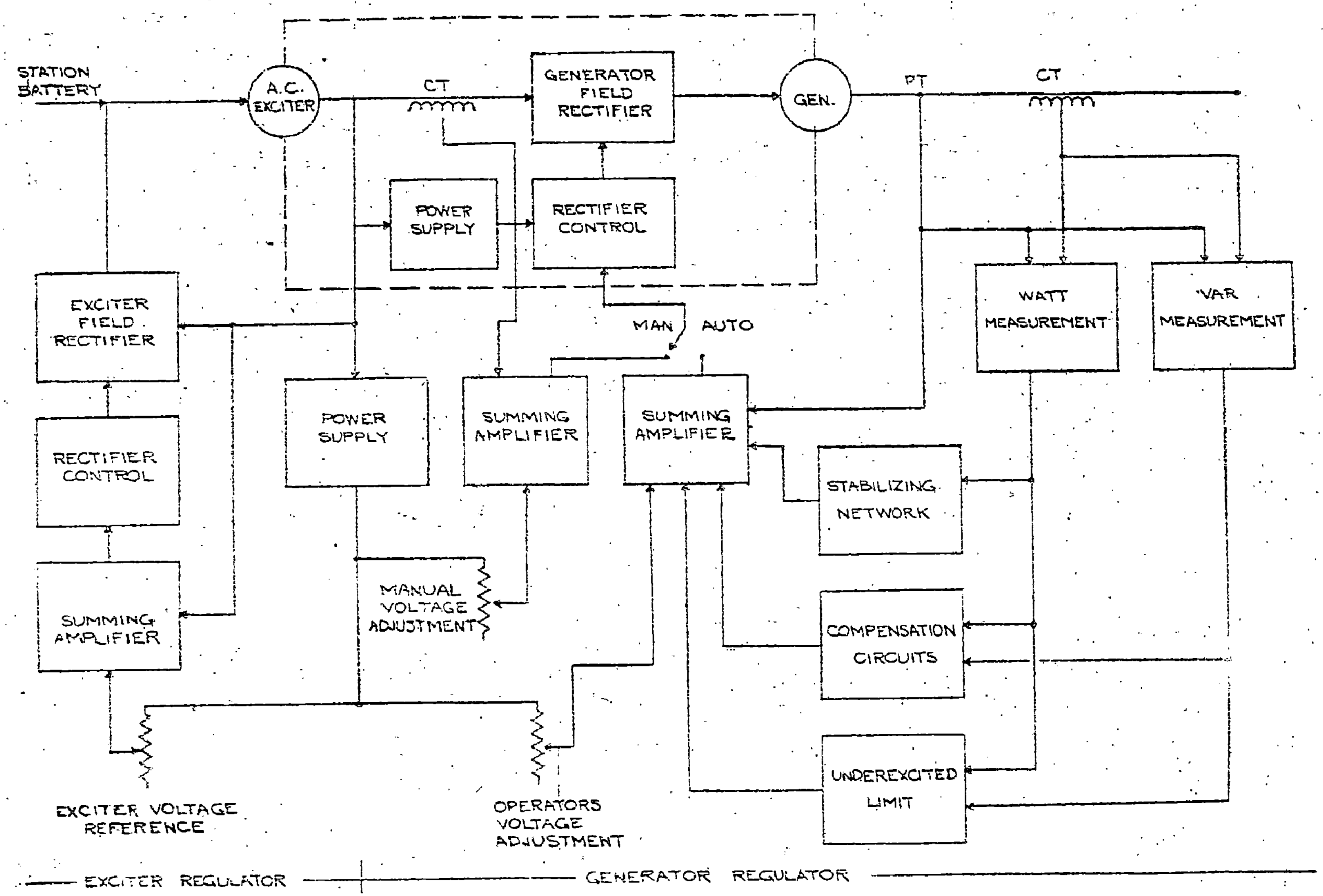


Fig 3.5 System Block Diagram

The generator regulator operates to maintain the generater terminal voltage at a nearly constant level as determined by the voltage adjustor setting and modified by the under excited limit, line compensation (or droop depending on the desired connection) and a stabilising signal derived from generator power.

The exciter has a rotating armature and stationary field winding. Typical exciter frequencies range from 16 to 30 Hz with a ceiling voltage to 1.5 P.U. based on generator rated field voltage.

The generator field rectifier is a double-way thyristor bridge circuit capable of inverting to reduce the generator field current. Since the voltage supplying the thyristor bridge is the ceiling voltage, the speed of response is a function of that ceiling.

The power supply and rectifier control included as part of the rotating element produce the necessary phase-controlled triggering signals in response to a d.c. control level supplied by the voltage regulator.

Generator field current measurement is obtained from current transformers located in the ac side of the generator field rectifier. The current level sensed is equivalent to the dc generator field current except for filtering losses are typically less than 1 % of the rated field current.

Not shown in Fig.(3.5) is an over voltage protection control which is combined with a field discharge resistor to protect the system in the event of out-of-step operation. The control and resistor provide full protection independent of the excitation system operation.

Self excitation power as well as control and measurement signals are transferred across the air-gap by collector rings and brushes sized for that application.

The exciter ac voltage is averaged, compared against the exciter voltage reference, and applied to the rectifier control and rectified in such a manner as to maintain the exciter terminal voltage at the desired level. Lag-lead compensation is used to stabilize the voltage control. A current limit is provided in the exciter field control to protect the system.

Standard potential and current transformers are used for sensing the generator terminal conditions. The potential signal is averaged and compared directly with the operators voltage adjustment (voltage reference) in the automatic mode of operation. The potential and current signals are combined in a set of transducers to produce the watt and Var signals for the complimentary-functions. These complimentary signals are then added in proper phase and polarity to modify the basic voltage regulation.

In the manual mode of operation, the generator field current is compared with a separate manual voltage adjustment (reference) and applied to the rotating thyristor bridge through separate regulating elements.

The generator regulator has lag-lead compensation to provide stable, responsive operation. In the automatic mode, the power derived stabilization signal is added above a minimum load (typically 25 %) to assist in damping power system oscillations.

CHAPTER 4

RELIABILITY MODELS

The most important aspect of any Reliability Study is a complete appreciation of the modes of failure and operation of the system under study [88]. Once the system is completely understood, it is possible to create a Reliability Block Diagram (or Logic Diagram) from the functional elements of the system. The functional elements can be represented in a block diagram by combinations of three basic reliability models. They are a series model, a parallel redundant model and a standby model. The basic reliability equation for a single component operating in the useful life period where the hazard rate $\lambda(t)$ is a constant, is as follows —

$$R(t) = e^{-\lambda t} \text{ where } \lambda = \text{failure rate}$$

R(t) is the probability of the component continuity to perform its intended function for a length of time t.

A measure of how well a system performs or meets its design objectives, is provided by the system reliability. If successful operation is derived for a specified period of time, reliability is defined as the probability that the system will perform satisfactorily for the required time interval. In general reliability can be defined as the probability of successful system operation in the manner and under the conditions of intended use. Hence the reliability relates to the frequency with which the failures occur and is closely connected with system maintainability, availability and cost. Due to the recognition of reliability as an important factor in all system engineering processes, a greater emphasis is being placed in the application of concepts in the system design.

System definition consists of defining, what the system is required to do, what its subsystems are, its operating environment, the functional relationship between its components and its basic design. Once the initial system objectives and requirements are established, the main task is to explore the design problem and to identify its elements such as parameters, constraints and criteria, consideration must also be given to system reliability requirements.

In reliability study, the distinction between physical and functional relationships of various elements of a system is an important one [7]. The system analyst should have a thorough knowledge of the functions of the different components and their effect on the performance of the system. These relationships can be represented by appropriate diagrams.

A diagram which depicts the physical relationships of the system is known as system diagram and the one which shows the functional relationships pictorially and indicates which elements must operate successfully for the system to accomplish its intended function is known as the logic diagram. The logic diagram may consist of many blocks connected either in series or in parallel or series-parallel. It has two ends, one designated as IN and the other as OUT and shows the way or ways in which the system can function successfully. For successful operation of the system, there should be at least one continuous path between IN and OUT terminals. The quantitative reliability of the system can be easily evaluated using logic diagrams.

The first step in evaluation of the reliability is therefore to prepare a logic diagram. This requires the knowledge of the functions of the various parts or components of the system and the various possible modes of failure of each part or component. A failure mode which, when occuring, results in system failure is shown as a series element in the logic diagram. A failure mode which, when occuring, does not affect the system operation is shown as a parallel element in the reliability block diagram. Any alternative means of performing the function is also shown in parallel, while failure of an element in the system diagram corresponds to the removal of the corresponding block in the section of the block diagram depicting that particular mode of failure.

If two components are connected in series, the reliability of the system (R_S) is given by the product of the individual component reliabilities. In the general case of n series components —

$$R_S = \prod_{i=1}^{n} R_i$$

$Q_S = (1-R_S)$ is the unreliability of the system.

It is important to appreciate that two components are in series in a reliability sense if the system requires both components to operate for system success. This is not dependent upon their electrical or mechanical (i.e. Physical) connection in the system.

In the case of a general n component series system,

$$R_S(t) = e^{-\sum_{i=1}^{n} \lambda_i t} \qquad (1)$$

The simplest case of redundancy is two components connected in parallel where only one component is required for system success,

$$R_S = R_1 + R_2 - R_1 R_2$$

$$R_S(t) = e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1 + \lambda_2)t} \qquad (2)$$

In the case of more components connected in parallel where the criterion of success is a single operable component, the reliability can be obtained from

$$Q_S = \prod_{i=1}^{n} Q_i \quad \text{and} \quad R_S = 1 - Q_S \qquad (3)$$

The case of an m out of n system can be handled using the Binomial Distribution or some other more general method. The general equation for redundant components assumes that the components are stochastically independent and that all failures are in a passive mode.

The simplest case of a standby system is one containing two identical components and a fully reliable sensing and switching mechanism. In this case, the system reliability is given by —

$$R_S(t) = e^{-\lambda t} + \lambda t\, e^{-\lambda t} \qquad (4)$$

If the two components are non-identical i.e. $\lambda_1 \neq \lambda_2$, the equation becomes —

$$R_S(t) = e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_2 - \lambda_1}\left[e^{-\lambda_1 t} - e^{-\lambda_2 t}\right] \qquad (5)$$

Components 1 and 2 are the main and standby components respectively. If the sensing and switching element reliability on an on-demand basis is R_{SS}, the above equation becomes —

$$R_S(t) = e^{-\lambda_1 t} + R_{SS}\frac{\lambda_1}{\lambda_2 - \lambda_1}\left[e^{-\lambda_1 t} - e^{-\lambda_2 t}\right] \qquad (6)$$

CHAPTER 5

RELIABILITY ANALYSIS

The procedure for reliability analysis of a system has been given in Chapter 1 of this thesis and it is well defined up to the point where suitable failure rate data is required. At this point, such data for many components in power system service are not available because the statistics required to generate them have not been kept. This thesis focuses attention on the results that could be obtained if such data were available and hopefully, it will help and clarify the actual data requirements.

Further the basic electronic components which are used in these excitation systems are similar to those used in military and space applications for which some failure rate data is available. It must be observed; however, that much of this is not directly relevant to the power system situation since the environmental conditions and the maintenance procedures are so different.

5.1 Reliability Evaluation of Static Excitation System No.1

The simplified system diagram shown in Fig.(3.1) can be redrawn from a reliability view point. This is shown in Fig.(5.1). This excitation system can be analyzed using the basic reliability building blocks previously described. This diagram can be reduced to the one shown in Fig.(5.2) by combining the series elements into equivalent components. The basic equations for the individual elements and the equivalent blocks are shown in Table I.

