RELIABILITY EVALUATION AND OPTIMIZATION OF THYRISTOR DRIVE SYSTEM

A DISSERTATION
Submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ADVANCED ELECTRICAL MACHINES

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ROORKEE, (INDIA)
JUNE, 1979

C E R T I F I C A T E

Certified that dissertation entitled 'RELIABILITY EVALUATION AND OPTIMIZATION OF THYRISTOR DRIVE SYSTEM' which is being submitted by Sri S.B.VAJPAYEE in partial fulfilment for the award of the degree of Master of Engineering in Advanced Electrical Machines 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.

This is further to certify that he has worked for a period of $4\frac{1}{2}$ months from January 1979 to February 1979 and from March 15,1979 to June 12 1979 for preparing this dissertation at this university.

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ACKNOWLEDGEMENT

The author expresses his deep sense of gratitude and indebtedness to Dr.K.B.MISRA, Professor and Sri H.O.Gupta, Lecturer in Electrical Engineering Department, University of Roorkee for providing inspirational guidance, encouragement and whole hearted cooperation during the course of this work.

The author is also thankful to the Head of Electrical Engineering Department, University of Roorkee, Roorkee for providing the necessary facilities.

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C O N T E N T S

ABSTRACT

With the progress in automation, there is a growing demand for reliable stepless variable speed drives which have the ability to respond quickly and accurately to external speed and torque demands. As a result of recent advances in solid state technology and with the availability of high power reliable and efficient thyristor convertors, the use of thyristors to control large amount of power is being made. Due to the complexity of control circuits and inability of electronic components to perform consistently, reliability of SCR controlled drives has been found to be very poor.

Generally, the SCR controlled drive systems are maintained systems in which the failed equipment is repaired and installed or is replaced by a spare. For such systems, the reliability function alone does not give the correct picture of systems performance. This dissertation brings out the availability of drive systems by introducing repair rate, installation rate and spares. The calculation of the steady state availability has been done by a symbolic method. Since all the maintenance facilities are connected with cost, the total cost of the system increases by providing these facilities. The optimization has been done for repair rate and number of spares for achieving the desired level of availability at minimum cost.

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In order to illustrate the procedure, the typical SCR controlled drives i.e. one AC and one DC are analysed. The failure rate of each subsystem has been calculated on the basis of available data. The repair rate, number of spares have been optimised to achieve desired availability at minimum cost for these drives.

LIST OF SYMBOLS

n	- number of units in the system.
P	- number of spare units
λ	- constant on-line failure rate of a unit.
μ	- constant repair (hazard) rate of a unit.
γ	- constant installation (hazard) rate of a unit.
u	- number of installation facilities
r	- number of repair facilities
K	- minimum number of operating units for successful operation of the system,
m	- total states in the system
0,1,2	- three states of unit; operating, failed, being installed respectively.
S_{ij}	- number of units having state $(j-1)$, $j=1,2,3$ when system is in state i, $i=1,2,\ldots m$
a_{ij}	- element of state transition matrix
P_i	- steady state probability of system-state i.
Ass	- steady state availability of system.

CHAPTER I

I N T R O D U C T I O N

1.1 GENERAL

As a result of recent advances in solid state technology and with the availability of high power, reliable and efficient thyristor converters, the use of thyristors(SCRs) to control large amount of power is being made. Due to almost unlimited capabilities and various useful characteristics, thyristors have also been instrumental in the rapid advancement of electric drives technology, both ac and dc. Also thyristor devices are fast replacing conventional rotating devices.

A measure of how well a system performs or meets its design objectives is provided by the system reliability. If successful operation is desired 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, its attributes, the functional relationship between its components and its basic design. The main task of the system definition phase, once the initial system objectives and requirements are established, is to explore the design problem and to identify its elements such as parameters, constraints and criteria, consideration must be given to system reliability (and perhaps even availability) requirements. Preliminary cost, versus effectiveness tradeoffs are sometimes performed in the selection of optimal design alternative. The reliability concept can be best described in simplest term by way of fig.1.

Any SCR controlled drive in its basic form consists of following subsystems:

1. Power supply
2. Control circuitry
3. Motor, whose speed is to be controlled.

Mostly, power supply and control circuitry use thousands of electronic components like transistors, resistors,capacitors, thyristors and ICS. Although electronic components are known for their unlimited capabilities, 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,

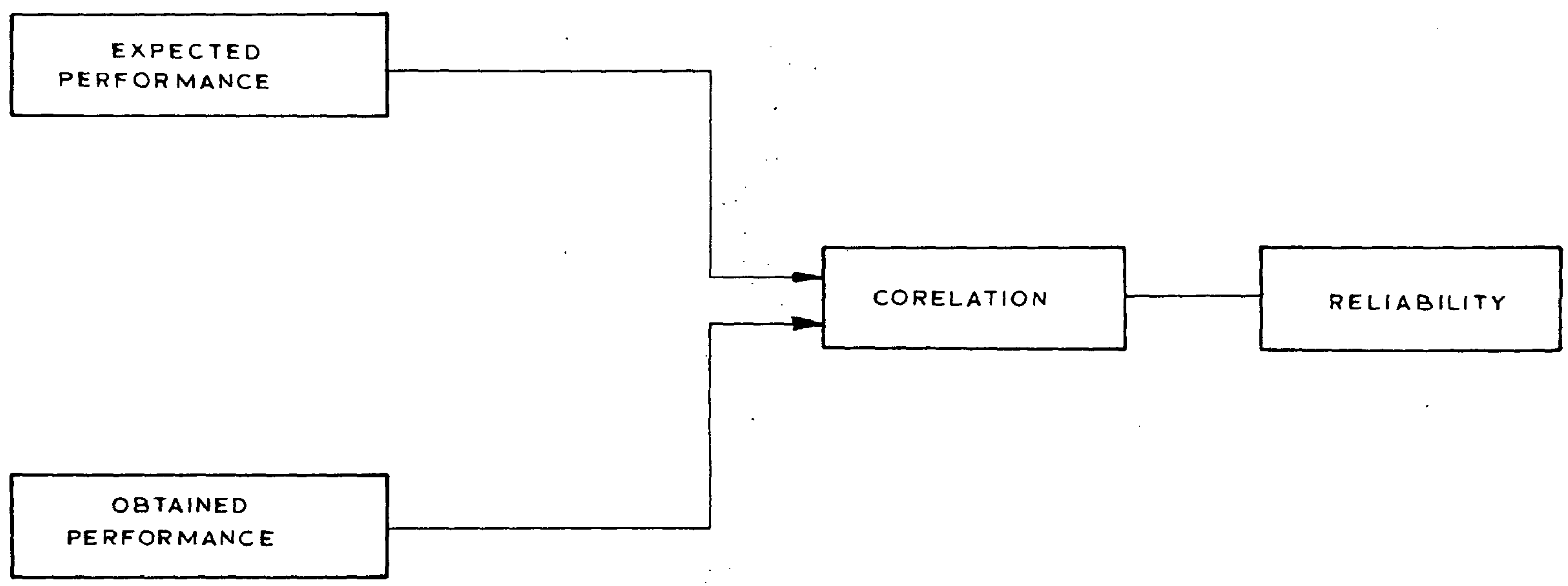

FIG. 1 _ CONCEPT OF RELIABILITY

one can expect their reliabilities to decrease.Consequently systems using electronic components are more susceptible to unplanned shut-downs which may have serious consequences in terms of cost, consumer confidence and safety. SCR controlled drives also display this trait of random failures and very low reliability when compared to conventional drives [11]. Conventional drives also provide a certain amount of warning to the experienced crew before breakdown occurs, which is not in case of SCR controlled drives.

One of the methods for coping with this low reliability problem is to design reliable subsystems using less reliable components. Another method to increase reliability is by using redundant components. As the experience has shown the reliability using less reliable components can be achieved only up to a certain level, keeping constraint of cost in picture, second method is commonly adopted for increasing the reliability.

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(These terms are explained in later chapters). Therefore because of rednndancy 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.

1.2 REVIEW OF LITERATURE

The reliability of SCR controlled drives as compared to conventional drives is very low and this has been brought out by D.R.Kohli and E.Balaguruswamy[12]. Also due to the low reliability of SCR drives,lot many techniques have been developed for improving the reliability of complex systems. Constructing reliable circuits using less reliable components approach has been made by Moore and Shannon[1]. Allocation of redundancy on least cost basis to different stages of system has been made by Moskowitz and Mclean[2]. Several mthods [3,6,8,13,14] have been suggested for optimal redundancy in order to maximize reliability. Reliability of special redundant systems considering exchange time and repair time has been discussed by T.Ito and C.Kr WAGUCHI[7]. Also optimal design and optimal redundancy have been brought out by R.M.Buston [8]. In the recent papers [15-17] methods have been suggested for obtaining optimum system availability by getting optimum redundancy and optimum component reliability. E.Balaguruswamy[11] has evaluated the reliability of SCR drives and has suggested the use of redundancy optimization in order to improve reliability. Very recently a 3 state model (operating, failed, being installed) has been developed for evaluation of symbolic steady state availability of K out of n:G system with spares by Gupta [20].

1.3 PRESENT WORK

Drives in the industries and other uses also are mostly maintained systems. Most of the contributions are purely mathematical or do not take the maintenance factors (repair of faulty subsystems and their installation) into consideration. Practically a subsystem which becomes faulty leading to shutdown of whole system is either replaced by spare or is repaired and installed so that the system starts working again.

Normally, the SCR controlled drives are large systems and their many subsystems having high failure rates. Only reliability of the system does not give the overall picture about the performance of the drive system. The importance of allowing repair of failed components and its installation in a system should be obvious when considering systems with redundant components. Since repair is possible of a failed component without affecting the overall system operation then it is desirable to know what the chances are of returning this component to either operation or an operable state before its lack of operation causes complete system failure. The difficulty lies in the fact that system reliability does not consider the effects of subsystem repairs and their installation. Consequently since it should be to our advantage to repair failed systems and components as rapidly as possible, we need some additional measure of system performance that considers effect of system repair.

Such a measure is provided by the concept of steady state availability of the system.

The present work presents a method for symbolic steady state availability evaluation of SCR controlled drives taking spares, failure rate, repair rate, installation rate and cost into consideration. Two typical drives, one AC and the other DC have been considered. As a first step reliability of these two drives has been calculated, based on the available data and afterwards assuming both the systems are being maintained, which is practically done in most of the cases, their steady state availability has been computed. As the spare, repair rate and installation rate are directly connected with cost and steady state availability, optimization for these two drives correlating the spares, repair rate and cost has been done, in order to achieve the desired level of steady state availability. The symbolic method [20] of computing steady state availability taking repair rate, installation rate and spares into consideration has been applied to evaluate steady state availability of SCR controlled drives.