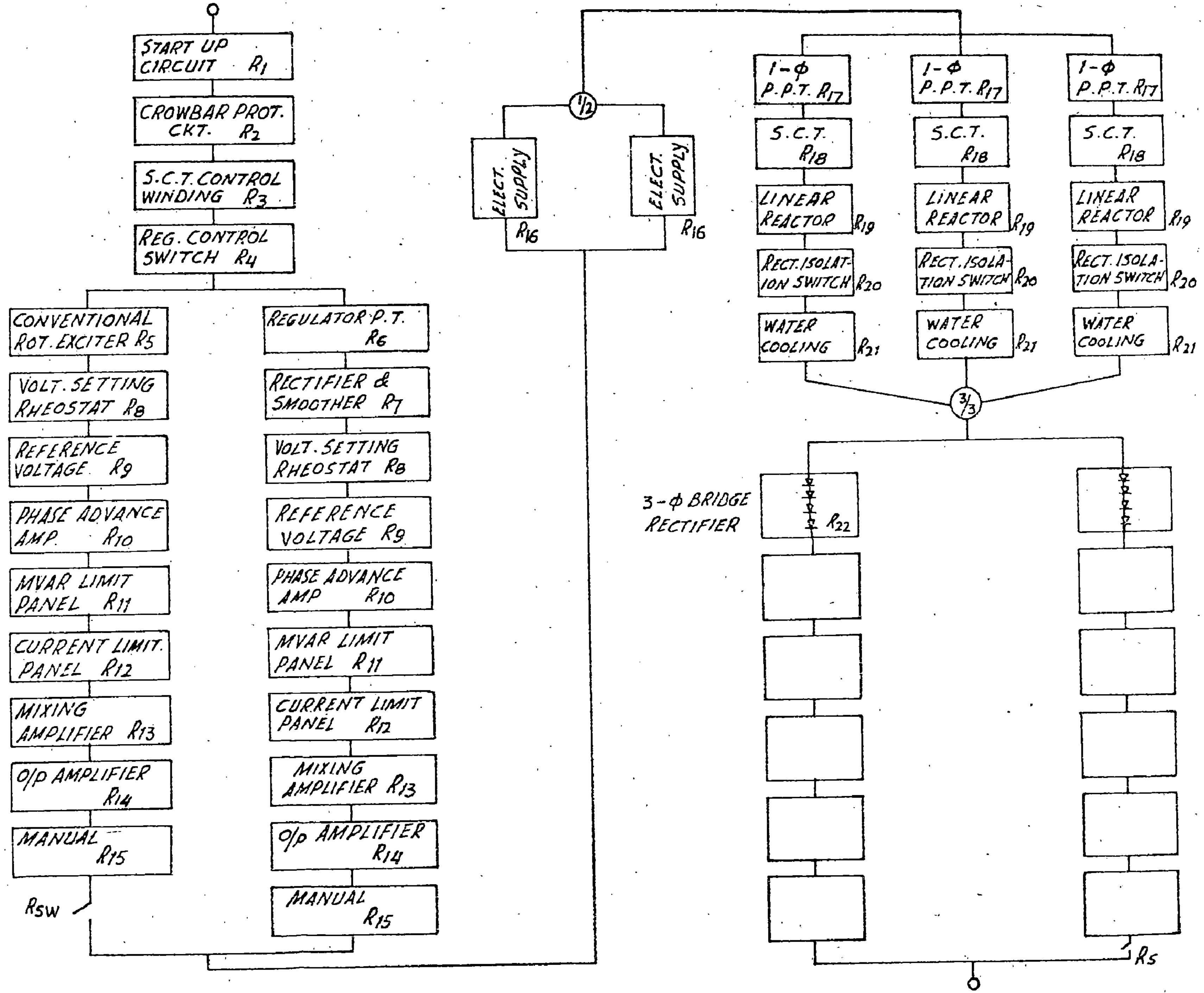


FIG5.1 RELIABILITY BLOCK DIAGRAM FOR EXCITER No.1

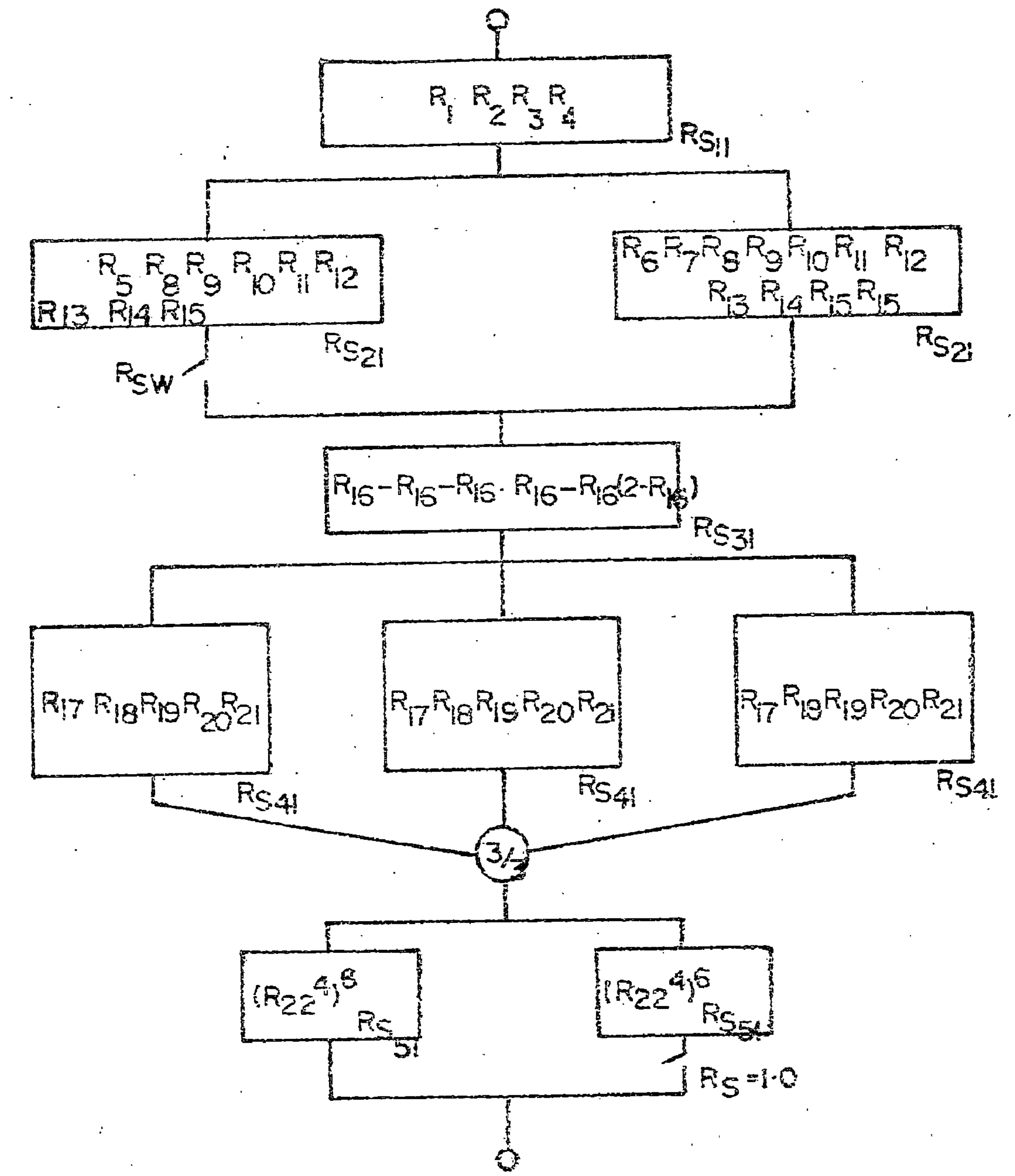


FIG. 5.2 REDUCED RELIABILITY DIAGRAM FOR THE BASIC SYSTEM CONFIG (1)

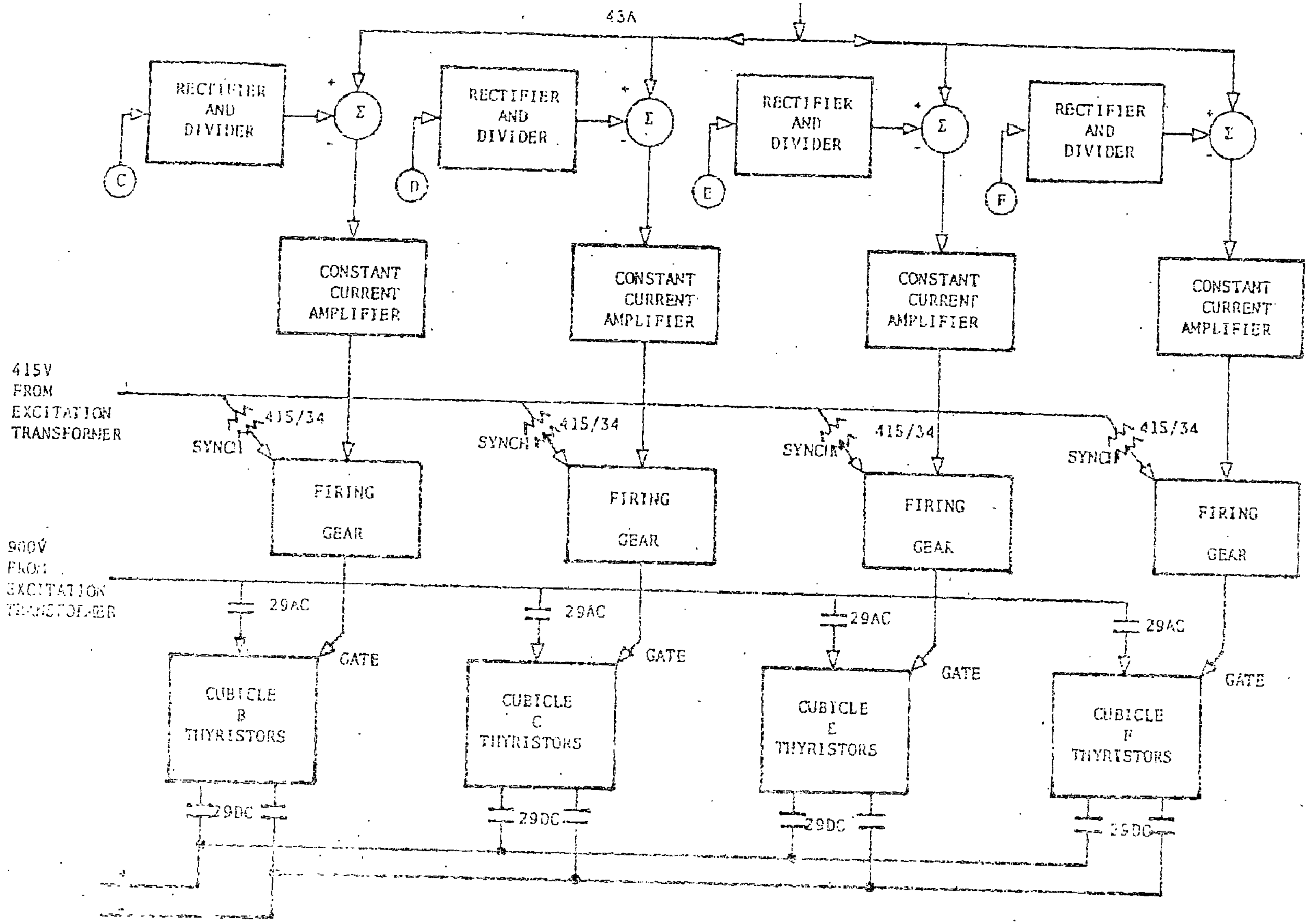
The reduced reliability block diagram shown in Fig.(5.2) is for the Actual System which has been designated as configuration 1. The design modification shown in Table II were considered in the reliability evaluation. Reliability Evaluation of different configuration was done with the help of computer TDC-312.

The procedure for formulating the basic reliability block diagram and the reliability equation is relatively straight forward after the system failure and operating conditions have been established. It becomes immediately obvious, however, that there is a real shortage of acceptable outage data and that present outage data collection procedures are inadequate for this purpose.

The failure data shown in Appendix I (Table I) has been used for the purpose of illustrating the relative impact of the design modifications given in Table II. The system reliabilities as function of time (RT) are shown for each design modification in Table III. In case 1, the switching reliability (RSW) associated with the change over to the standby avr (d.c. voltage regulator) is assumed to be 0.98 and in case 2, it is taken 1.0.

5.2 Reliability Evaluation of Static Excitation System No.2

The simplified block diagram shown in Fig.(3.2) can be redrawn from a reliability point of view. This is shown in Fig.(5.5 and 5.6) This system can also be analyzed using the basic reliability building blocks previously described. This



29AC - ac isolator switch
29DC - dc isolator switch

Figure 5.5 Control and firing circuits and thyristor bridges.

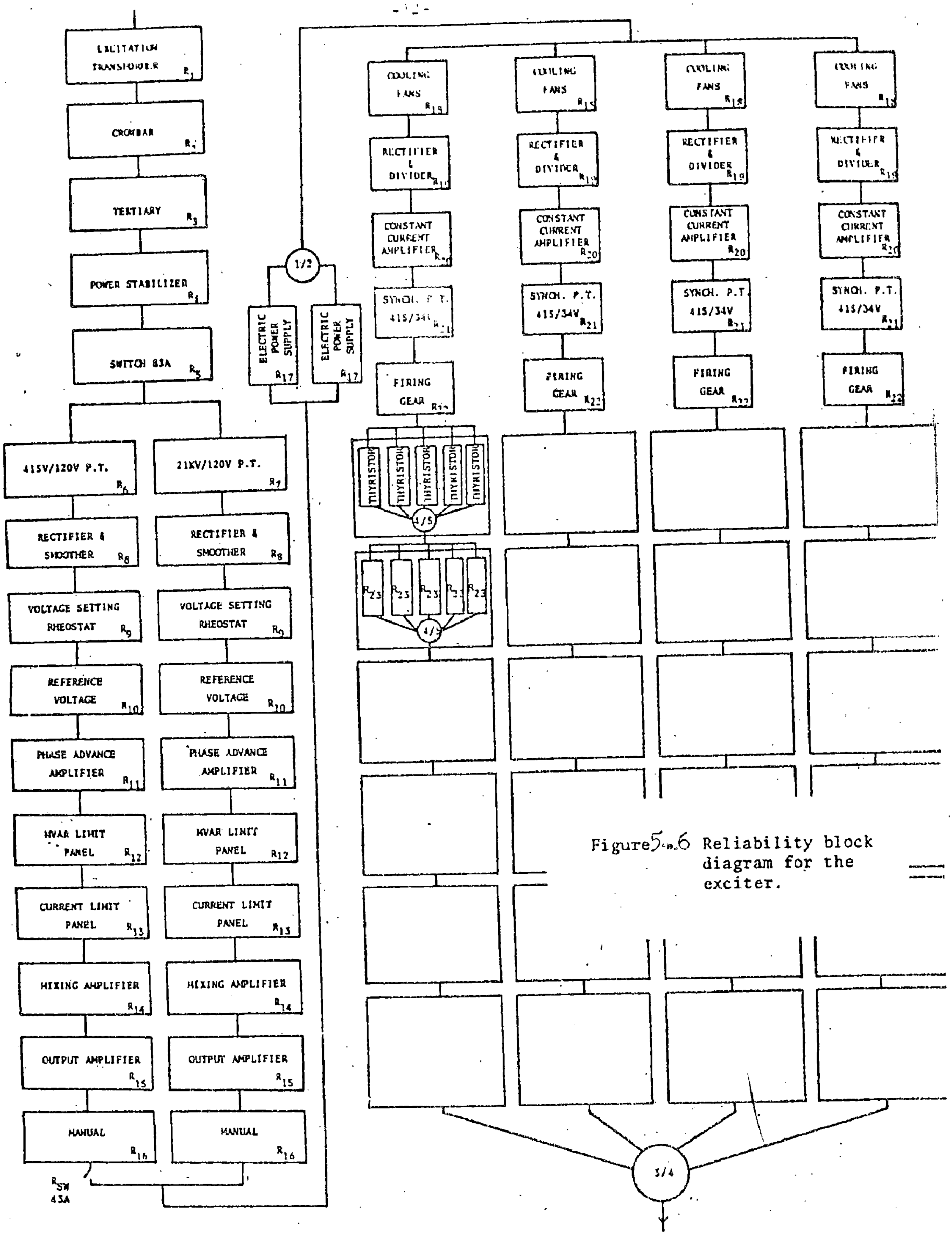


Figure 5.6 Reliability block diagram for the exciter.

diagram can also be reduced to the one shown in Fig.(5.7). The Actual System Equations are shown in Table IV.

The reduced reliability block diagram shown in Fig.(5.7) is for the Actual System which has been designated as Configuration 1. The design modification shown in Table V were considered in the reliability evaluation. The COMPUTER PROGRAM for reliability evaluation of different configurations was run on computer TDC-312.

The failure data shown in Appendix I (Table II) was suggested by Calgary Power Ltd. [88] for the purpose of illustrating the relative impact of the design modifications. The system reliabilities as functions of time are shown for different configurations in Table VI. In case 1, the switching reliability (RSW) associated with the change over to the standby avr is assumed to be 0.98 and in case 2, it is taken 1.0 as for Static Excitation System No.1.

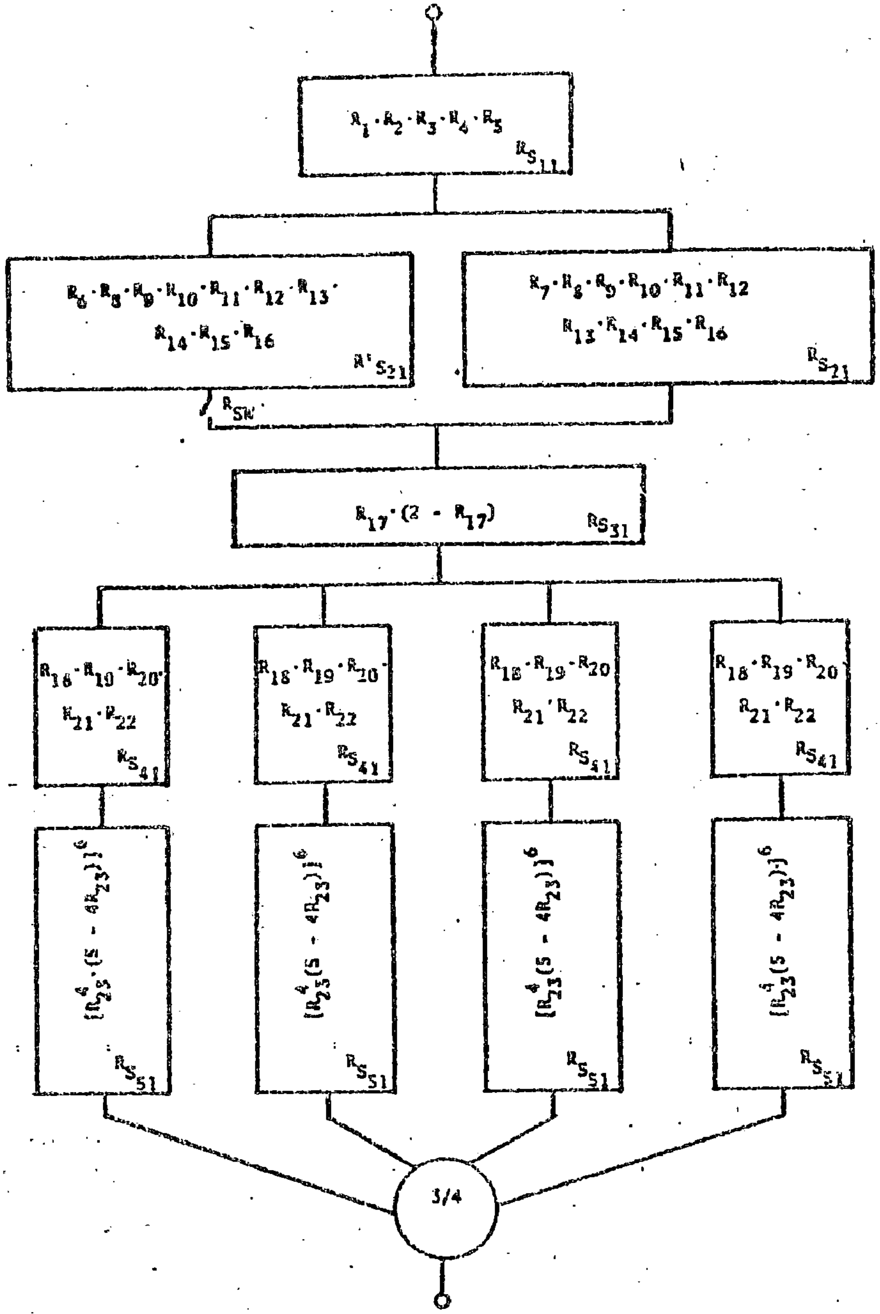


Figure 5.7 Reduced reliability diagram for the basic system - Configuration #1.

TABLE I

ACTUAL SYSTEM EQUATIONS

FOR

STATIC EXCITATION SYSTEM No.1

If $\lambda_{S_2} = \lambda'_{S_2}$

then $R(t) = R_{S_1}(t).R_{S_2}(t)[1+R_{S_W}\lambda_{S_2}t]\, R_{S_3}(t).R_{S_7}(t)$

If $\lambda_{S_2} \neq \lambda'_{S_2}$

then $$R(t) = R_{S_1}(t)[R_{S_2}(t) + R_{S_W}\frac{\lambda_{S_2}}{\lambda'_{S_2}-\lambda_{S_2}}(R_{S_2}(t)-R'_{S_2}(t))]R_{S_3}(t).\; R_{S_7}(t)$$

Where —

$R_{S_1}(t) = e^{-\lambda_{S_1}t}$, $\lambda_{S_1} = \lambda_1+\lambda_2+\lambda_3+\lambda_4$

$R_{S_2}(t) = e^{-\lambda_{S_2}t}$, $\lambda_{S_2} = \lambda_6+\lambda_7+\lambda_8+\lambda_9+\lambda_{10}+\lambda_{11}+\lambda_{12}+\lambda_{13}+\lambda_{14}+\lambda_{15}$

$R'_{S_2}(t) = e^{-\lambda'_{S_2}t}$, $\lambda'_{S_2} = \lambda_5+\lambda_8+\lambda_9+\lambda_{10}+\lambda_{11}+\lambda_{12}+\lambda_{13}+\lambda_{14}+\lambda_{15}$

$R_{S_3}(t) = e^{-\lambda_{16}t}(2-e^{-\lambda_{16}t})$

$R_{S_4}(t) = e^{-\lambda_{S_4}t}$, $\lambda_{S_4} = \lambda_{17}+\lambda_{18}+\lambda_{19}+\lambda_{20}+\lambda_{21}$

Assuming a fully reliable sensing and switching mechanism (i.e. $R_S = 1.0$) —

$$R_{S_5}(t) = e^{-24\lambda_{22}t} + 24\lambda_{22}t\ e^{-24\lambda_{22}t}$$

$$R_{S_6}(t) = [R_{S_4}(t)]^3$$

$$R_{S_7}(t) = R_{S_5}(t).R_{S_6}(t)$$

$$= [R_{S_4}(t)]^3[e^{-24\lambda_{22}t} + 24\lambda_{22}t\ e^{-24\lambda_{22}t}]$$

Each of the design modifications has a different impact on the reduced reliability block diagram shown in Fig.(5.2). These effects are shown in Fig.(5.3 and 5.4).

TABLE II

DESIGN MODIFICATIONS FOR EXCITATION SYSTEM No. 1

The design condition shows the modifications made to the ACTUAL System.