CHAPTER II

DEFINITIONS

2.1 CONCEPT OF RELIABILITY

'The probability that the system will perform its intended function for a given period of time under stated environmental conditions', is the most widely used definition of reliability. However, the important point is that any definition must be useful in making design decisions in the planning of a new system. Historically, the reliability has always been considered during the system design. However, as systems have become increasingly complex, the reliability problem has become more acute.

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. As shown in Fig.2 [9] an important part of disciplined design activity

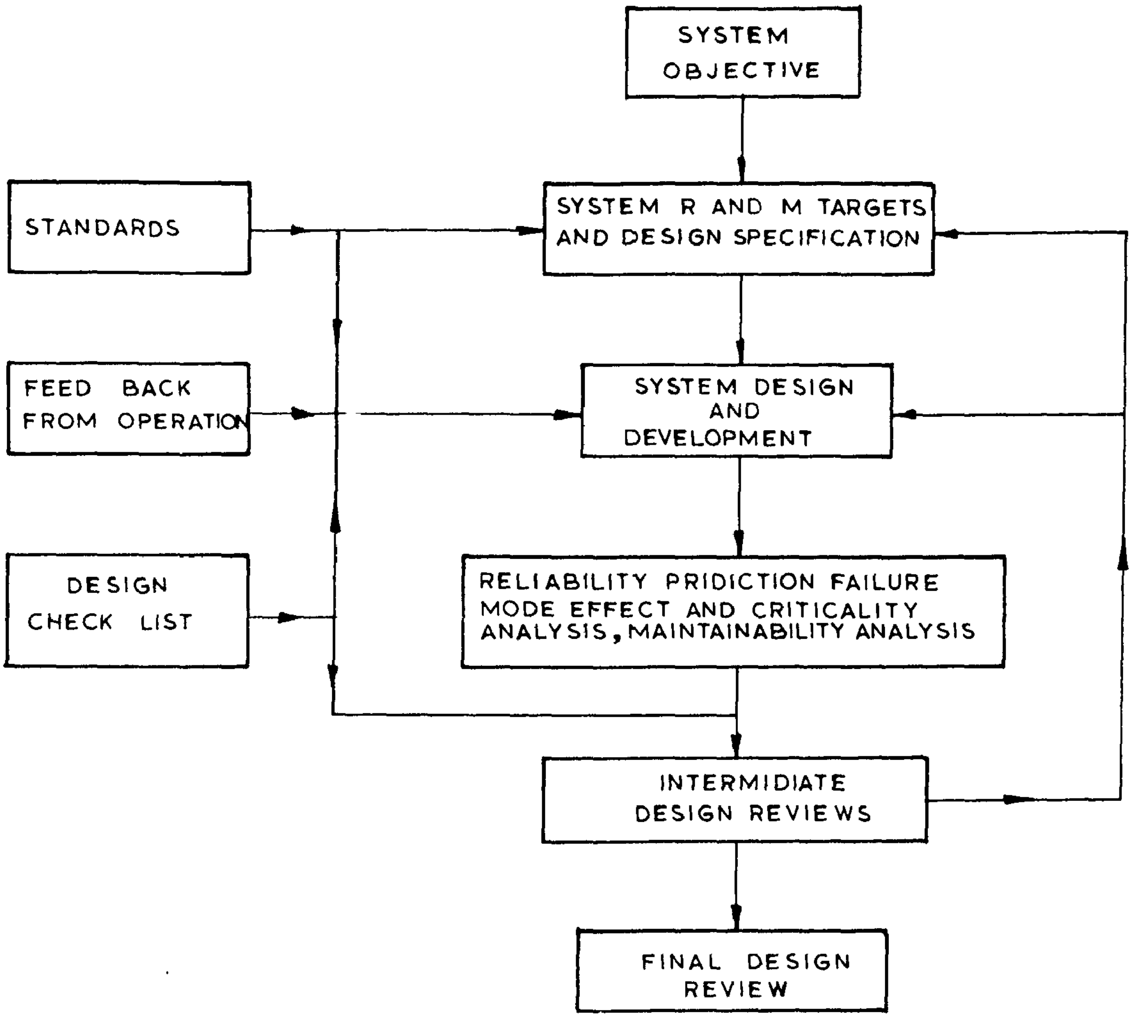

FIG. 2 _ BASIC RELIABILITY PROGRAM TASKS IN SYSTEM DESIGN is these studies which enumerate and identify the potential effects of component failure.

If T is the time to failure of the system, then the probability that it will not fail in given environmental constraints before time t, or its reliability is

$$R(t) = P(T > t) \qquad \dots (2.1)$$

Reliability depends upon environmental conditions and is always a function of time. As the reliability is the probability its numerical value is always between zero and one.

As mentioned earlier, reliability depends upon the failure rate. In order to formulate the reliability function, R(t), let λ is the failure rate and is constant. Then R(t) can be expressed as:

$$R(t) = e^{-\lambda t} = e^{-t/T_m} \qquad \dots (2.2)$$

where, T_m - is known as mean-time-to-failure (MTTF) and is a reciprocal of failure rate λ.

At very initial stages of planning a system measures of reliability effectiveness must be defined and system reliability goal must be developed. The measures of system effectiveness are criteria by which alternate design policies can be compared and judged. It determines the system philosophy with regard to the use of redundant equipment and a maintenance philosophy. Four major measures of system reliability effectiveness in use are:

(a) Availability

(b) Probability of survival

(c) Mean-time-to failure

(d) Duration of single downtimes.

2.1.1 Availability

This measure is applicable to the maintained systems and will be discussed in detail later.

2.1.2 Probability of Survival

The probability of the system survival is a measure of the probability that a system will not reach a completely failed state during a given time interval,given that at the beginning of the interval the system was in fully operable state.

2.1.3 Meam Time to System Failure

For non-maintained systems MTTF is a measure of expected time the system is in operable state before all the equipment reach a failed state. For maintained systems, MTTF is a measure of the expected time the system is in operable state allowing individual equipments to be repaired, as they fail given that all equipments were initially operable when we began counting time.

2.1.4 Durations of Single Downtimes

For some systems duration of single downtimes may be the most meaningful measure of system reliability effectiveness, i.e. in case of an early warning radar.

2.2 REDUNDANCY

From the known failure characteristics of the elements making up the system, the reliability of the system can be calculated. Due to the complexity of equipment in electronic systems, reliability becomes very low and needs improvement. One of the first tasks in system development is to synthesize a system configuration which is expected to meet reliability goals, preferably at least cost. Basically following avenues are available:

(a) Utilize existing equipments and determine their best configurations.

(b) Improve upon existing equipments to improve their reliability.

(c) Design new equipments to meet reliability standards.

(d) A combination of any of these approaches.

The 'best' policy is primarily a function of the increase in reliability that can be achieved for a given expenditure. In general, there is more to be gained on the system level through the use of redundancy than through other approaches.

There is no doubt that redundancy results in increasing the reliability of operation, it increases the weight, size and cost of the system.

Redundancy can be applied either at systemllevel itself or at component level of the system. Generally, a compromise is reached between the two. Redundancy is of two types.

2.2.1 Active Redundancy

Active redundant system is one which has duplicating element(s),permanently connected in parallel with the main element(s). Hence in active redundancy all the elements operate simultaneously for performing the task. An active redundant system will only fail when all the units connected in parallel have failed.

2.2.2 'Stand-by' Redundancy- In this type of redundancy, the duplicate element is switched into service when a primary element fails. Replacement of the failed unit is done manually or automatically by a spare unit immediately. Hence, unlike active redundancy, spare units are not in operation until their turn comes to replace the operating unit. Also it is assumed that while on stand-by duty, spare units will not fail.

2.3 AVAILABILITY

We shall no doubt do our best to achieve the highest reliability at minimum cost, but we have to recognise that every equipment will break down sooner or later. When this happens, the speed and ease with which it can be repaired become vitally important. For any equipment, we can express the mean time to repair (MTTR) in a similar way to the mean time between failures. Thus we have:

The MTBF telling us, how long on average, an equipment operates before it fails, and this we want to be as long as feasible.

The MTTR telling us how long on average, it takes to put the equipment right after it has failed and this we want to be as short as possible.

If we are responsible for operating an equipment we shall want to know the probability it will be available for use. Hence we use a quantity called availability, which is defined as:

$$\text{Av. Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

In the case where we want to use the equipment continuously, the average availability expresses the probability it will actually be working. An average availability of 0.80 means that the equipment is working satisfactorily for 80% of time, and under repair including waiting for spares etc. for the remaining 20% .

In the maintained systems the maintenance activities take place, when the system has failed, if there is no spare, and on the failed spares in case they are provisioned. Since the failed equipments will be restored to operation in a finite time an additional figure-of-merit of a system's reliability is introduced. This figure of merit, called AVAILABILITY, will be employed to determine the probability that the system is in an acceptable state at any time 't', given that the system was fully operating at t = 0. Also the portion of time the system will spend in acceptable states is referred to as system's availability. For the systems that are to be operating continuously for a long time the steady state solutions are usually sufficient. Several measures of availability in existence are generally categorised as below.

2.3.1 Instantaneous Availability

It is defined as the probability that the system will be available at any random time t.

2.3.2 Average up time

It is the proportion of time in a specified interval (0,T) that the system is available for use.

2.3.3 Steady-state Availability

This is defined as the proportion of time that the system is available for use, when the time interval considered is very large.

In the limit these three measures of availability approach the steady state availability. Selection of measure for use depends upon the system mission and its condition of use. Systems which are to be operated continuously as is in the case of SCR controlled drives, steady-state availability may be the satisfactory measure.

CHAPTER III

SCR CONTROLLED DRIVES AND THEIR RELIABILITY

3.1 INTRODUCTION

In many industries there is a growing need for precise and reliable speed drives capable of giving long term stability and good reliability. The most popular method for obtaining an electrical variable speed drive for industrial purposes has for many years been through the use of dc motors, although its commutation has been a source of constant problem and also requires a rigorous maintenance schedule.

An induction motor makes a very attractive type of ac drive, because of its simple construction,ruggedness, low capital cost and absence of commutator problems. Many conventional methods such as pole changing, pole amplitude modulation, stator voltage control, frequency changing, rotor resistance control, and slip energy recovery schemes have been employed in the past to obtain multispeed or variable speed operation.Despite the simplicity and economy of induction motor,its use as a variable speed drive has been limited until recently because of high cost and complexity of auxiliary equipment.

With the recent advances in solid state technology, advent of SCRS, and the availability of high power, reliable and efficient thyristor convertors there has been a rapid development in the technology of electric drives in the recent years. Due to continuous reduction in cost also, drives with SCR control are becoming very popular. However, due to complexity of electronic control equipment and inability of electronic equipment to perform consistently, SCR controlled drives are noted for their low reliability also.

The reliability of an electric drive system is usually analysed according to the reliability indices of the constituent elements. In this case the accuracy of the reliability analysis depends mainly on the dependability of the intiail statistical data, obtained in service operation of the system, on the basis of which objective conclusions can be drawn, or more efficient ways of increasing reliability can be planned.