Configuration	Design Conditions
2	No redundancy in the static exciter
3	No d.c. voltage regulator (i.e. Standby AVR)

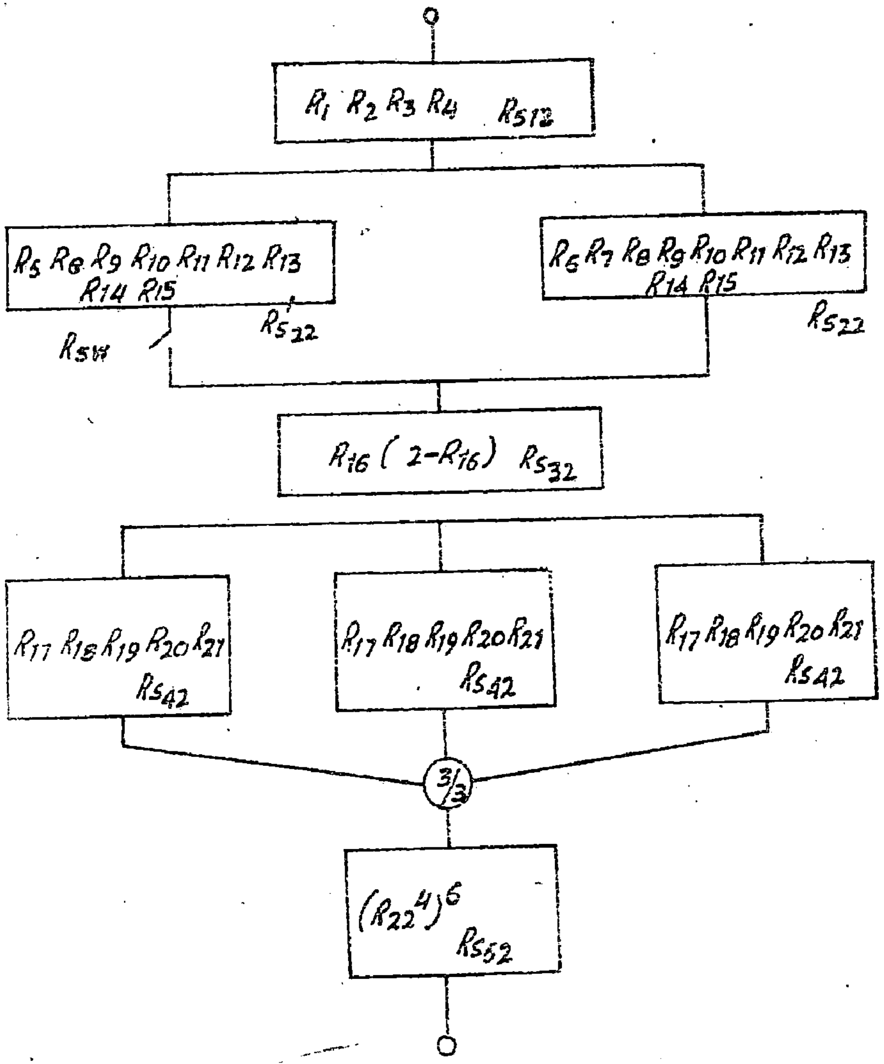


FIG. 5.3 RELIABILITY DIAGRAM FOR CONFIG. (2)
-NO REDUNDANCY IN STATIC EXCITER

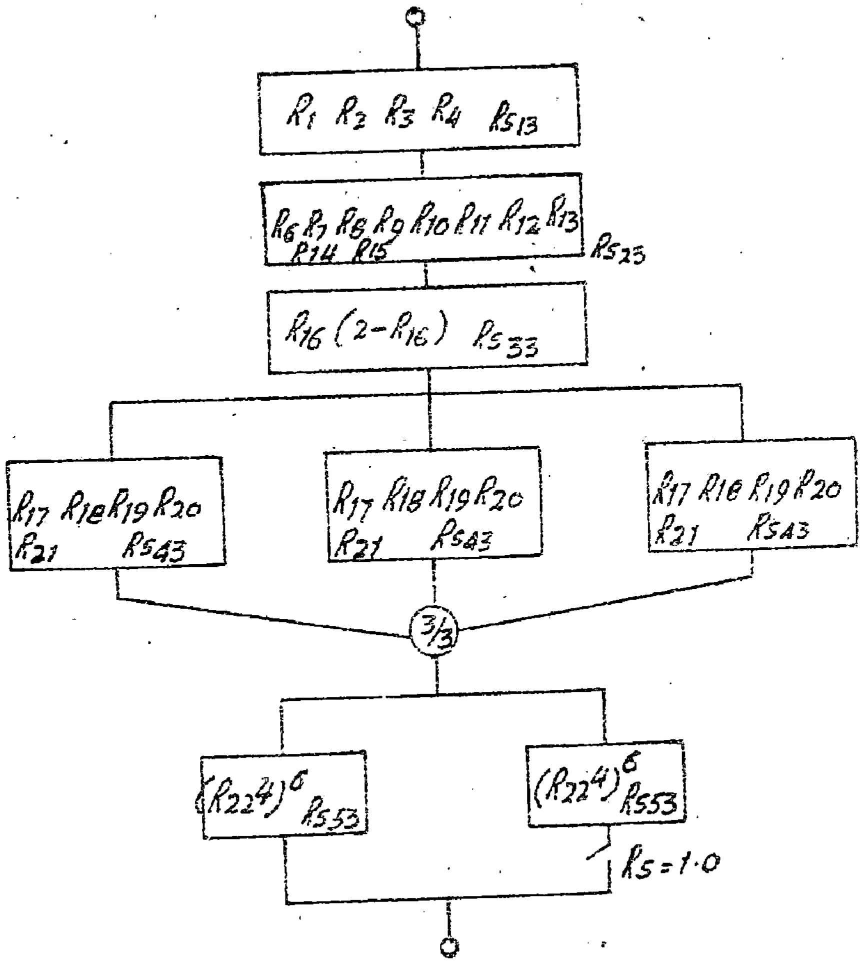


FIG. 5.4 RELIABILITY DIAGRAM FOR CONFIG. (3)
-NO STANDBY AVR (i.e. d.c. REGULATO

TABLE III

RELIABILITY (RT) OF EXCITATION SYSTEM NO.1

TIME (HOURS)	Case I (RSW = 0.98) CONFIGURATIONS			Case II (RSW = 1.0) CONFIGURATIONS		
	1	2	3	1	2	3
100	0.9194223	0.8771974	0.8895591	0.9200317	0.8950988	0.8895591
200	0.8443197	0.7825589	0.7911173	0.8454055	0.7985296	0.7911173
300	0.7744674	0.6979608	0.7033975	0.7759178	0.7122050	0.7033975
400	0.7096286	0.6223628	0.6252584	0.7113505	0.6350642	0.6252584
500	0.6495512	0.5548264	0.5556727	0.6514671	0.5661495	0.5556727
600	0.5939777	0.4945095	0.4937222	0.5960238	0.5046016	0.4937222
700	0.5426573	0.4406560	0.4385850	0.5447813	0.4996490	0.4385850
800	0.4953312	0.3925861	0.3895247	0.4974905	0.4005981	0.3895247
900	0.4517510	0.3496893	0.3458824	0.4539116	0.3568259	0.3458824
1000	0.4116723	0.3114196	0.3070705	0.4138070	0.3177751	0.3070705

TABLE IV

ACTUAL System Equations
For
Static Excitation System No.2

If $\lambda_{S_2} = \lambda'_{S_2}$

$$R(t) = R_{S_1}(t).R_{S_2}(t)[1 + R_{SW}\,\lambda_{S_2}t]R_{S_3}(t).R_{S_7}(t)$$

If $\lambda_{S_2} \neq \lambda'_{S_2}$

$$R(t) = R_{S_1}(t)[R_{S_2}(t) + R_{SW}\frac{\lambda_{S_2}}{\lambda'_{S_2} - \lambda_{S_2}}(R_{S_2}(t) - R'_{S_2}(t))]R_{S_3}(t).R_{S_7}(t)$$

Where

$$R_{S_1}(t) = e^{-\lambda_{S_1}t}, \quad \lambda_{S_1} = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5$$

$$R_{S_2}(t) = e^{-\lambda_{S_2}t}, \quad \lambda_{S_2} = \lambda_7 + \lambda_8 + \lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15} + \lambda_{16}$$

$$R'_{S_2}(t) = e^{-\lambda'_{S_2}t}, \quad \lambda'_{S_2} = \lambda_6 + \lambda_8 + \lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15} + \lambda_{16}$$

$$R_{S_3}(t) = e^{-\lambda_{17}t}(2 - e^{-\lambda_{17}t})$$

$$R_{S_4}(t) = e^{-\lambda_{S_4}t}, \quad \lambda_{S_4} = \lambda_{18} + \lambda_{19} + \lambda_{20} + \lambda_{21} + \lambda_{22}$$

$$R_{S_5}(t) = [e^{-4\lambda_{23}t}(5-4e^{-\lambda_{23}t})]^6$$

$$= e^{-24\lambda_{23}t}(5-4e^{-\lambda_{23}t})$$

$$R_{S_6}(t) = e^{-(\lambda_{S_4} + 24\lambda_{23})t}.(5-4e^{-\lambda_{23}t})^6$$

Contd....

TABLE IV (Continued)

$$R_{S_7}(t) = 4e^{-3(\lambda_{S_4} + 24\lambda_{23})t}(5-4e^{-\lambda_{23}t})^{18}$$

$$-3e^{-4(\lambda_{S_4} + 24\lambda_{23})t}(5-4e^{-\lambda_{23}t})^{24}$$

Each of the following design modification given in Table V has a different impact on the reduced reliability block diagram shown in Fig.(5.7). These effects has been shown in Figures(5.8 to 5.15).

TABLE V

Possible Design Modification For Excitation System No.2

The design condition shows the modification made to the ACTUAL System.

Configuration	Design Condition
2	Two power stabilizers
3	Synchronizing PT's connected to the 900V line
4	Two power stabilizers Synchronizing PT's connected to the 900V line
5	No redundancy in the static exciter
6	No redundancy in the static exciter Two power stabilizers
7	No redundancy in the static exciter Synchronizing PT's connected to the 900V line
8	No redundancy in the static exciter Two power stabilizers Synchronizing P.T's connected to the 900V line
9	No standby avr

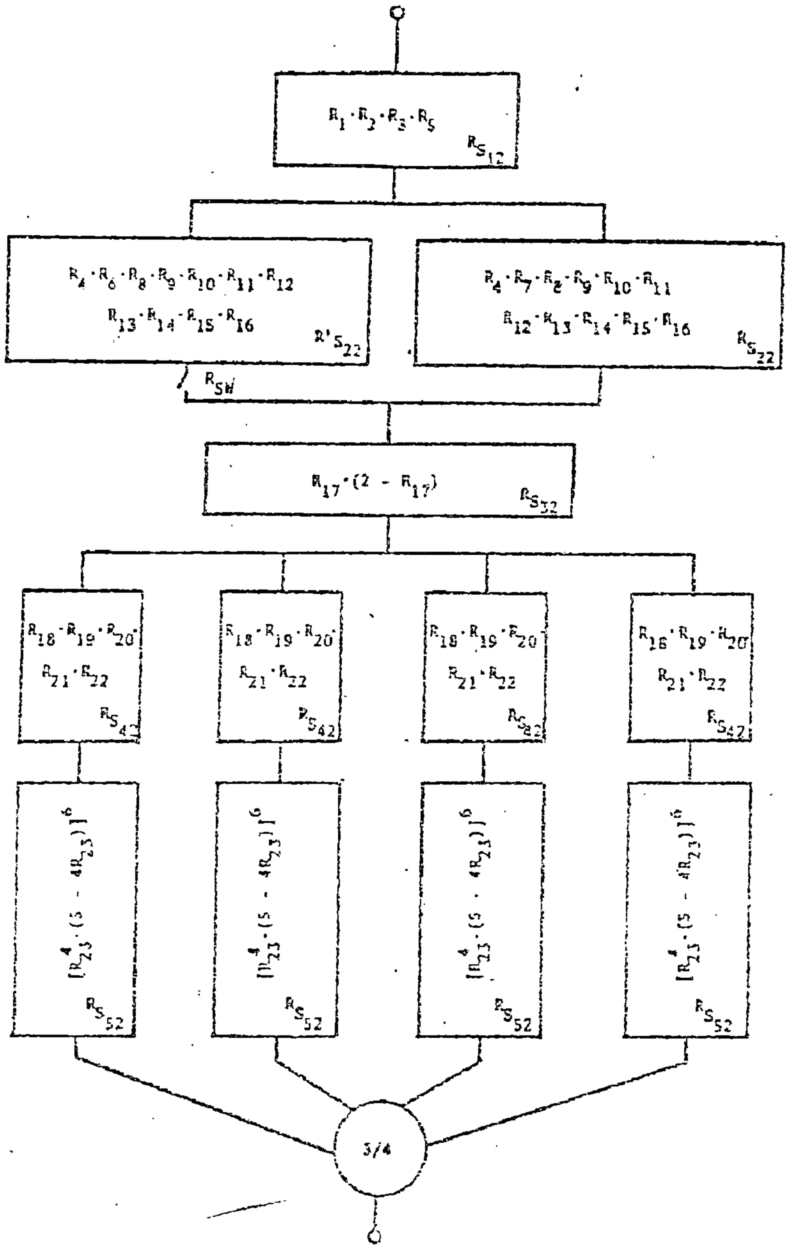


Figure 5.8 Reliability diagram for Configuration #2 - two power stabilizers.

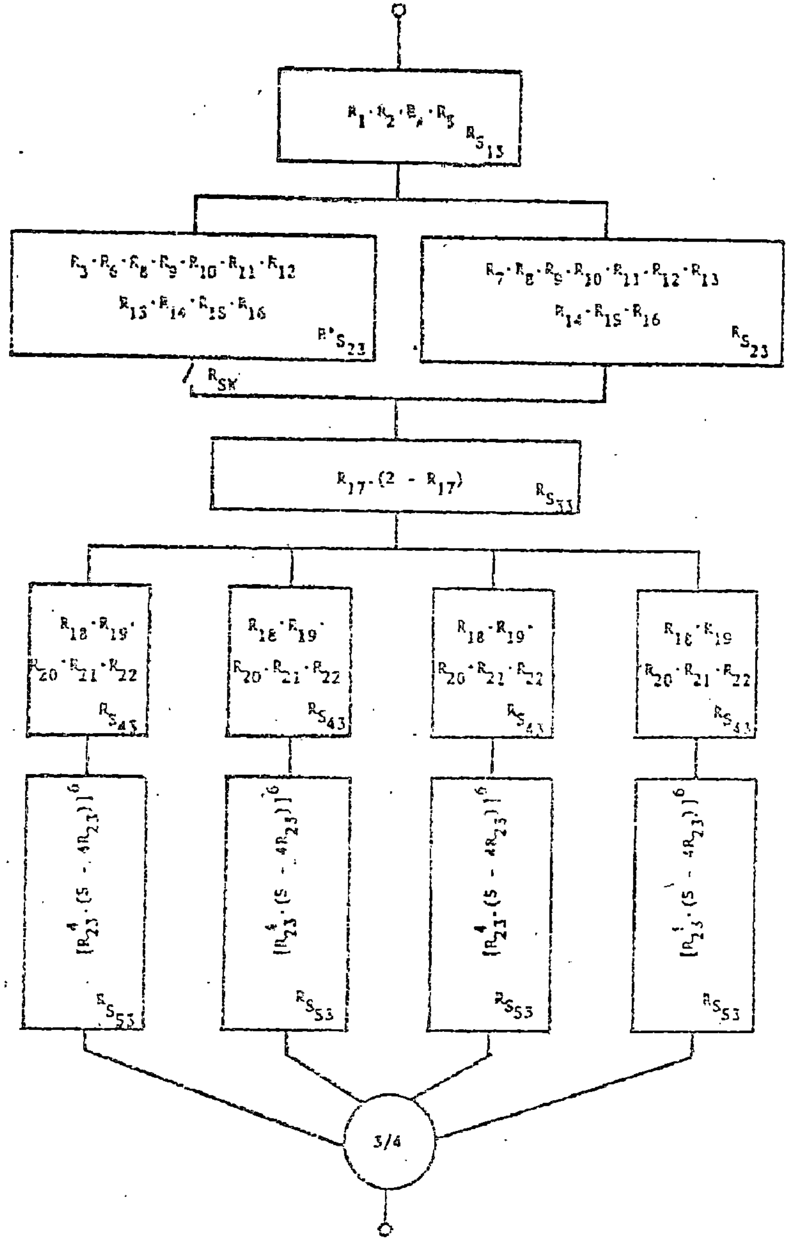


Figure 5.9 Reliability diagram for Configuration #3 - synchronizing PTs connected to 900V line.

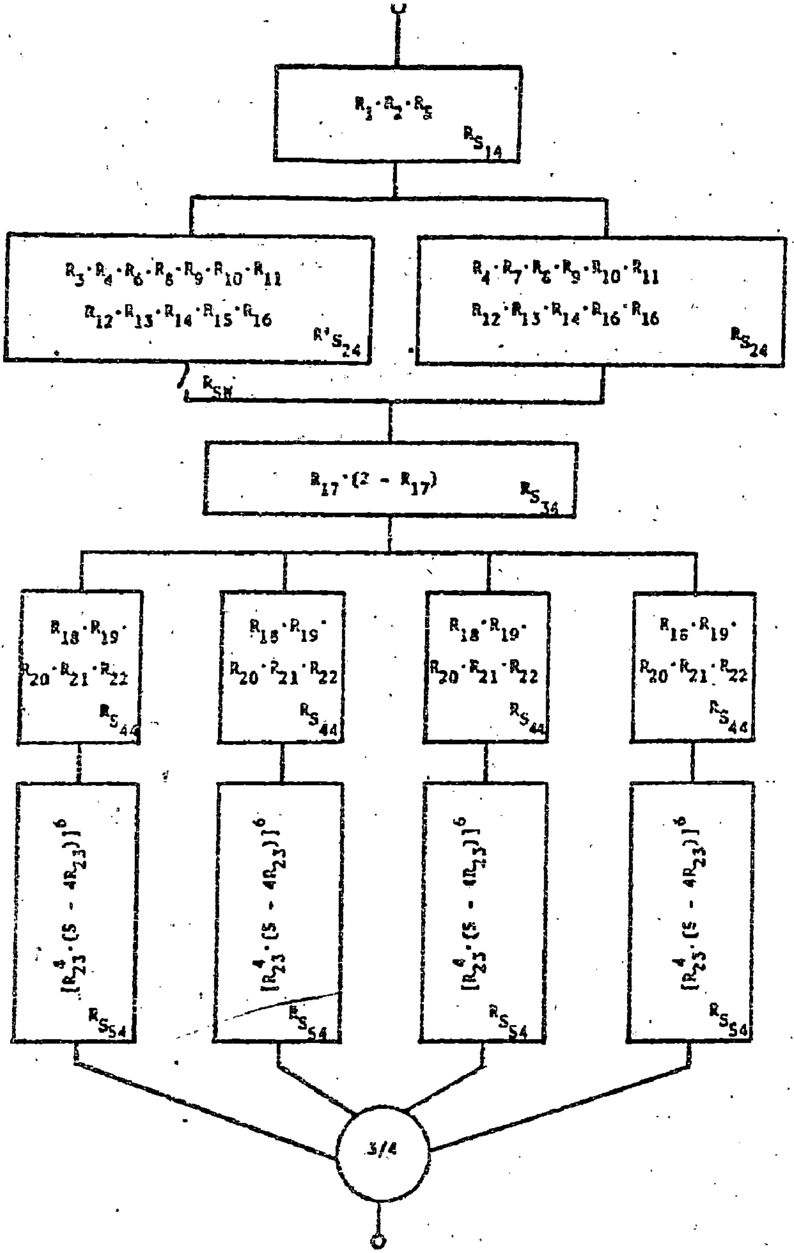


Figure 5.10 Reliability diagram for Configuation #4 - two power stabilizers ~~and~~ synchronizing PTs connected to 900V line.

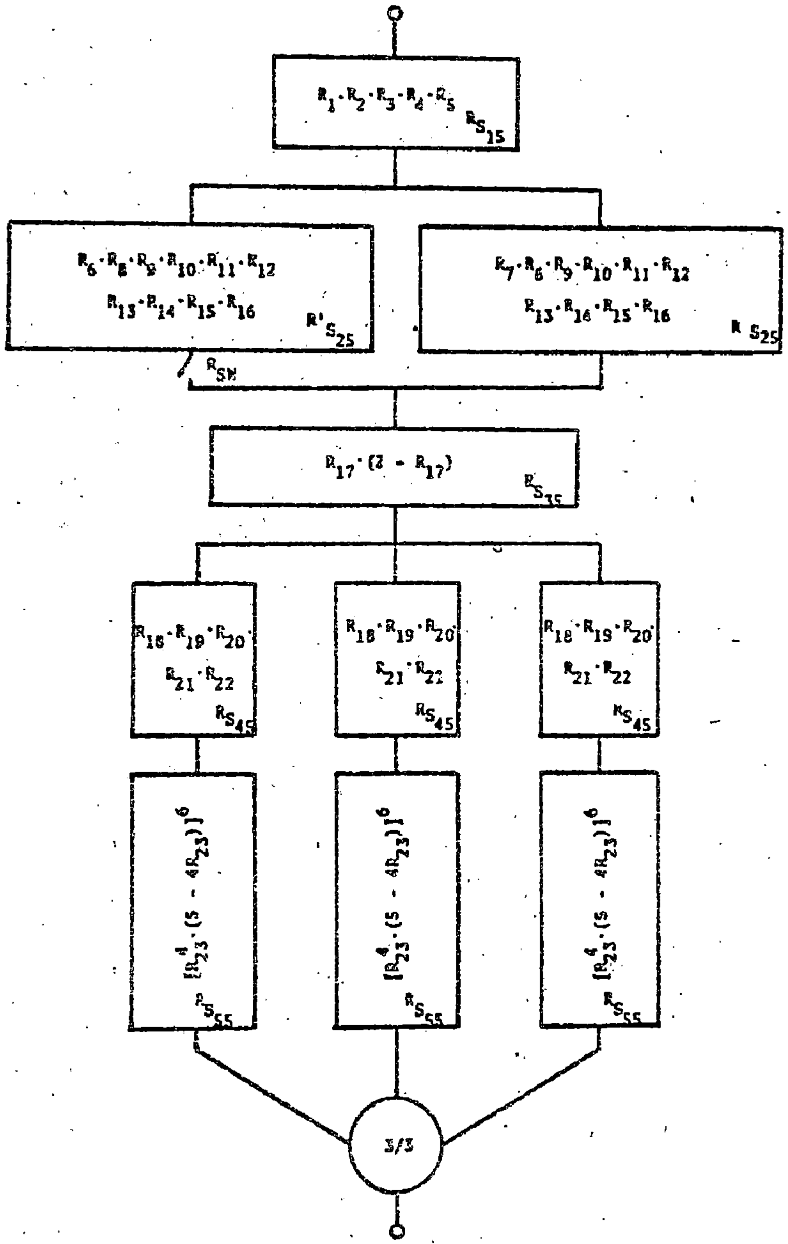


Figure 5.11 Reliability diagram for Configuration #5 - no redundancy in static exciter.

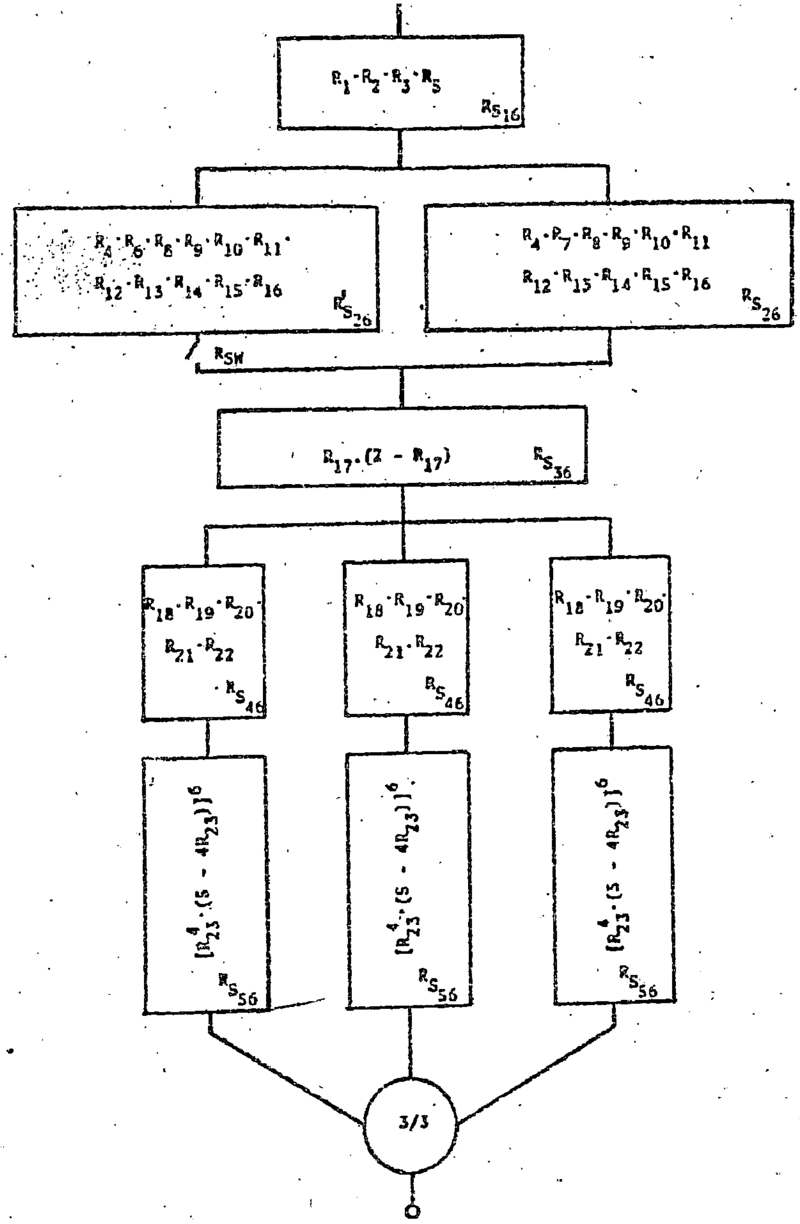


Figure 5.12 Reliability diagram for Configuration #6 - no redundancy in static exciter, two power stabilizers.