It has been brought out by E.Balaguruswamy [11],SCRs controlled drives have lowest reliability when compared to conventional drives. D.R.Kohli [12] et al. have concluded that reliability of SCR controlled drive also varies considerably depending upon the type of control scheme used and firing circuit of control scheme being the major contributing factor towards low reliability. Methods for improving reliability have also been suggested. In this dissertation taking SCR controlled drives as maintained systems it has been suggested to improve steady state availability by introducing repair of failed components and installation of spare or already repaired component. By providing spares for selected subsystems stand-by redundancy has also been introduced. As the number of spares and repair rate have direct bearing on cost and steady state availability, repair rate and number of spares have been optimized with respect to the cost in order to achieve a certain level of availability. The installation rate has very little affect on steady state availability and hence it is taken as constant. In order to illustrate the suggested method two typical SCR controlled drives i.e. one ac and dc have been taken. After brief description of each drive,on the basis of the available data, their reliability and logic diagrams have been evaluated. Thus after evaluating the reliability,weaker subsystems from the point of view of reliability have also been pointed out.

3.2 SLIP POWER CONTROL DRIVE:WOUND ROTOR MOTOR

Due to advances in solid state technology the use of schemes which employ stator voltage control, frequency changing, rotor resistance control and slip energy recovery are becoming more popular. Out of these,the best is slip-energy recovery scheme.The schematic diagram of this scheme is shown in Fig.3. Also schematic of a subsystem of this drive, 3Ø line commuted inverter is shown in Fig.4.

The slip energy scheme utilises the slip energy

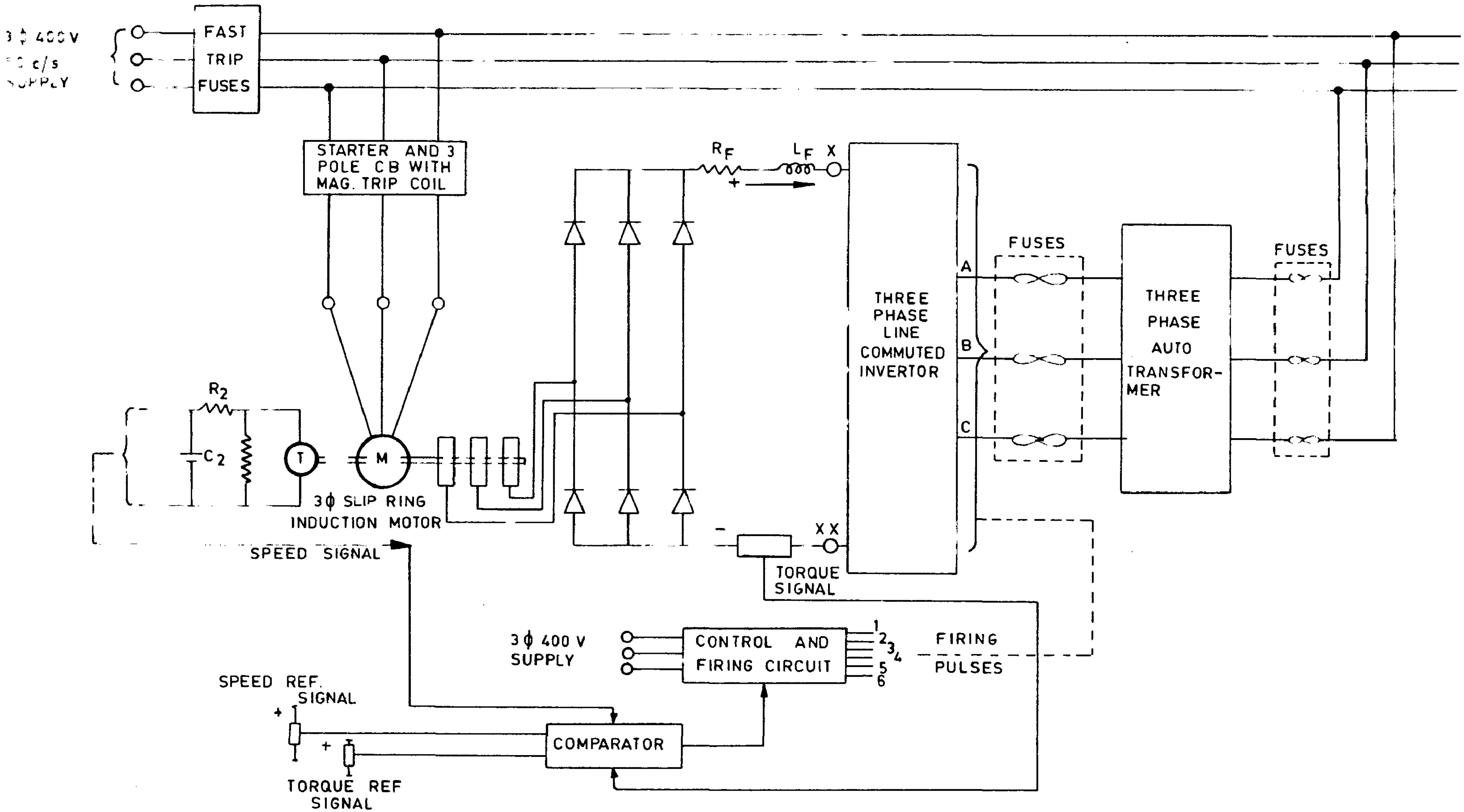

FIG. 3 – SCHEMATIC OF SLIP POWER CONTROL DRIVE - WOUND ROTOR MOTOR

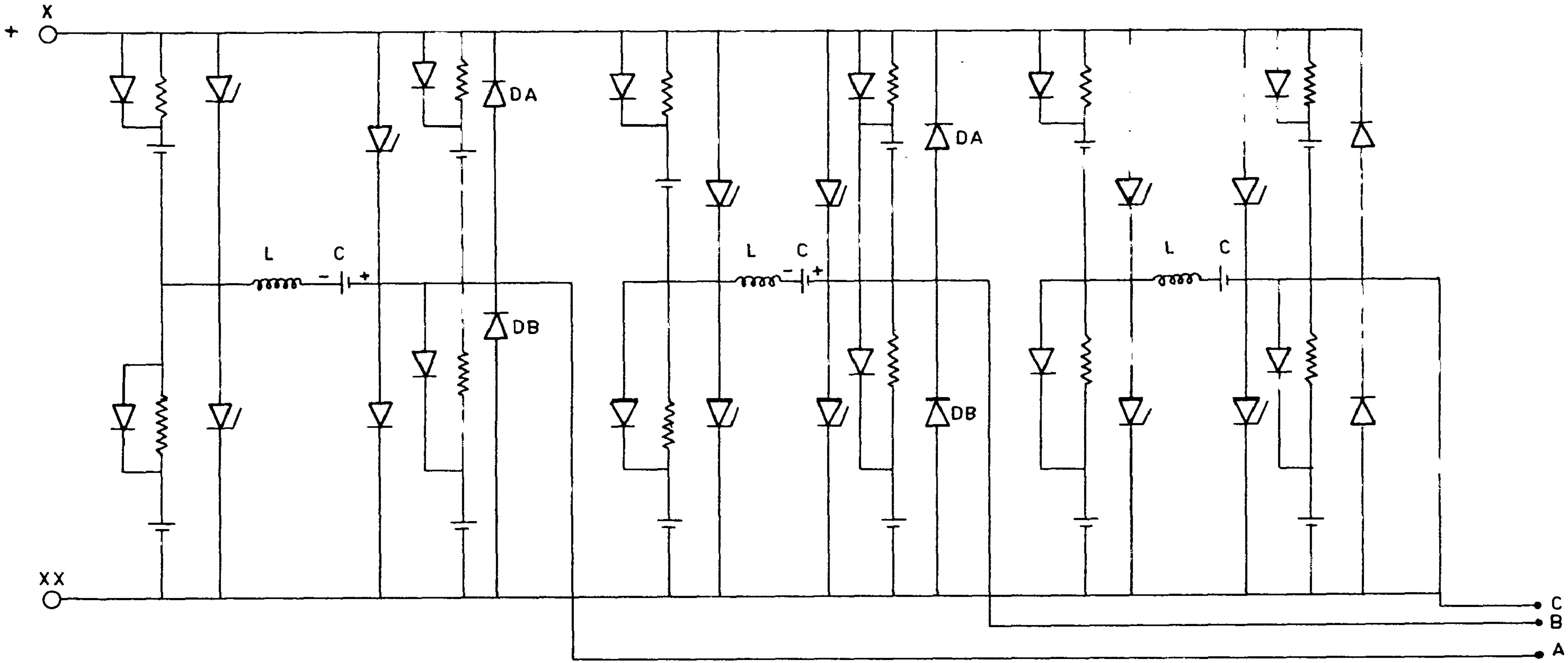

FIG. 4 _ THREE PHASE LINE COMMUTED INVERTOR OF SLIP POWER CONTROL DRIVE available at the slip rings instead of dissipating it in external rotor resistances. The recovered slip energy is either added to the main motor shaft itself or returned to the supply, thus resulting in constant horse power and constant torque drives. In the constant horse power drive slip energy is supplied to the auxiliary rotating machine. In constant torque drive the slip frequency of recovered energy is first converted to supply frequency and then recovered energy is returned to the supply. Control of speed is achieved by charging the firing angle.

The schematic shown in fig.3 is of constant torque drive. The main components of this drive are 3Ø controlled rectifier bridge, filter circuit and 3Ø line commuted inverter. The slip energy is extracted from the rotor and returned to the supply at a rate fixed by the supply voltage and inverter firing angle. The control of speed over sub-synchronous region from zero to rated speed is achieved by varying firing angle of thyristor. This drive has got close loop control. incorporated in it and uses tachogenerator as the sensing element.

In order to evaluate the reliability of the above mentioned drive, reliability logic diagram is first prepared for the scheme. It may be seen from the schematic diagram that failure of one equipment causes either the failure of the entire system or the loss of desired performance which is inadmissible. This assumption has been kept in mind while preparing the logic diagram. Thus we find that it is a non-redundant series system, where system will be down by failure of any one equipment. The logic diagram of the scheme is shown in fig.5.

The failure rate data of various electronic and electrical equipments is given in Appendix A. The drive system has been divided in sub-systems as shown in the logic diagram. With the help of available failure rate data, the failure rate of subsystem has been calculated. A typical calculation for failure rate of control and firing circuit is shown in Table 3.1. The circuit diagram of firing circuit is shown in Fig.5. The calculated failure rates of subsystems are shown in figure 6. It may be seen that failure rate of firing and control unit is maximum and thus it is the major contributing factor in the low reliability of SCR controlled drives. Being series non-redundant system, failure rates of all the sub-systems are added for evaluation of reliability.