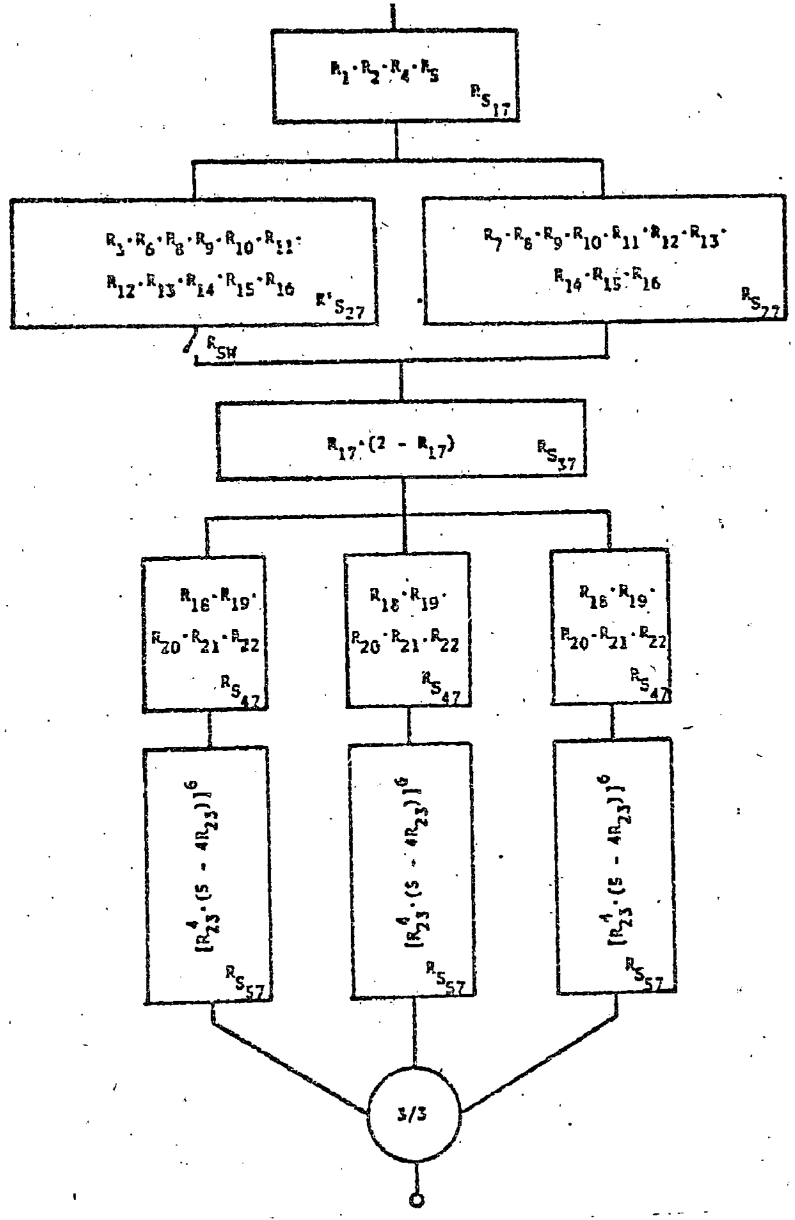


Figure 5.13 Reliability diagram for Configuration #7.- no redundancy in static exciter, synchronizing PTs connected to 900V line.

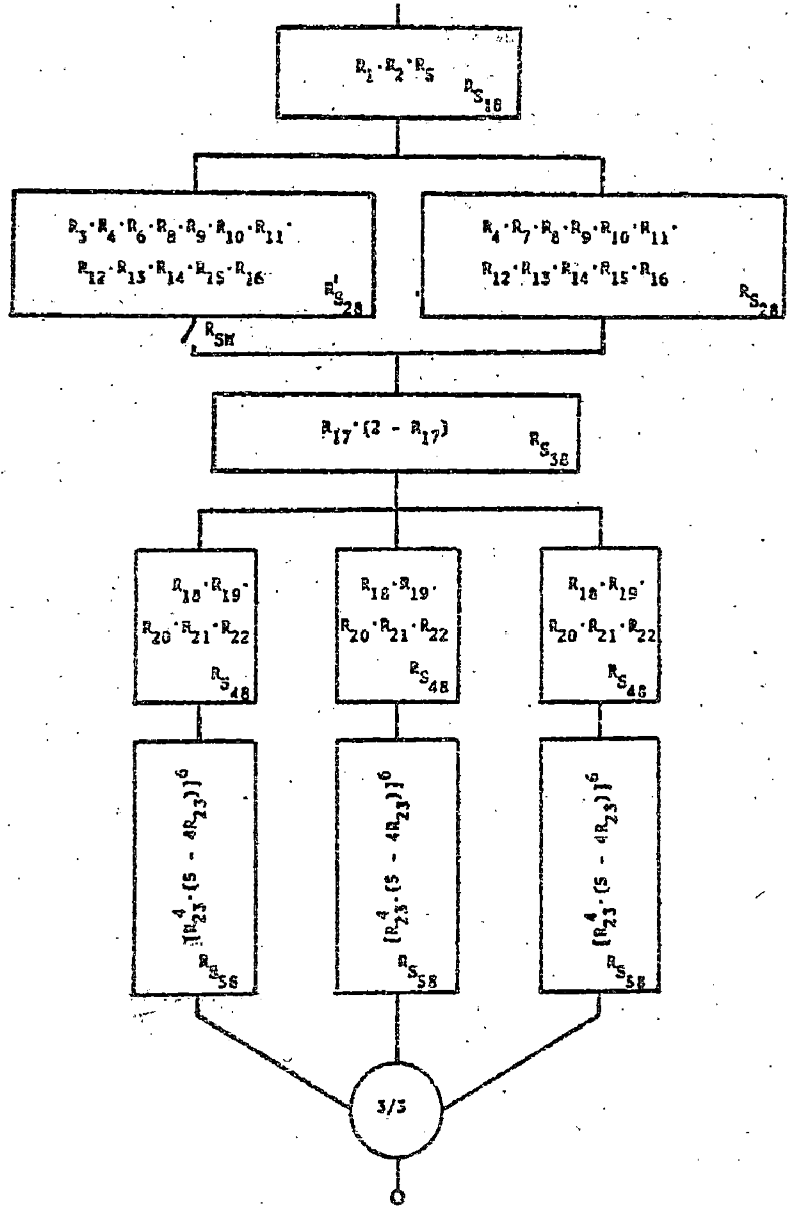


Figure 5.14 Reliability diagram for Configuration #8 - no redundancy in static exciter, two power stabilizers, Synch. P.T's Connected to 500V Line

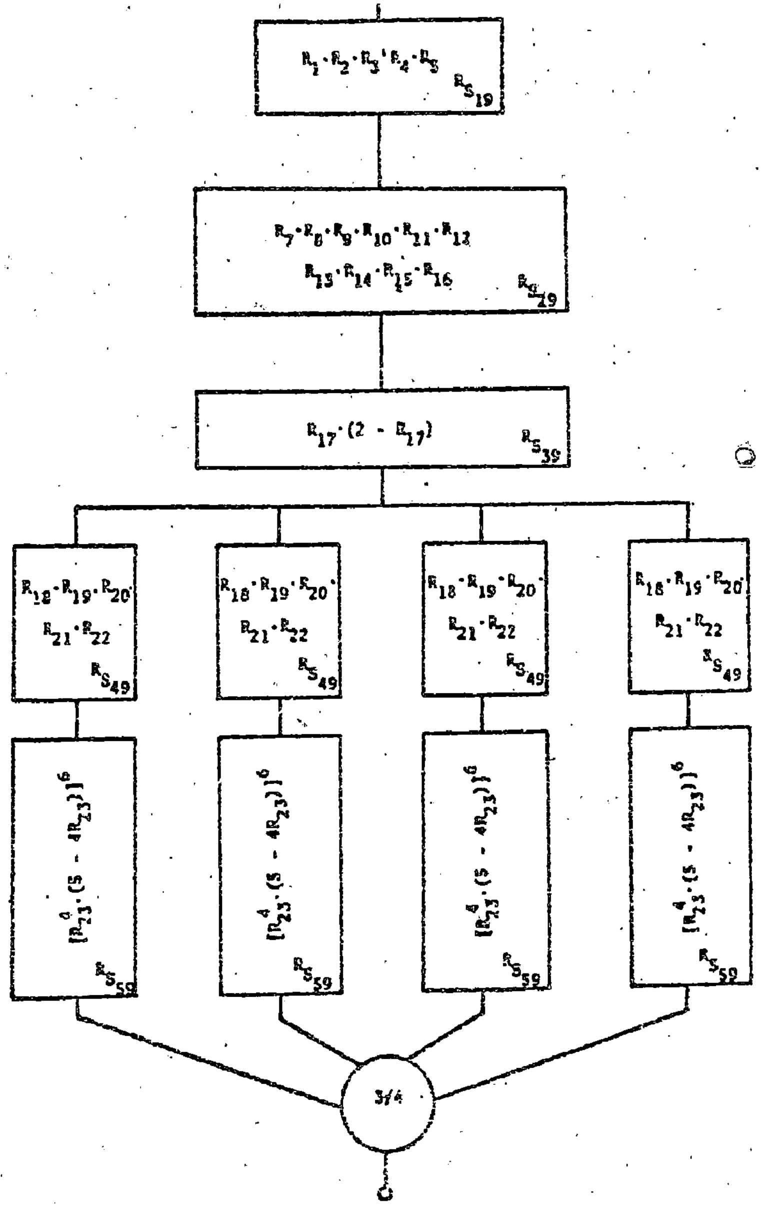


Figure 5.15 Reliability diagram for Configuration #9 - no standby avr.

TABLE VI

RELIABILITY (RT) OF EXCITATION SYSTEM NO.2

TIME (HOURS)	Case I (RSW = 0.98) CONFIGURATIONS								
	1	2	3	4	5	6	7	8	9
100	0.9784114	0.9819372	0.9793731	0.9829031	0.9135353	0.9168273	0.9144329	0.9177289	0.9466831
200	0.9502986	0.9569318	0.9521406	0.9587820	0.8327173	0.8385297	0.8343311	0.8401508	0.8906004
300	0.9169054	0.9262134	0.9195354	0.9288614	0.7574313	0.7651205	0.7596040	0.7673079	0.8331356
400	0.8793733	0.8909240	0.8826904	0.8942661	0.6875415	0.6965725	0.6901350	0.6991854	0.7754179
500	0.8387426	0.8521186	0.8426446	0.8560598	0.6228783	0.6328118	0.6257761	0.6357386	0.7183600
600	0.7959270	0.8107339	0.8003175	0.8151659	0.5632195	0.5736971	0.5663263	0.5768332	0.6626675
700	0.7517482	0.7676210	0.7565232	0.7724607	0.5083442	0.5190775	0.5115731	0.5223503	0.6088945
800	0.7069079	0.7235153	0.7119862	0.7286605	0.4579896	0.4687491	0.4612798	0.4720826	0.5574422
900	0.6620262	0.6790726	0.6673167	0.6844342	0.4119222	0.4225287	0.4152140	0.4258648	0.5086080
1000	0.6176054	0.6348316	0.6230294	0.6403429	0.3698634	0.3801797	0.3731118	0.3834803	0.4625705

Contd.......

TABLE VI

RELIABILITY (RT) OF EXCITATION SYSTEM NO.2

TIME (HOURS)	Case I (RSW = 0.98) CONFIGURATIONS								
	1	2	3	4	5	6	7	8	9
100	0.9784114	0.9819372	0.9793731	0.9829031	0.9135353	0.9168273	0.9144329	0.9177289	0.9466831
200	0.9502986	0.9569318	0.9521406	0.9587820	0.8327173	0.8385297	0.8343311	0.8401508	0.8906004
300	0.9169054	0.9262134	0.9195354	0.9288614	0.7574313	0.7651205	0.7596040	0.7673079	0.8331356
400	0.8793733	0.8909240	0.8826904	0.8942661	0.6875415	0.6965725	0.6901350	0.6991854	0.7754179
500	0.8387426	0.8521186	0.8426446	0.8560598	0.6228783	0.6328118	0.6257761	0.6357386	0.7183600
600	0.7959270	0.8107339	0.8003175	0.8151659	0.5632195	0.5736971	0.5663263	0.5768332	0.6626675
700	0.7517482	0.7676210	0.7565232	0.7724607	0.5083442	0.5190775	0.5115731	0.5223503	0.6088945
800	0.7069079	0.7235153	0.7119862	0.7286605	0.4579896	0.4687491	0.4612798	0.4720826	0.5574422
900	0.6620262	0.6790726	0.6673167	0.6844342	0.4119222	0.4225287	0.4152140	0.4258648	0.5086080
1000	0.6176054	0.6348316	0.6230294	0.6403429	0.3698634	0.3801797	0.3731118	0.3834803	0.462570

Contd......