$\therefore$ Total $\lambda = 2.10825$ (for 10^4 hr)

Since $R(t) = e^{-\lambda t}$

Hence, $R(10^4 \text{ hr}) = e^{-2.10825}$

$= 0.1215.$

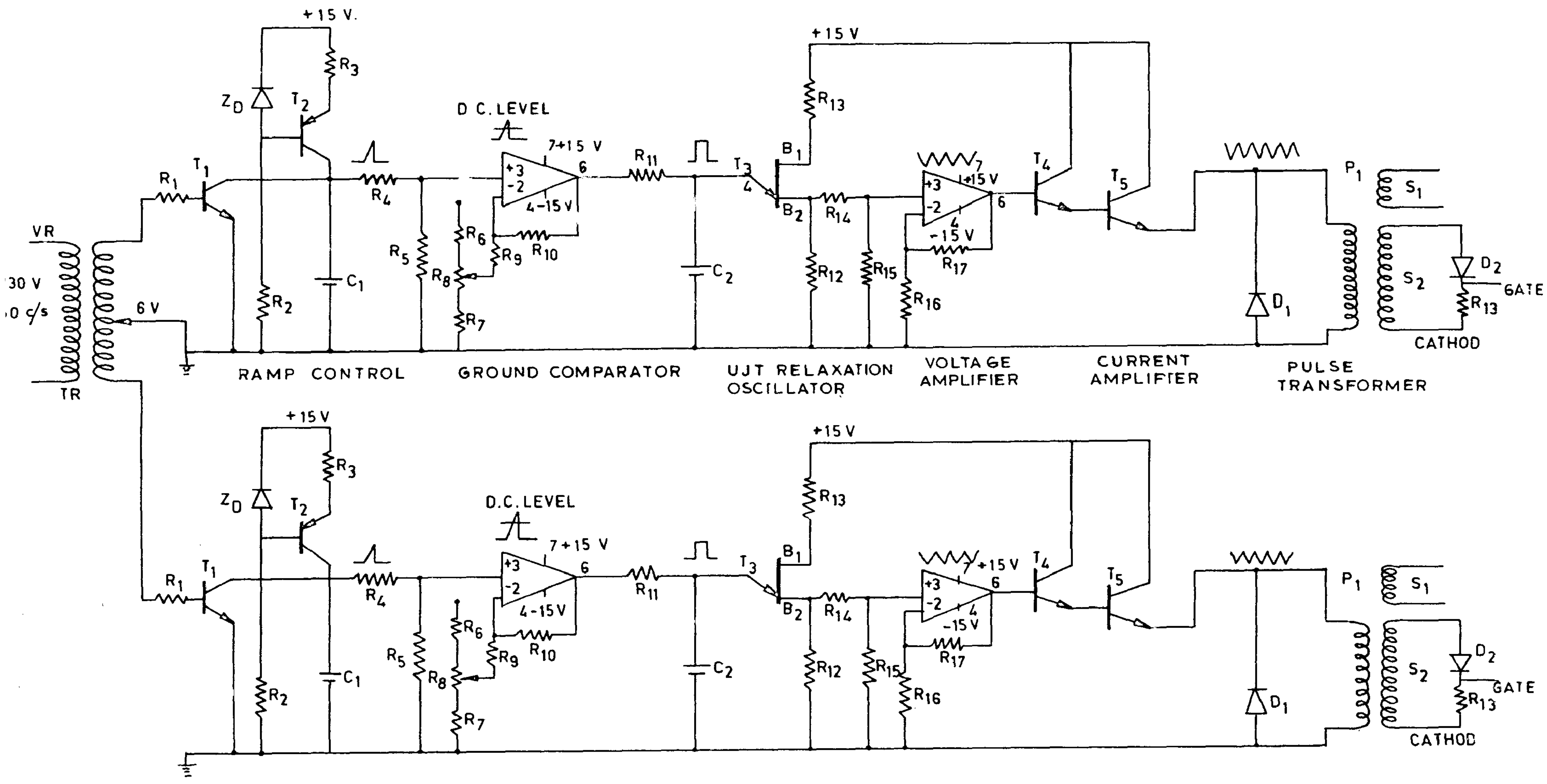

FIG. 5 _FIRING CIRCUIT FOR THREE PHASE INVERTOR (CIRCUITS FOR OTHER TWO PHASES ARE SIMILAR)

Table 3.1

Calculation of Failure Rate

Control and Firing Circuit for One Phase (Fig.5)

Component	n_i	λ_i for 10^6 hr.	$n_i\lambda_i$
Small transformers	3	0.200	0.600
Resistors	36	0.600	21.600
Variable resistors	2	3.000	6.000
Transistors	10	0.610	6.100
IC	4	4	16.000
Diodes	6	0.200	1.2000
Capacitors	4	0.600	2.400

$$\sum n_i\lambda_i = 53.900$$

Failure rate of subsystem for 3 phases = 53.900x3
= 161.700 for 10^6 hrs.

∴ Failure rate for 10^4 hrs. = 1.6170

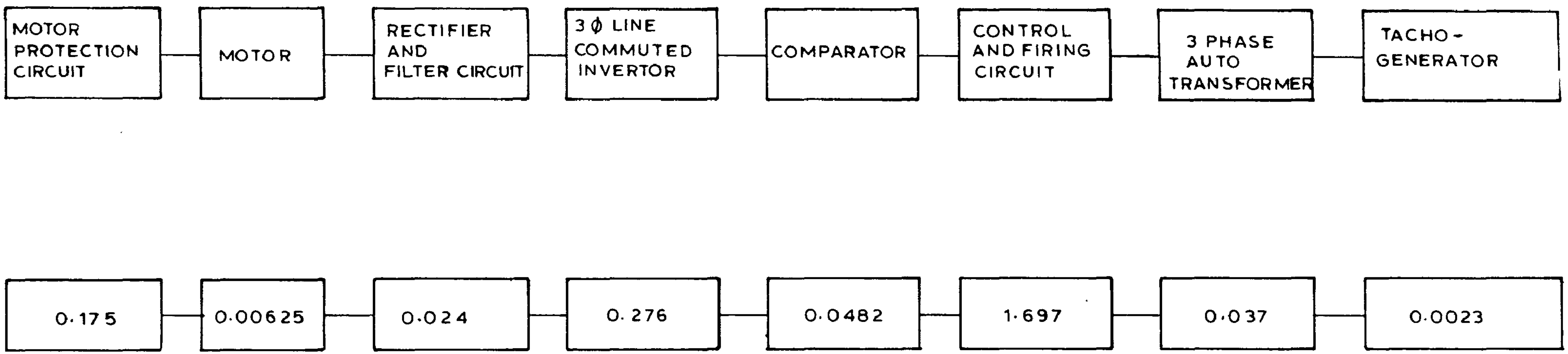

FIG. 6 _ LOGIC DIAGRAM OF SLIP POWER CONTROL DRIVE AND FAILURE RATES OF SUB SYSTEMS FOR 10^4 hr

3.3 THYRISTORIZED REVERSING ROLLER DRIVE USING D.C.MOTOR

D.C. motors have generally been preferred over other types in large number of drive applications due to its adaptability to control of its speed and torque, instead of its disadvantages due to continuous commutator problem and tight maintenance schedule. Compared to other types of conventional drives, SCR controlled drives are most promising due to high efficiency, low weight and quick responses. However, again due to complexity of electronic control circuit, reliability of system becomes very low.

Control systems for solid state dc drives include three essential portions:

(a) Thyristor firing circuit

(b) Speed and current sensing means

(c) Reference, comparison and amplifier circuits.

There is a vide variation in the circuits and the hardware used to accomplish these functions depending upon the type of drive and the manufacturer.

3.3.1 Firing Circuit

Solid state firing circuits use capacitors as the source of firing energy and release it through some type of solid state device which breaks down and conducts at threshold voltage. The choice of one type over the other depends upon the required range of control, the length of pulse and the relative cost.

3.3.2 Speed Sensing

Except for some FHP drives, all solid state dc drives employ some feedback (closed-loop) means of speed control. The speed setting dial controls a reference voltage. This reference voltage is compared by the control system with a voltage proportional to speed. The difference is the error voltage which is amplified to control the firing circuits in a direction to minimize the error voltage. The speed regulating ability of the drive depends upon the fidelity of speed sensing signal. The most accurate drives are built using pulse or digital speed signal and reference techniques.

3.3.3 Current Sensing

A signal proportional to the line or armature current is required on almost every dc drive system for following reasons:

(a) to develop IR compensation signal when armature voltage speed sensing is used.

(b) to monitor possible misfiring of the thyristors in reversing drives.

(c) to use for regulating current, torque or acceleration when the motor is called upon to make change in speed.

Three techniques are used for current sensing

(a) resistance shunt in armature circuit.

(b) a dc transducer is armature circuit.

(c) current transformers in ac lines to controlled rectifiers.

3.3.4 Schematic and Reliability Evaluation

The schematic of the thyristorized reversing roller drive using d.c. motor is shown in fig.7. This typical drive is installed and is used in blooming mill of Lenin Metallurgical Works USSR. The reversing drive includes two sets of thyristorized three phase fully controlled rectifier bridge in inverse parallel connection. The schematic reveals the present realization to be a so-called reversing drive with loop current control. The firing angle of the bridge,operated in inverting mode is adjusted by the control so that the loop current presented by a reference signal should be maintained. The other bridge supplies the motor with terminal voltage corresponding to speed reference voltage. The control is of the sub-ordinate current control type.The motor accelerates or decelerates with a current adjusted to the current limiting reference voltage. The maximum current permitted by the limiter is 2.8 times the rated current. Circulating current type reversing drives have advantage of no dead zone as compared to drives with no circulating current, but control is somewhat more complicated. The other advantage is that current and speed transients are almost independent of load. A drawback is the bulk and substantial weight of