TABLE VI (Continued)

RELIABILITY (RT) OF EXCITATION SYSTEM NO.2

Case 2 (RSW = 1.0)

TIME (HOURS)	CONFIGURATIONS								
	1	2	3	4	5	6	7	8	9
100	0.9790592	0.9826570	0.9800209	0.9836229	0.9141401	0.9174993	0.9150379	0.9184011	0.9466831
200	0.9515171	0.9582855	0.9533601	0.9601371	0.8337848	0.8397157	0.8353998	0.8413383	0.8906004
300	0.9186151	0.9281131	0.9212476	0.9307640	0.7588437	0.7666897	0.7610183	0.7688796	0.8331356
400	0.8814949	0.8932815	0.8848163	0.8966282	0.6892002	0.6984157	0.6917970	0.7010322	0.7754179
500	0.8411994	0.8548486	0.8451076	0.8587965	0.6247029	0.6348392	0.6276052	0.6377711	0.7183600
600	0.7986466	0.8137556	0.8030454	0.8181964	0.5651440	0.5758353	0.5682565	0.5789778	0.6626675
700	0.7546635	0.7708602	0.7594488	0.7757116	0.5103156	0.5212680	0.5135514	0.5245486	0.6088945
800	0.7099582	0.7269046	0.7150488	0.7320633	0.4599659	0.4709450	0.4632640	0.4742872	0.5574422
900	0.6651571	0.6825515	0.6704619	0.6879286	0.4138702	0.4246934	0.4171710	0.4280391	0.5086080
1000	0.6207695	0.6383472	0.6262093	0.6438760	0.3717583	0.3822851	0.3750161	0.3855960	0.4625705

TABLE VI (Continued)

Design Feature \ Configuration	1	2	3	4	5	6	7	8	9
3/4 redundancy in exciter	x	x	x	x					x
No redundancy in exciter					x	x	x	x	
One Power Stabilizer	x		x		x		x		x
Two Power Stabilizer		x		x		x		x	
Synch. PT's to 415 V line	x	x			x	x			x
Synch. PT's to 900 V line			x	x			x	x	
No standby avr									x

CHAPTER 6

ANALYSIS OF RESULTS

The information presented in Table III for Static Excitation System No.1 and in Table VI for Static Excitation System No.2 can be analyzed in several ways. The specific results would of course depend upon the numerical values used for the component reliabilities. A number of specific conclusions can be drawn from the particular set of values shown in Table III and Table VI about the relative merits of the various design alternatives tested by the analysis. Here Excitation System No.1 and Excitation System No.2 will be analyzed separately.

6.1 Analysis of Results of Excitation System No.1: A comparison of the probabilities of having a satisfactory operating system after 1000 hours of operation for the three configuration can be used to bring out a number of interesting facts —

(a) A comparison of configuration 1 and 2 shows that the improvement associated with, going from single bridge rectifier to twin bridge rectifier is large being in the range of 0.096 to 0.1002. Therefore redundancy in the power rectifier is very effective since the probability of successful operation drops about 0.10 when redundancy is removed.

(b) A comparison of the results for configuration 1 and 3 indicates that there is signicant reliability advantage in having a standby d.c. voltage regulator since it results in an improvement in probability of successful operation of about 0.106.

(c) The small difference in the assumed reliability of the change over switch (R_{SW}) illustrated by case 1 and case 2 results in a difference in probabilities of successful operation in the order of 0.002 to 0.006.

The actual numerical values were obtained at t = 1000 hours. The numerical results can be compared for any specified time and similar conclusions may be drawn.

6.2 Analysis of Results of Excitation System No.2

Results of Excitation System No.2 are also analyzed in similar way as for Excitation System No.1 . A comparison of the probabilities of having a satisfactory operating system after 1000 hours of operation for the nine configurations can be used to bring out a number of interesting facts —

(a) A comparison of the results for the group 1,2,3 or 4 with group 5,6,7 and 8 shows that the 3/4 redundancy in the exciter is very effective since the probability of successful operation drops about 0.27 when that redundancy is removed.

(b) A comparison of the configuration pairs 1-2, 3-4, 5-6 and 7-8 shows that the improvement associated with, going from one to two power stabilizers is small being in the range of 0.010 to 0.017.

(c) Pairs 1-3, 2-4, 5-7 and 6-8 show that the improvement which would result from supplying the synchronizing P.Ts from the 900V line instead of through the tertiary of the excitation transformer is in the order of 0.003 to 0.005.

(d) A comparison of the results for configuration 1 and 9 indicates that there is a significant reliability advantage in having a standby AVR since it results in an improvement in probability of successful operation of 0.155.

(e) The small difference in the assumed reliability of the change over switch (RSW) illustrated by case 1 and case 2 results in a difference in probabilities of successful operation in the order of 0.003.

The actual numerical values were obtained at t = 1000 hours. The numerical results can also be compared for any specified time and similar conclusions may be drawn.

CHAPTER 7

CONCLUSICN & SUGGESTIONS

Though a perfectly designed, thoroughly tested and properly maintained system should never fail but the experience shows a failure in such cases too. The present thesis is a step forward in the direction of suggesting the improvement which can be considered at the design stage.

In Chapter I, a brief introduction to conventional as well as static excitation systems has been given. Different types of excitation systems has been presented in Chapter II. As the static excitation system for a.c. generators is better than usual rotating exciters due to flexibility of installation, simplicity in the a.c. generator design and excellent reliability and performance, these have been described in detail in Chapter III.

In Chapter IV different basic reliability models for simplifying the reliability block diagram have been presented. A Computer Program for Reliability Analysis has been developed in Chapter V. The numerical results presented and discussed in Table III & Table VI for Static Excitation Systems 1 & 2 in this thesis illustrate that the method described gives a reliability index for complex excitation systems. This index can be used to compare the relative reliability merits of alternative system designs. The complete analytical procedures for this analysis have been given in Table I & Table IV of this Chapter. Different design modifications which have been considered for reliability evaluation, have also been given in Table II & Table V.

In Chapter VI, analysis of results have been done separately for static excitation system 1 & 2.

It is concluded from the results of static excitation system 1 that redundancy in power rectifier as well as standby d.c. voltage regulator improves the reliability. While from the results of static excitation system 2, it is inferred that 3/4 redundancy in exciter is very effective and also there is reliability improvement in having a standby AVR.

As the accuracy of reliability results depends upon the accuracy of failure data, therefore reliable failure data for each component should be available if these analysis are to be useful to designers & users of such equipment. So a failure data bank should be established in the country where exact failure field data of all the power system components may be kept.

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APPENDIX I

TABLE I

Component Failure Rates [71,84 and 88]

COMPONENT		FAILURE RATE (FAILURE /HOUR)
1. Start Up Circuit	(λ_1)	0.000100
2. Crowbar Protection Circuit	(λ_2)	0.000057
3. S.C.T. Control Winding	(λ_3)	0.000010
4. Regulator Control Switch	(λ_4)	0.000057
5. Conventional Rotating exciter	(λ_5)	0.000000625
6. Regulator Potential Transformer	(λ_6)	0.000010
7. Rectifier and Smoother	(λ_7)	0.000023
8. Voltage Setting Rheostat	(λ_8)	0.000057
9. Reference Voltage	(λ_9)	0.000023
10. Phase Advance Amplifier	(λ_{10})	0.000023
11. MVAR Limit Panel	(λ_{11})	0.000023
12. Current Limit Panel	(λ_{12})	0.000023
13. Mixing Amplifier	(λ_{13})	0.000023
14. Output Amplifier	(λ_{14})	0.000023
15. Manual	(λ_{15})	0.000114
16. Electric Power Supply	(λ_{16})	0.000114
17. P.P.T.	(λ_{17})	0.000010
18. S.C.T.	(λ_{18})	0.000010
19. Linear Reactor	(λ_{19})	0.000010
20. Rectifier Isolation Switch	(λ_{20})	0.000057
21. Water Cooling Path	(λ_{21})	0.000114
22. Diode	(λ_{22})	0.00000005

Case I RSW = 0.98

Case II RSW = 1.0

Note:- The power magnetic components (PPT's, SCT's and linear reactors) are designed to the same standards as other critical transformers in the power station and are therefore considered in a high reliability class. In this thesis, failure rate of all these components have been assumed equal for reliability evaluation.

TABLE II

Component Failure Rates [88]

COMPONENT		FAILURE RATE (FAILURE / HOUR)
1. Excitation transformer	(λ_1)	0.000010
2. Crowbar	(λ_2)	0.000057
3. Tertiary	(λ_3)	0.000010
4. Power Stabilizer	(λ_4)	0.000038
5. Switch	(λ_5)	0.000057
6. 415/120 V P.T.	(λ_6)	0.000010
7. 21 kV/120V P.T.	(λ_7)	0.000010
8. Rectifier and Smoother	(λ_8)	0.000023
9. Voltage Setting Rheostat	(λ_9)	0.000057
10. Reference Voltage	(λ_{10})	0.000023
11. Phase Advance Amplifier	(λ_{11})	0.000023
12. MVAR Limit Panel	(λ_{12})	0.000023
13. Current Limit Panel	(λ_{13})	0.000023
14. Mixing Amplifier	(λ_{14})	0.000023
15. Output Amplifier	(λ_{15})	0.000023
16. Manual	(λ_{16})	0.000114
17. Power Supply	(λ_{17})	0.000114
18. Cooling fans	(λ_{18})	0.000114
19. Rectifier and Divider	(λ_{19})	0.000038
20. Constant Current Amplifier	(λ_{20})	0.000038
21. Synchronizing P.T. 415/34V	(λ_{21})	0.000010
22. Firing Gear	(λ_{22})	0.000038
23. Thyristors	(λ_{23})	0.000016

Case I RSW = 0.98

Case II RSW = 1.0

APPENDIX II

1. Computer Program for Reliability Analysis of Basic Static Excitation System No.1

```
C:  P.K. GOEL RELIABILITY ANALYSIS CONFIGURATION(1) SYSTEM(1)
    DIMENSION AL(22), ALS(22), ALSP(2)
    READ N
    DO 5 I = 1,N
C:  AL = LEMDA
    READ AL (I)
5:  CONTINUE
C:  ALS = LEMDAS
    RSW = 0.98
     T  = 100.0
    ALS (1) = AL(1) + AL(2) + AL(3) + AL(4)
    ALEM = 0.0
    DO 6I = 6,15
    ALEM = ALEM + AL(I)
6:  CONTINUE
    ALS(2) = ALEM
    ALE = AL(5)
    DO 10 I = 8, 15
    ALE = ALE + AL (I)
10: CONTINUE
    ALSP(2) = ALE
    ALS(4)  = AL(17) + AL(18) + AL(19) + AL(20) + AL(21)
    WRITE 20, ALS(1), ALS(2), ALSP(2), ALS(4)
```

```
11: A = ALS(1)
    RSIT = EXPF(-A*T)
    B = ALS(2)
    RS2T = EXPF(-B*T)
    C = ALSP(2)
    RS2P = EXPF(-C*T)
    D = AL(16)
    RS3T = EXPF(-D*T)*(2.0-EXPF(-D*T))
    E = ALS(4)
    RS4T = EXPF(-E*T)
    F = AL(22)
    RS5T = EXPF(-24.0*F*T)+(24.0*F*T*EXPF(-24.0*F*T))
    RS6T = RS4T**3
    RS7T = RS5T*RS6T
    WRITE  20,RSIT,RS2T,RS2P,RS3T,RS4T,RS5T,RS6T,RS7T
    IF (ALSP(2)-ALS(2))14,15,14
14: RT = RSIT*(RS2T+(RSW*ALS(2))/(ALSP(2)-ALS(2))
             *(RS2T-RS2P))*RS3T*RS7T
    GO TO 25
15: RT = RSIT*RS2T*(1.0+RSW*ALS(2)*T)*RS3T*RS7T
25: WRITE  30,RSW,T,RT
20: FORMAT (///,E,"   ",E,"   ",E,"   ",E)
30: FORMAT (///,"RSW =    ",E,"TIME =   ",E,"RT =   ",E)
    T = T + 100.0
    IF (T-1000.0)11,11,22
```