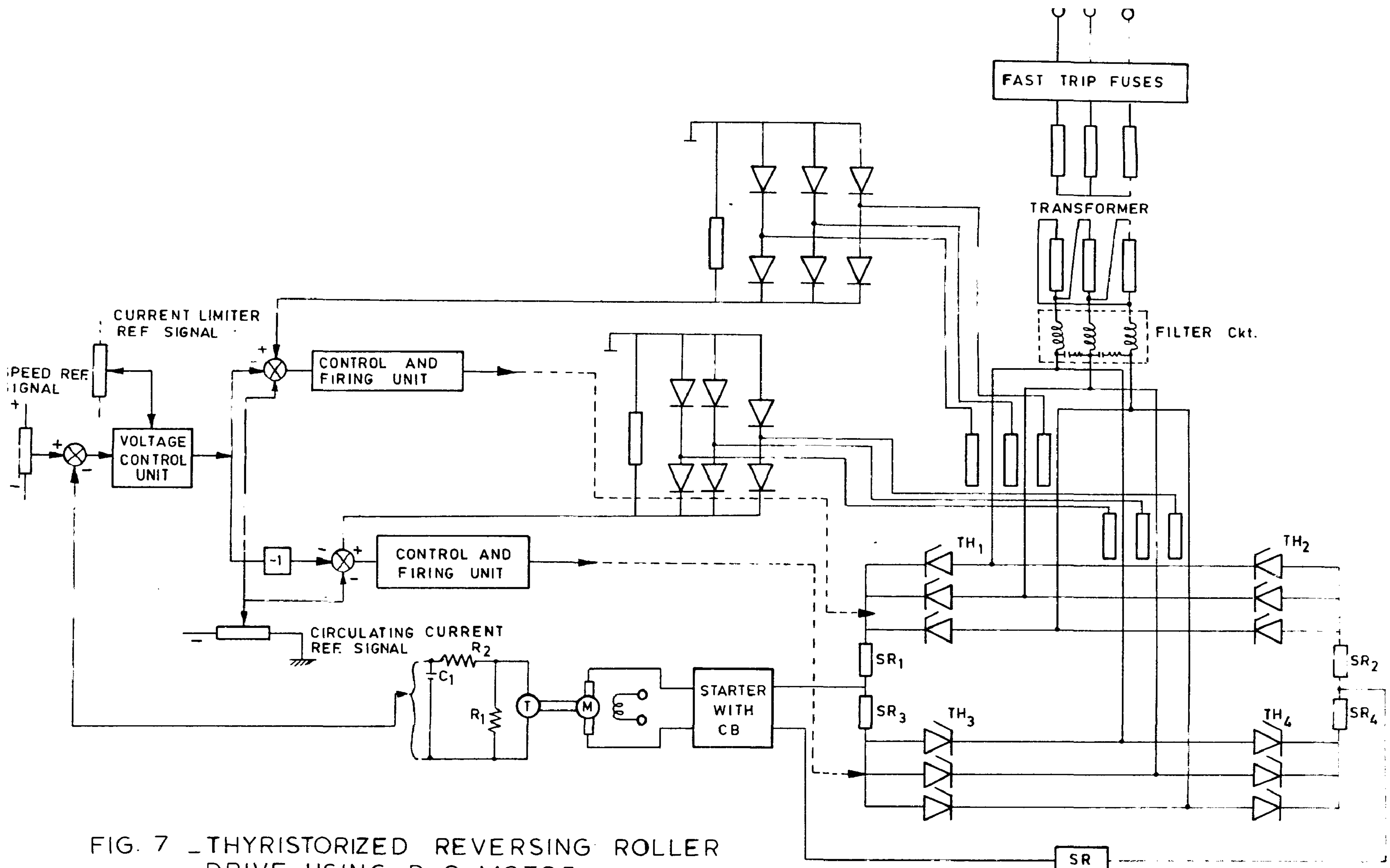

FIG. 7 _THYRISTORIZED REVERSING ROLLER DRIVE USING D.C. MOTOR

smoothing reactors included in the circuit.

Reliability studies on the same drive have been carried out by A.S.LENOVICH [10] et al., which happens to be the first soviet thyristor drive. After collecting data based on 18 months experience they have brought out histograms for the probabilities of failure, no fault operation, fault flow parameters of thyristor and thyristor fuses. . Certain methods to decrease the failure rate of thyristors have also been suggested. As such reliability characteristics of entire drive system have not been studied by them.

After studying the system it can be pointed out straight-way that it is also a series non-redundant system in which failure in one component will result in failure of complete system or deterioration in performance which is inadmissible. The logic diagram of drive system is shown in figure 8. Again for each subsystem, the failure rate is calculated based on available data. Calculation of failure rate λ for current monitering circuit has been shown in table 3.2. The failure rates of all other subsystem for 10^4 hr. after calculation are shown in fig.8.

Now adding all the failure rqtes of subsystems (being non-redundant series system)

Total failure rate $\lambda = 3.6915$

Since $R(t) = e^{-\lambda t}$

Hence $R(10^4 \text{ hr}) = e^{-3.6915}$

$= 0.0249$

Table 3.2

Current Monitoring Circuits
Calculation of Failure Rate

Component	n_i	λ_i (for 10^6 hrs)	$n_i\lambda_i$
Current transformers	6	0.200	1.200
Diodes	12	0.200	2.400
Resistors	2	0.600	1.200

Total $\sum n_i\lambda_i = 4.800$ for 10^6 hrs.

Failure rate of two sets of current monitoring system for 10^4 hr.

$= 2 \times 0.0480$

$= 0.0960.$

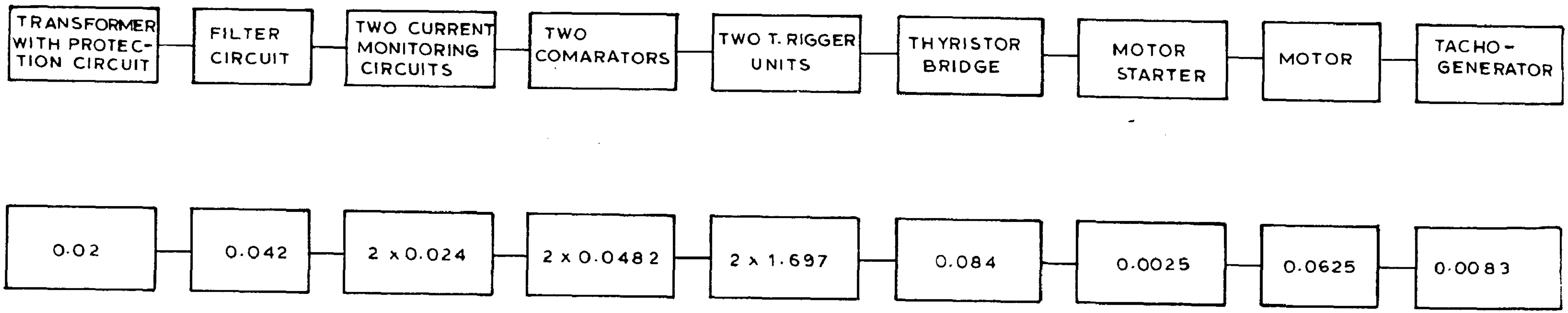

FIG. 8 – LOGIC DIAGRAM OF REVERSIBLE ROLLER DRIVE AND FAILURE RATES OF SUB SYSTEMS FOR 10^4 hr

The computed reliability of this drive system is very poor. Compared to the ac drive also the reliability is very low but this is due to the duplication of electronic circuitry as the drive is reversible.

After computing the reliability of both the drives it is clear that major cause of low reliability is the firing and control circuit. Although a good firing circuit has been taken in both the schemes as suggested by Mittle, V.N. [18] ,firing and control circuitry needs continous improvement in order to achieve higher reliability, keeping cost as constraint.

CHAPTER IV

METHOD FOR SYMBOLIC STEADY STATE AVAILABILITY EVALUATION

4.1 INTRODUCTION

Steady state availability is defined as the proportion of time that the system is available for use when time interval considered is very large. The steady state availability of a system with constant transition rates can be calculated by solving a set of algebraic equations derived from the system state equations. Also, if the steady state availability of a system having fixed configuration is to be evaluated for several failure, repair and installation rates, these algebraic equations must be solved repeatedly. A method [19] has been suggested recently for computing the symbolic steady state availability of a k-out-of n:G system with no spare which avoids these repeated calculations. For any given set of failure, repair and installation rates, the steady state availability is evaluated simply by substituting the numerical values of these rates in availability expression. Further this method has been extended by Gupta [20] to accommodate spares. As the redundancy is to be taken in account in both the drive systems discussed earlier, method taking spares into account is followed. It is presumed that number of spares for any subsystem in the drive is not going to exceed three for achieving a particular level of availability. Thus the steady state availability expressions have been derived only upto three spares.

In this method firstly, the states and transition matrix of the system are generated (in case of large systems it is done with the help of computer). Then intrees are evaluated from the state transition diagram of the system and with the help of them, expression for steady state probabilities are determined using Shubert's formula. From steady state probabilities the expression for steady state availability is determined.

In order to evaluate steady state availability of complete drive system, every subsystem of the drive is taken as a small system and then the expression is developed.

4.2 SYSTEM MODEL

(a) The system is K out of n:G system with spares.

(b) Units and spares are identical and each in the system is in one of the three states (0,1,2)

(c) When a unit fails it is removed from the operating site and repaired. After repair it is ready for installation.

(d) Repair is perfect viz. it returns a unit to like new and damages nothing, but it does take time and it costs.

(e) All transition rates are constant.

(f) Repair and installation facilities are limited.

(g) Δt is sufficiently small time so that only one transition can take place.

4.3 GENERATION OF STATE TRANSITION MATRIX

An algorithm to generate all possible states of the system is worked out and evaluation of state transition matrix is done. The transition diagram of a unit is shown in figure 9.

For this system,

$$m = (q+1)(q+2p+2)/2 \qquad \ldots (4.1)$$

where $q = n-k+1$ $\qquad \ldots (4.2)$

S_{i1}, S_{i2} and S_{i3} units in the system state i are given by,

$$S_{i2} = \begin{cases} x \text{ for } i = x(q+1)+1, [x(q+1)+2], \ldots (x+1)(q+1) \\ \quad \text{and } x = 0,1,\ldots.p-1 & \ldots (4.3) \\ p+y \text{ for } i = [p(q+1)+1+y(2q-y+3)/2], \ldots, \\ \quad (y+1)(2q-y+2/2+p(q+1) \end{cases}$$

and $y = 0,1,\ldots q.$ $\qquad \ldots (4.4)$

$$S_{i1} = \begin{cases} (q+1)(S_{i2}+1)+(n-q)-i, \quad i=1,2,\ldots p(q+1) & \ldots (4.5) \\ p(q+1)+(n-q)+(S_{i2}-p+1)(2(q+1)+p-S_{i2}/2-i, & \ldots (4.6) \\ \quad \text{for } i = p(q+1)+1, p(q+1)+2, \ldots m. \end{cases}$$

$$S_{i3} = \begin{cases} i+p-S_{i2}(q+2)-1, \quad i=1,2,\ldots p(q+1) & \ldots (4.7) \\ i-q(p-1)-S_{i2}-(S_{i2}-p+1)(2(q+1)+p-S_{i2})/2, \\ \quad i = p(q+1)+1,\ p(q+1)+2,\ldots m & \ldots (4.8) \end{cases}$$

The state transition is derived with the help of above equations

$$a_{ij} = \begin{cases} \lambda_{sji} \quad \text{if } S_{j1} = n-q \text{ and } i = j+q+2 \quad \text{for } j=1,2,\ldots p(q+1) \\ \qquad i = j+q+p+1-S_{j2} \quad \text{for } j=p(q+1)+1, p(q+1)+2,\ldots m. \\ \mu \min(S_{j2},r) \text{ if } S_{j2}=0,\ i=j-q+1 \text{ for } j=q+2,q+3,\ldots p(q+1) \\ \qquad i=j+S_{j2}-(q+p+1) \text{ for } j=p(q+1)+1,\ldots m \\ & \ldots (4.9) \\ Y_{\min}[(n-S_{j1}),\ S_{j3},u],\ i=j-1 \text{ for } j=2,3\ldots m. \\ 0 \text{ otherwise.} \end{cases}$$

$$a_{ii} = -\sum_{\substack{j=1 \\ j\neq i}}^{m} a_{ji} = \begin{cases} -(\lambda_{si1}+\mu_{\min}(S_{i2},r)+\min[(n-S_{i1}),S_{i3},\mu]) \\ \qquad \text{if } S_{i1} \quad K. \\ -(\mu \min(S_{i2},r)+Y \min[g,S_{i3},u) \text{ if } S_{i1}=K-1 \\ & \ldots (4.10) \end{cases}$$

A single state or group of states of the desired characteristic can be determined as follows:

Let the state of a system which is having N_0, N_1 and N_2 units in 0,1,2 respectively is required. Let the state be the ith state of the system, then from (4.5) and (4.6)

$$i=\begin{cases}(q+1)(N_1+1)+(n-q)-N_o & \text{if } N_1 \quad (p-1)\\ p(q+1)+(N_1-p+1)\left[2(q+1)-N_1+p\right]/2+n-q+N_o\end{cases} \qquad \ldots (4.11)$$

4.4 AVAILABILITY EVALUATION

The state transition diagram is drawn with the help of transition matrix which is a diagraph. All intrees of this digraph are generated by algorithm given in [19]. Let ϕ_i be the class of all intrees corresponding to node i and an intree is denoted as f(V,Q),where V is the set of nodes and Q is the set of branches in the intrees. The steady state probability corresponding to the state i of the system [20] is,

$$P_i = C \sum_{\epsilon \phi_i} {}_{(i,j)} \prod_{\epsilon Q} a_{ij} \qquad \ldots (4.12)$$

where C is a normalizing constant determined from

$$P_1+P_2+ \ldots + P_m = 1 \qquad \ldots (4.13)$$

(i,j) is the branch connecting between node i and j. Thus by knowing the steady state probability vector of the system we can determine the symbolic expression for S.S. availability of the system.

4.4.1 S.S. Availability with Zero Spare

Consider a 1-out-of 1:G system with nil spare unit. There is a single repair and installation facility. For

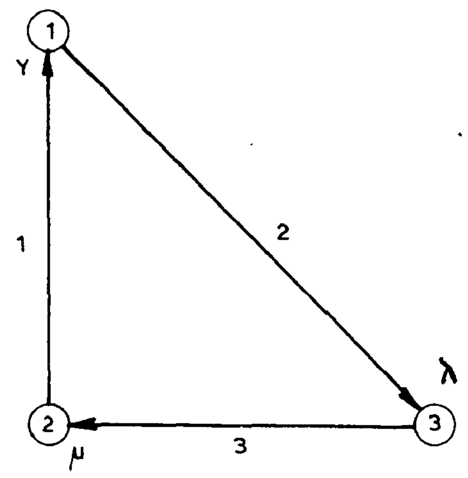

FIG. 9 _TRANSITION DIAGRAM OF A UNIT WITH ZERO SPARE UNIT

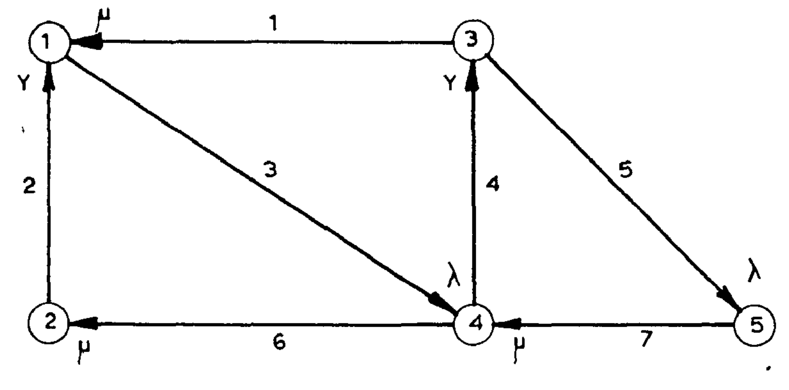

FIG.10 _TRANSITION DIAGRAM OF A UNIT WITH ONE SPARE UNIT

this system,

$$m = 3, \; q = 1$$

The matrix S obtained is,

$$S = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The state transition matrix comes out to be

$$A = \begin{bmatrix} -\lambda & Y & 0 \\ 0 & -Y & \mu \\ \lambda & 0 & -\mu \end{bmatrix}$$

The transition diagram (a digraph) corresponding to transition matrix A is shown in Fig.9 in which branches are designated by numerical numbers and nodes represent system states,

Sets $\emptyset_i$, $i = 1,2,3$ obtained are

$$\emptyset_1 = (1,3)$$
$$\emptyset_2 = (3,2)$$
$$\emptyset_3 = (2,1)$$

The steady state probabilities obtained are

$$P_1 = C(\mu Y)$$
$$P_2 = C(\lambda\mu)$$
$$P_3 = C(\lambda Y)$$

where $\frac{1}{C} = \mu Y+\lambda(\mu+Y)$

SS availability is given by

$$A_{ss} = P_1 = C\mu Y.$$

4.4.2 Steady State Availability with one Spare

Considering again 1-out-of-1:G system with one spare and single installation and repair facility. For this system,

$$m = 5, \; q = 1$$

The transition diagram for this arrangement is shown in fig.10.

The matrix S obtained is

$$S = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

and the state transition matrix A comes out to be

$$A = \begin{bmatrix} -\lambda & Y & \mu & 0 & 0 \\ 0 & -Y & 0 & \mu & 0 \\ 0 & 0 & -\mu-\lambda & Y & 0 \\ \lambda & 0 & 0 & -\mu-Y & \mu \\ 0 & 0 & \lambda & 0 & -\mu \end{bmatrix}$$

Sets $\emptyset_i$, i = 1,2,...5 obtained are

$$\emptyset_1 = [(2,6,7,5),\ (1,2,4,7),\ (1,2,6,7)]$$
$$\emptyset_2 = [(6,3,7,1),\ (6,3,7,5)]$$
$$\emptyset_3 = [(4,3,7,2)]$$
$$\emptyset_4 = [(3,7,1,2),\ (3,7,2,5)]$$
$$\emptyset_5 = [(5,4,3,2)]$$

The steady state probabilities obtained are:

$$P_1 = C[\lambda\mu^2Y+\mu^3Y+\mu^2Y^2]$$
$$P_2 = C[\lambda^2\mu^2+\lambda\mu^3]$$
$$P_3 = C[\lambda\mu Y^2]$$
$$P_4 = C[\lambda^2\mu Y+\lambda\mu^2 Y]$$
$$P_5 = C[\lambda^2Y^2]$$

where

$$1/C = \lambda^2(\mu^2+\mu Y+Y^2)+\lambda(\mu^3+2\mu^2Y+\mu Y^2)+\mu^3Y+\mu^2Y^2$$

The steady state availability A_{ss} is given by

$$A_{ss} = P_1+P_3 = C\mu Y(\lambda+\mu)(\mu+Y)$$

4.4.3 STEADY STATE AVAILABILITY WITH TWO SPARES

For 1-out-of 1:G system with two spares and single installation and repair facility,

$m = 7$, $q = 1$

The transition diagram for such system is shown in figure 11. The matrix S obtained is,

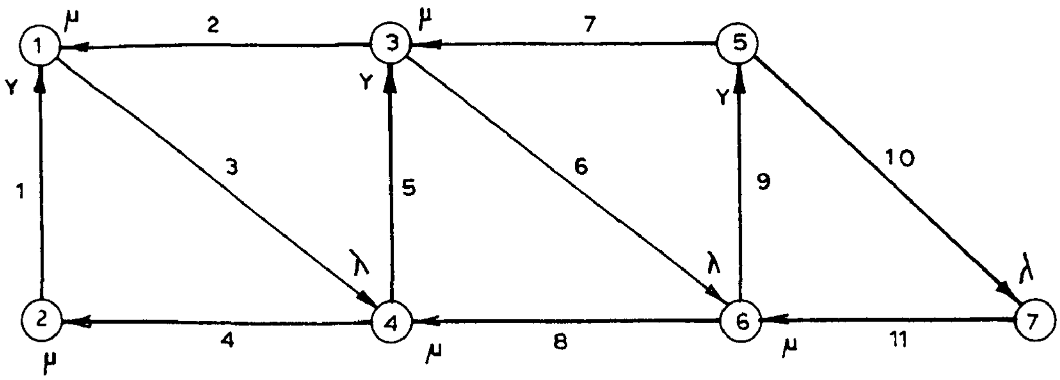

FIG. 11 _ TRANSITION DIAGRAM OF A UNIT WITH TWO SPARE UNITS

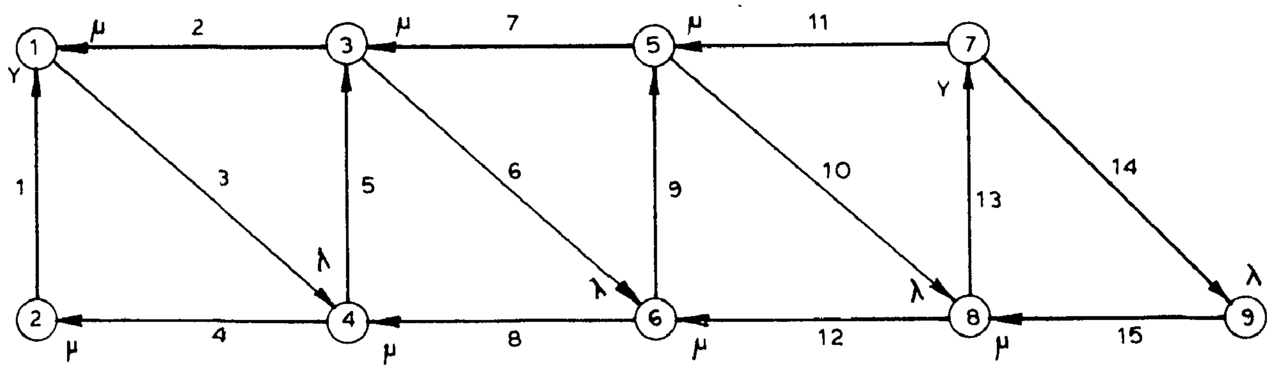

FIG. 12 _ TRANSITION DIAGRAM OF A UNIT WITH THREE SPARE UNIT

$$S = \begin{bmatrix} 1 & 0 & 2 \\ 0 & 0 & 3 \\ 1 & 1 & 1 \\ 0 & 1 & 2 \\ 1 & 2 & 1 \\ 0 & 3 & 0 \end{bmatrix}$$