2. Computer Program for Reliability Analysis of Basic Static Excitation System No.2

```
C: P.K. GOEL RELIABILITY ANALYSIS CONFIGURATION (1) SYSTEM (2)
   DIMENSION AL(23), ALS(23), ALSP(2)
   READ N
   DO 15 I = 1,N
C: AL = LEMDA
   READ AL(I)
15:CONTINUE
C: ALS = LEMDAS
   RSW = 0.98
   T = 100.0
   ALS(1) = AL(1)+AL(2)+AL(3)+AL(4)+AL(5)
   ALEM = 0.0
   DO 16 I = 7,16
   ALEM = ALEM + AL(I)
16:CONTINUE
   ALS(2) = ALEM
   ALE = AL(6)
   DO 17 I = 8,16
   ALE = ALE + AL(I)
17:CONTINUE
   ALSP(2) = ALE
   ALS(4) = AL(18)+AL(19)+AL(20)+AL(21)+AL(22)
   WRITE 20,ALS(1),ALS(2),ALSP(2),ALS(4)
18:A = ALS(1)
   RS1T = EXPF(-A*T)
   B = ALS(2)
   RS2T = EXPF(-B*T)
   C = ALSP(2)
   RS2P = EXPF(-C*T)
   D = AL(17)
   RS3T = EXPF(-D*T)*(2.0-EXPF(-D*T))
   E = ALS(4)
   RS4T = EXPF(-E*T)
```

```
     F = AL(23)
     RS5T = EXPF(-24.0*F*T)*((5.0-4.0*EXPF(-F*T))**6)
     RS6T = RS4T*RS5T
     A = (4.0*EXPF(-3.0*(E+24.0*F)*T)
         *((5.0-4.0*EXPF(-F*T))**18))
     B = (3.0*EXPF(-4.0*(E+24.0*F)*T)
         *((5.0-4.0*EXPF(-F*T))**24))
     RS7T = A-B
     WRITE 20,RS1T,RS2T,RS2P,RS3T,RS4T,RS5T,RS6T,RS7T
     IF (ALSP(2)-ALS(2))25,30,25
25:  RT = RS1T*(RS2T+(RSW*ALS(2))/(ALSP(2)-ALS(2))
          *(RS2T-RS2P))*RS3T*RS7T
     GO TO  31
30:  RT = RS1T*RS2T*(1.0+RSW*ALS(2)*T)*RS3T*RS7T
31:  WRITE 23,RSW,T,RT
20:  FORMAT (///,E,"   ",E,"   ",E,"   ",E)
23:  FORMAT (///,"RSW =   ",E,"TIME =   ",E,"RT =   ",E)
     T = T + 100.0
     IF (T - 1000.0)18,18,22
22:  IF (RSW - 0.98)33,33,44
33:  RSW = 1.0
     T = 100.0
     GO TO 18
44:  STOP
     END
```

APPENDIX III

Rectifier Theory:

For the purpose of maintaining and operating rectifier equipment, it is necessary to understand the theory of rectifier system in a graphic and qualitative manner [62].

Idealized Rectifier: An idealized 3-ø full wave bridge circuit supplying a highly inductive load is considered. The chief assumption required for idealization is that the ac power source have zero reactance. Other assumptions are that rectifier elements be perfect i.e. that they exhibit zero forward voltage drop and infinite reverse impedance, that the supply voltage be sinusoidal, that the resistance in the ac supply windings be zero, and that there be no phase control i.e. that the beginning of conduction of a rectifier not be retarded beyond the point at which conduction would normally begin. The later assumptions usually are fairly well met in practice in the case of diode rectifiers. The major assumption, zero reactance, is far from true.

The operation of such an idealized rectifier is described by reference to the circuit diagram Fig(III-I) Conduction of the upper bank of rectifiers A,B,C is governed by the instantaneous magnitudes of the supply phase voltages E_{N-A}, E_{N-B}, E_{N-C} with respect to each other, that rectifier whose anode is connected to the phase of the highest positive voltage at any given instant conducts. Switching of current from one rectifier to another, commonly called commutation, occurs when phase voltages are equal and in the idealized system occurs

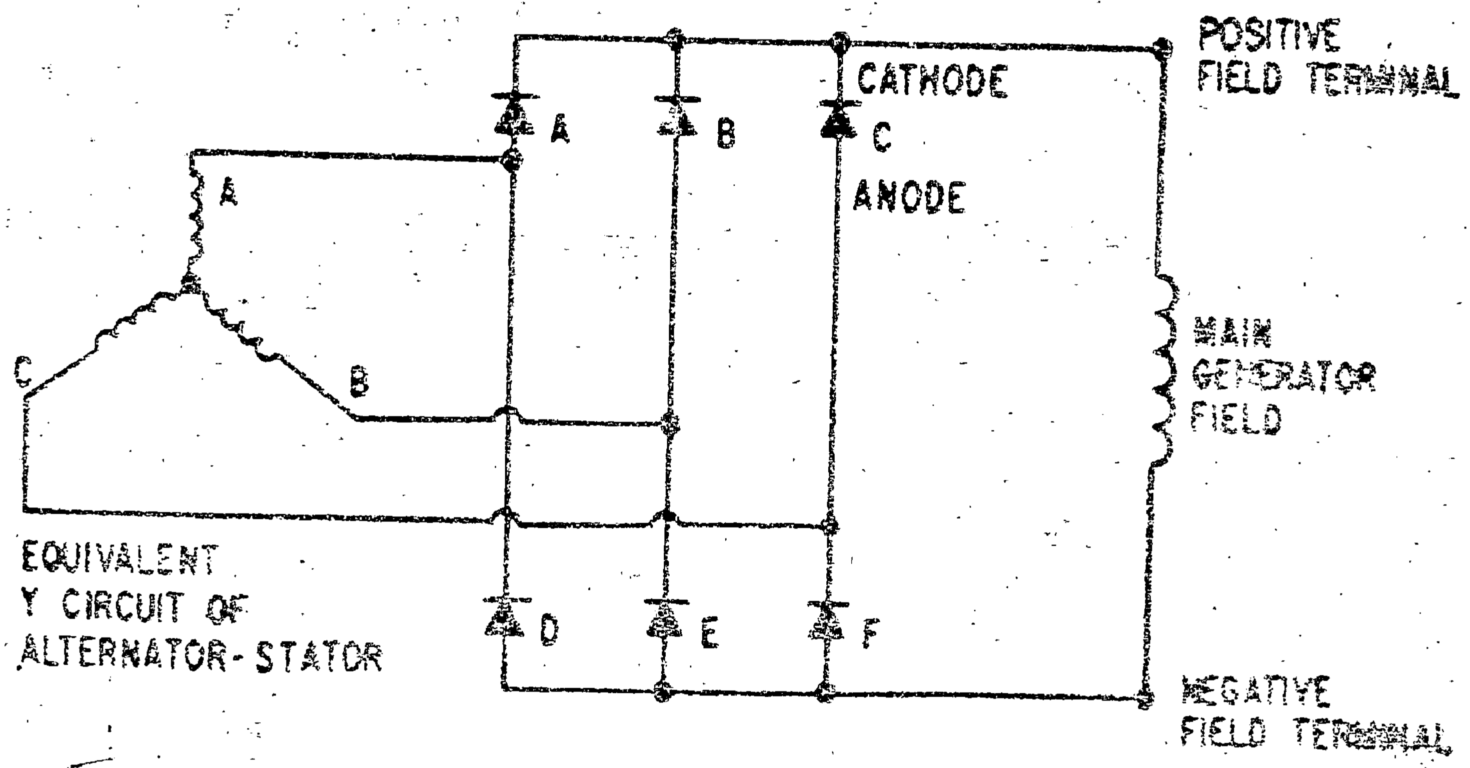

Fig.III-I Simplified Alterrex system.

instantaneously. Thus each rectifier begins conduction at $\pi/6$ or 30°, in its anode neutral-to-line wave, and ceases at $5\pi/6$ or 150°. Conduction for each rectifier then lasts for 120°, or one third of a cycle.

Similarly, in the lower bank consisting of rectifier D,E,F, that rectifier whose cathode is connected to the phase of the most negative voltage conducts. Switching again occurs at the 30° and 150° points in the negative half cycles, it coincides with the midpoints of the conduction periods of the positive rectifiers.

Because the load is inductive, load current is smooth dc, and the rectifier and therefore, ac line, current pulses are flat topped, i.e. rectangular.

The positive field terminal is connected alternately to line A, line B and line C through the appropriate conducting diode A,B and C. The negative field terminal in connected alternately to line A, line B and line C through the appropriate conducting diode D,E and F. Thus the potential of the positive field voltage terminal w.r.t. neutral in depicted by the envelope of conduction in the top, while the potential of the negative field terminal w.r.t. neutral is depicted by the envelope of conduction in the lower portion. The voltage across the field is the instantaneous voltage difference between the upper and lower envelopes.

The line-to-line voltage E_{B-A} is determined by the instantaneous relationship $E_{B-A} = E_{N-A} - E_{N-B}$

During conduction of the diode, the voltage is, of course zero. When the diode is not conducting, the voltage across the diode is the voltage of the positive field terminal w.r.t. neutral minus the instantaneous voltage of line A w.r.t. neutral. The peak value of this reverse voltage is a major factor in rating the diodes. It should be noted that the peak reverse voltage is equal to the peak of the line-to-line voltage, as is the peak of the field voltage.

Non-idealized Rectifier Operation: It has been noted that the chief assumption which distinguishes the idealized rectifier from the actual one is that the reactance of the power source is neglected. The only additional assumption of significance is that rectifier leg voltage drop is zero.

Let us consider the second assumption first. Silicon diodes exhibit a forward voltage drop of 0.5 to about 2 volts, depending on cell temperature and magnitude of current. The variation of voltage with current at a given temperature is relatively small, perhaps 0.5 volt in the normal operating range. For all practical purposes for rectifying systems of the type discussed in this thesis, the forward rectifier cell drop can be considered to be constant. A figure of about 1.0 volt per diode or a total rectifier drop of 6 volts per ckt. (since in the 3-phase full wave bridge ckt. current flows through two legs in series with 3 diodes in each leg) is a reasonable value. In system analysis, this can be subtracted from theoretical rectifier output voltage to determine actual load voltage. Since the value is small compared to the operating direct voltage, it will not be considered in the following analysis:

The presence of reactance in the alternating voltage sources the alternator, has the effect of preventing the instantaneous transfer of current from one rectifier leg to another. It forces commutation to require a finite time,when the voltage of the phase to which current is to be transferred, for example, phase B equals that of the phase in which current is flowing, phase A, conduction begins in the rectifier of the second phase B. As the instantaneous difference between the two phase voltages increases, the current increases in rectifier leg B and decreases in rectifier leg A, because rectifier circuit load is highly inductive, the sum of the two rectifier currents which is equal to load current, is constant. When the current in rectifier B reaches the value I_{field}, the field current value, that in rectifier A reaches zero and commutation is complete. The magnitude of the current in the on comming diode cannot exceed the field current value, since the outgoing diode has ceased conduction, leaving the only path for current flow into the highly inductive field, whose current cannot change. The current in line B and line C will have a shape identical to that of line A. Line B current is displaced 120° to the right and line C current is displaced 240° to the right.

Note that during the commutating interval both rectifiers A and B are conducting. Hence phases A and B can be considered to be short circuited through the rectifier legs, and the current flowing in leg B during the commutating period can be considered to be a circulating current, equal in value during the interval it flows to the instantaneous line-to-line short circuit current of the alternator exciter. This current is determined by the instantaneous voltage difference between the conducting phases and the associated reactances.

Since the phase voltage difference is split evenly between the two commutating reactances during the commutating interval, the voltage appearing at the machine terminals during this interval is the instantaneous average of the 2-phase voltages.

During the first commutating interval E_{N-A} is replaced by $\frac{E_{N-A} + E_{N-C}}{2}$. During the second commutation interval E_{N-B} is replaced by $\frac{E_{N-B} + E_{N-C}}{2}$.

During the 3rd interval, E_{N-A} and E_{N-B} are replaced by $\frac{E_{N-A} + E_{N-B}}{2}$.