The state transition matrix comes out to be,

$$A = \begin{bmatrix} -\lambda & Y & \mu & 0 & 0 & 0 & 0 \\ 0 & -Y & 0 & \mu & 0 & 0 & 0 \\ 0 & 0 & -\mu-\lambda & Y & \mu & 0 & 0 \\ \lambda & 0 & 0 & -\mu-Y & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & -\mu-Y & Y & 0 \\ 0 & 0 & \lambda & 0 & 0 & -\mu-Y & \mu \\ 0 & 0 & 0 & 0 & \lambda & 0 & -\mu \end{bmatrix}$$

Sets ϕ_i, $i = 1,2,....7$ obtained are

ϕ_1 = [(1,4,8,6,11,10),(1,2,4,8,11,10), (1,2,5,8,11,10)
(1,2,4,7,8,11)(1,2,4,7,9,11),(1,2,5,7,8,11),
(1,2,5,7,9,11)(1,4,8,6,11,7)]

ϕ_2 = [(4,3,2,7,9,11),(4,3,8,6,11,10),(4,3,8,2,11,7),
(4,3,8,2,11,10)]

ϕ_4 = [(3,1,2,7,9,11), (3,8,1,6,11,7),(3,8,1,6,11,10)
(3,8,12,11,7),(3,8,1,2,11,10)]

$\phi_5 = [(9,6,11,5,3,1)]$

$\phi_6 = [(10,9,6,5,3,1)]$

$\phi_7 = [(10,9,6,5,3,1)]$

The steady state probabilities obtained are:-

$$P_1 = C[\lambda^2\mu^3Y+2\lambda\mu^4Y+\lambda\mu^3Y^2+\mu^5Y+2\mu^4Y^2+\mu^3Y^3]$$

$$P_2 = C[\lambda^3\mu^3+\lambda^2\mu^4+\lambda\mu^5+\lambda\mu^4Y]$$

$$P_3 = C[\lambda^2\mu^2Y^2+\lambda\mu^3Y^2+\lambda\mu^2Y^3]$$

$$P_4 = C[\lambda^3\mu^2Y+2\lambda^2\mu^3Y+\lambda\mu^4Y+\lambda\mu^3Y^2)$$

$$P_5 = C[\lambda^2\mu Y^3]$$

$$P_6 = C[\lambda^3=Y^2+\lambda^2\mu^2Y^2]$$

$$P_7 = C[\lambda^3Y^3]$$

where, $1/C = \lambda^3(\mu^3+\mu^2Y+\mu Y^2+Y^3)+\lambda^2(3\mu^3Y+2\mu^2Y^2+\mu Y^3+\mu^4)$
$+\lambda(4\mu^4Y+\mu^5+3\mu^3Y^2+\mu^2Y^3)+\mu^5Y+2\mu^4Y^2+\mu^3Y^3$

The steady state availability is given by,

$$A_{ss} = P_1+P_3+P_5$$

$$= C\mu Y[(\lambda+\mu)^2(\mu+Y)^2-\lambda\mu Y(\lambda+2\mu+Y)]$$

4.4.4 STEADY STATE AVAILABILITY WITH THREE SPARES

For 1-out-of 1:G system with three spares and single installation and repair facility,

$m = 9, \; q = 1$

The transition diagram of the system is shown in figure 12. The matrix 'S' obtained is,

$$S = \begin{bmatrix} 1 & 0 & 3 \\ 0 & 0 & 4 \\ 1 & 1 & 2 \\ 0 & 1 & 3 \\ 1 & 2 & 1 \\ 0 & 2 & 2 \\ 1 & 3 & 1 \\ 0 & 3 & 1 \\ 0 & 4 & 0 \end{bmatrix}$$

The state transition matrix evaluated is:

$$A = \begin{bmatrix} -\lambda & Y & \mu & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -Y & 0 & \mu & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\mu-\lambda & Y & \mu & 0 & 0 & 0 & 0 \\ \lambda & 0 & 0 & -Y-\mu & 0 & \mu & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\lambda-\mu & Y & \mu & 0 & 0 \\ 0 & 0 & \lambda & 0 & 0 & -Y-\mu & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\mu-\lambda & Y & 0 \\ 0 & 0 & 0 & 0 & \lambda & 0 & 0 & -\mu-Y & \mu \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda & 0 & -\mu \end{bmatrix}$$

Sets $\emptyset_i$, $i = 1,2,3,\ldots 9$, obtained are

Sets $\emptyset_i$, i =1,2,3,... 9, obtained are

$\emptyset_1$ = [(1,4,8,6,7,11,13,15),(1,4,8,6,12,10,15,11),
(1,4,8,6,10,12,15,14), (1,2,4,8,12,10,15,11)
(1,2,4,8,12,10,15,14), (1,2,5,8,12,10,15,11),
(1,2,5,8,12,10,15,14), (1,2,4,7,8,12,15,14),
(1,2,4,7,9,12,15,14), (1,2,4,7,8,11,12,15),
(1,2,4,7,8,11,13,15), (1,2,4,7,9,11,12,15)
(1,2,4,7,9,11,13,15), (1,2,5,7,8,11,12,15),
(1,2,5,7,8,11,13,15), (1,2,5,7,8,11,13,15),
(1,2,5,7,8,12,15,14), (1,2,5,7,9,11,12,15),
(1,2,5,7,9,11,13,15), (1,2,5,7,9,12,15,14)].

$\emptyset_2$ = [(2,3,4,7,9,12,14,15), (2,3,4,7,9,11,12,15),
(2,3,4,7,9,11,13,15), (2,3,4,7,8,11,13,15),
(2,3,4,7,8,12,14,15), (2,3,4,7,8,11,12,15),
(2,3,4,8,10,11,12,15),(2,3,4,8,10,12,14,15),
(2,3,4,7,8,12,14,15), (2,3,4,7,8,11,12,15),
(3,4,6,7,8,11,13,15), (3,4,6,7,8,11,12,15),
(3,4,6,7,8,12,14,15), (3,4,6,8,10,11,12,15)
(3,4,6,8,10,12,14,15)].

$\emptyset_3$ = [(5,3,8,1,12,10,15,11), (5,3,8,1,12,10,15,14),
(5,7,39,1,12,15,14),(5,7,3,9,11,1,12,15),
(5,7,3,9,11,1,13,15), (5,7,3,8,1,12,15,14),
(5,7,3,8,11,1,12,15), (5,7,3,8,11,1,13,15)]

$\bar{\emptyset}_4$ = [(1,2,3,7,9,12,14,15),(1,2,3,7,9,11,12,15),
(1,2,3,7,9,11,13,15),(1,2,3,7,8,11,13,15),
(1,3,6,7,8,11,13,15), (1,2,3,7,8,11,12,15),
(1,2,3,7,8,12,14,15), (1,2,3,8,10,11,12,15),
(1,2,3,8,10,12,14,15),(1,3,6,7,8,11,12,15),
(1,3,6,7,8,12,14,15), (1,3,6,8,10,11,12,15),
(1,3,6,8,10,12,14,15)]

$\bar{\emptyset}_5$ = [(9,6,12,5,15,3,14,1), (9,11,6,12,5,15,3,1),
(9,11,6,13,5,15,3,1)]

$\bar{\emptyset}_6$ = [(1,3,5,6,7,11,13,15), (1,3,5,7,11,12,15),
(1,3,5,6,7,12,14,15)]

$\bar{\emptyset}_7$ = [(13,10,15,9,6,5,3,1)]

$\bar{\emptyset}_8$ = [(1,3,5,6,9,10,13,14), (1,3,5,6,9,10,14,15)]

$\bar{\emptyset}_9$ = [(1,3,5,6,9,10,13,14)]

The steady state probabilities obtained are:

$$P_1 = C\left[\lambda^3\mu^4Y+2\lambda^2\mu^5Y+\lambda^2\mu^4Y^2+2\lambda\mu^6Y+4\lambda\mu^5Y^2+\lambda\mu^4Y^3+\mu^7Y +3\mu^6Y^2+3\mu^5Y^3+\mu^4Y^4\right]$$

$$P_2 = C\left[\lambda^4\mu^4+3\lambda^3\mu^5+4\lambda^2\mu^6+\lambda^2\mu^5Y+3\lambda\mu^7+2\lambda\mu^6Y+\lambda\mu^5Y^2\right]$$

$$P_3 = C\left[\lambda^3\mu^3Y^2+2\lambda^2\mu^4Y^2+\lambda^2\mu^3Y^3+\lambda\mu^5Y^2+2\lambda\mu^4Y^3+\lambda\mu^3Y^4\right]$$

$$P_4 = C\left[\lambda^4\mu^3Y+3\lambda^3\mu^4Y+3\lambda^2\mu^5Y+2\lambda^2\mu^4Y^2+\lambda\mu^6Y+2\lambda\mu^5Y^2+\lambda\mu^4Y^3\right]$$

$$P_5 = C\left[\lambda^3\mu^2Y^3+\lambda^2\mu^3Y^3+\lambda^2\mu^2Y^4\right]$$

$$P_6 = C[\lambda^3\mu^3Y^2+\lambda^2\mu^4Y^2+\lambda^2\mu^3Y^3]$$

$$P_7 = C[\lambda^3\mu Y^4]$$

$$P_8 = C[\lambda^4\mu Y^3+\lambda^4Y^4]$$

$$9_9 = C[\lambda^4Y^4]$$

where $1/C = P_1+P_2+P_3+P_4+P_5+P_6+P_7+P_8+P_9$

$$= [\lambda^4\mu^3Y+\lambda^4\mu Y^2+3\lambda^4Y^4+3\lambda^3\mu^5+4\lambda^3\mu^4Y+2\lambda^3\mu^3Y^2$$
$$+\lambda^3\mu^2Y^3+\lambda^3\mu Y^4+4\lambda^2\mu^6+6\lambda^2\mu^5Y+6\lambda^2\mu^4Y^2+3\lambda^2\mu^3Y^3$$
$$+\lambda^2\mu^2Y^4+3\lambda\mu^7+5\lambda\mu^6Y+8\lambda\mu^5Y^2+4\lambda\mu^4Y^3+\lambda\mu^3Y^4$$
$$+\mu^7Y+3\mu^6Y^2+3\mu^5Y^3+\mu^4Y^4].$$

The steady state availability is given by,

$$A_{ss} = P_1+P_3+P_5+P_7$$
$$= C\mu Y[(\mu+Y)^3(\lambda+\mu)^3-\lambda\mu Y[(\lambda+\mu+Y)(2\lambda\mu+2\lambda Y+4\mu^2+3\mu Y)$$
$$+\mu(\mu^2+\mu Y+Y^2)-2\lambda\mu^4(\lambda+\mu+Y)]]$$

Thus we have got four expressions for steady state availability with zero spare, one spare, two spares and three spares. Simply by putting the values of failure rate, repair rate and installation rate, steady state availability can be calculated for different number of spares. These expressions have been utilised in further chapters for evaluation of steady state availability of SCR controlled drives.

CHAPTER V

STEADY STATE AVAILABILITY EVALUATION AND OPTIMIZATION OF REPAIR AND NUMBER OF SPARES FOR MINIMUM COST

5.1 INTRODUCTION

The different expressions of S.S. availability obtained for various number of spares take into account the failure rate, repair rate and installation rate but the cost is not included. The failure rate of equipments as calculated is constant, because the calculations have been carried out based on available data collected from past experience. The repair rates and installation rates of components are directly proportional to the cost. The higher repair and installation rate will be, higher will be the cost. Similarly inclusion of spares or increase in their number, increases cost. Also the increase in repair rate and number of spares results in increase of SS availability. However, the variation in installation rate has got negligible effect on S.S. availability. In order to achieve a particular level of S.S. availability, repair rate and number of spares have been optimized for the least cost. The installation rate has been assumed constant due to aforesaid reason.

Reliability should be improved upto the point where the cost of improving it further is greater than the cost of buying more effectiveness by simply buying more systems.

This is the OPTIMUM RELIABILITY because the cost of achieving a given level of effectiveness is a minimum at this point.

Improvement in the reliability of the system results from changes in subsystems. The payoff in system reliability due to a given change in a subsystem is determined by the way the system works and the conditions under which it will be used. The priority of changes that may be made to improve the reliability of the subsystems depends also upon:

1. How much of an improvement is made, and
2. How much the improvement costs.

5.2 RELIABILITY AND MAINTENANCE COSTS

The cost of achieving any desired reliability and the subsequent cost of maintenance are related to each other roughly as shown in Fig.13[23]. Consider first the cost of achieving reliability. At A the reliability is very low and, since presumably neither the designers nor the production unit care much about it, the amount spent on reliability is also low. Indeed the reliability could be appreciably improved, without spending much, merely by taking a little more care. Hence cost riseslittle as reliability is improved. If we go on improving the reliability, however, we gradually reach the situation where all

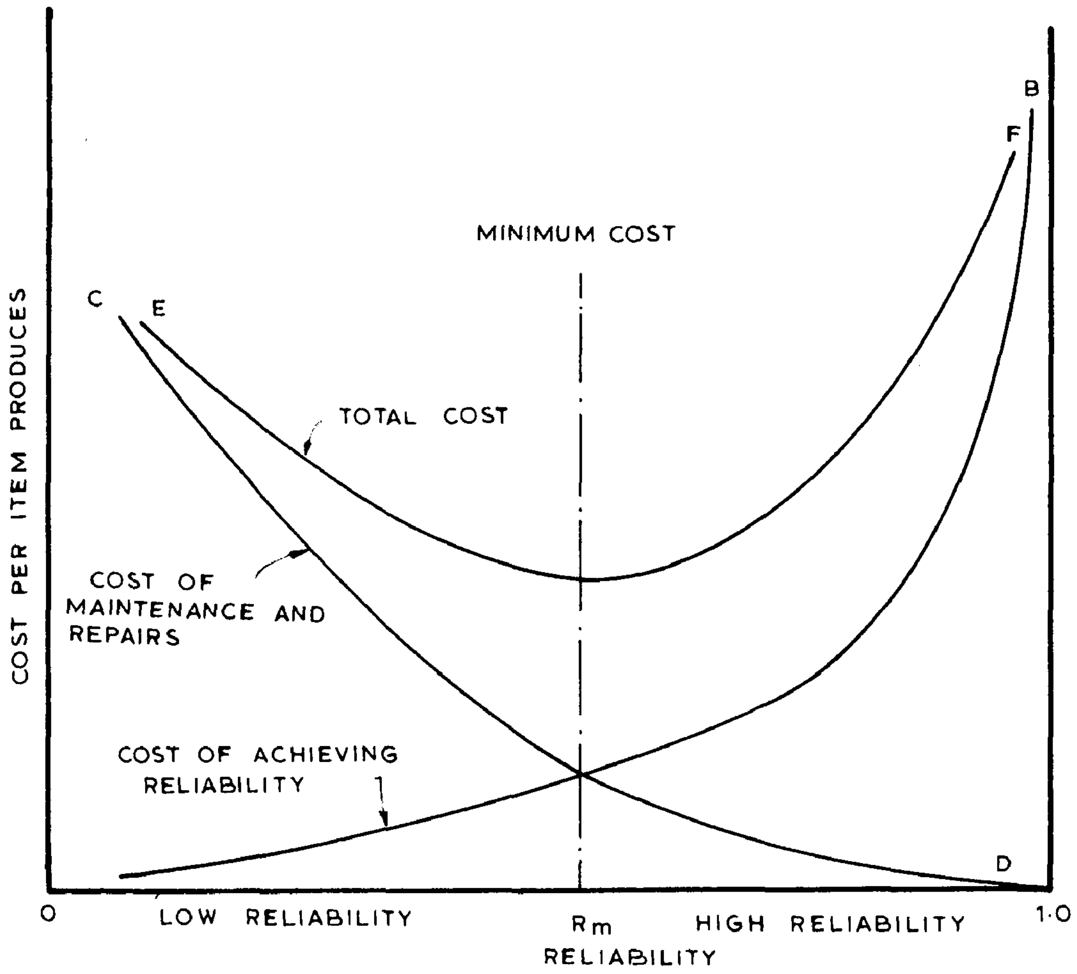

FIG.13 _ THE RELATION BETWEEN RELIABILITY AND MAINTENANCE COSTS obvious things have been done, and from now onwards we shall have to spend increasingly more to achieve a given reliability improvement. If we were unwise enough to demand an impossible reliability of 1.0, costs would sweep away to infinity beyond B.

However, when reliability is low, maintenance costs from all the breakdowns are inevitably high, as shown at C. As the reliability improves, the cost of maintenance falls until at D, as reliability approaches 1.00, maintenance costs approach zero. By getting reliability and maintenance costs together we get curve EF and find that there is particular reliability R_m for which the overall cost is a minimum.

5.3 ALLOCATION OF REPAIR RATE AND INSTALLATION RATE

These two rates come under maintenance activity of the system and are responsible for bringing back the system to the working condition, thus increasing availability of the system. By introduction of these two facilities the total cost of the system also goes up. Having developed the system configuration (redundancy pattern), a range of values can be specified for repair and installation rates that would satisfy a system availability requirement.

5.4 COST OF SUB SYSTEM, SPARE, REPAIR AND INSTALLATION

For the drive systems the cost of each subsystem has been taken on unit basis. On each sub-system the type of repair, its cost, and time taken in repair, installation can vary from fault to fault. However for the purpose of calculation, the cost of subsystem and the rate of installation are shown for each subsystem in Appendix B and C. Further it has been taken that out of the system cost it can be repaired 5 times whereas installation of subsystem at the rate shown in Appendices will cost equal to the subsystem cost. Understandably, the cost of the spare of subsystem is taken equal to the cost of subsystem.

5.5 STEADY STATE AVAILABILITY WITH NO SPARES AND MINIMUM REPAIR AND INSTALLATION RATE

Let $A_1, A_2 \ldots A_n$ is the steady state availability of the subsystems 1,2,... .n forming the system. Then steady state availability A_{ss} of the systems is given by

$$A_{ss} = A_1 x A_2 x A_3 x \ldots x A_n$$

Thus for calculating steady state availability of SCR controlled drive, firstly SS availability of subsystems is calculated and then SS availability of drive system is evaluated. For low repair rate of subsystems and without any spare SS availability of two already considered SCR drives is calculated.

5.5.1 SLIP POWER CONTROL DRIVE

For the drive, failure rate, installation rate, low repair rate, and corresponding SS availability of sub-systems without any spare are as below:

S.No.	Sub-system	Failure Rate (10^4 hr)	Installation Rate (10^4hr)	Repair Rate (10^4hr)	A_{ss}
1.	Motor Protection Circuit	0.175	10^4	5	0.9661
2.	Motor	0.00625	1.5×10^3	1	0.9937
3.	Rectifier and filter circuit	0.024	0.5×10^4	2	0.9881
4.	3Ø line commuted inverter	0.276	0.25×10^4	3	0.9156
5.	Comparator	0.0482	0.5×10^4	5	0.9904
6.	Control and firing circuit	1.617	10^4	8	0.8284
7.	3Ø Auto transformer	0.037	2×10^3	5	0.9926
8.	Tachogenerator	0.0023	10^4	1	0.9997

Thus the SS availability of the system is

$$A_{ss} = 0.9661 \times 0.9937 \times 0.9881 \times 0.9156 \times 0.9904 \times 0.8284 \times 0.9926 \times 0.9997$$
$$= 0.7040$$

5.5.2 Reversible D.C.Motor Drive

Similarly for this drive failure rate, low repair rate, installation rate and corresponding SS availability of subsystems are as below.

S.No.	Sub-system	Failure Rate (10^4hr)	Installation Rate (10^4hr)	Repair Rate (10^4hr)	A_{ss}
1.	Transformer with protection circuit	0.02	$2x10^3$	2	0.9901
2.	Filter circuit	0.042	$0.5x10^4$	2	0.979
3.	Current Monitoring Circuits	0.024	10^4	2	0.9765
4.	Comparator	0.0482	10^4	2	0.9540
5.	Trigger units	1.617	10^4	8	0.6803
6.	Thyrister bridge	0.084	$0.25x10^4$	2	0.9596
7.	Motor starter	0.0025	10^4	2	0.9987
8	Motor	0.0625	$1.5x10^3$	1	0.9937.
9.	Tachogenerator	0.0023	10^4	1	0.9997

Thus the steady state availability A_{ss} of system is ,

$$A_{ss} = 0.9901x0.979x0.9765x0.9540x0.6803$$
$$x0.9596x0.9987x0.9937x0.9997$$

$$= 0.5843$$

As seen the SS availability of drive systems is very low and thus needs improvement. This can be done by increasing repair rate of subsystems and providing spares for subsystems having high failure rates. However, this should be done at minimum increase in the cost. Thus in order to achieve SS availability of the order of 0.96(app.) optimization of number of spares and repair rate for minimum cost is carried out. Installation rate has been taken constant.

5.6 OPTIMIZATION OF SPARES AND REPAIR RATE

In order to achieve reliability of the order of about 0.96, the optimization of spares and repair rate has been done for minimum cost. Reference is made to table 5.1 and 5.2. Starting with zero spares and minimum possible repair rate SS availability and cost of each subsystem is calculated. In the end total cost of system and S.S. availability is evaluated. Keeping the criteria that subsystem which has got max. $\frac{1-A_{ss}}{cost}$, has been given priority in increasing S.S. availability. The increase in SS availability has been done first by increasing the repair rate. But beyond 5, the cost of repair rate increases the cost of spare. By adding an spare unit SS availability of subsystem also increases tremendously compared to increase in repair rate. Thus while μ has been kept below 5, spare has been added to increase SS-availability.

The optimization has been done by direct search technique. Wherever desired level of SS availability has reached with min. cost, these values of repair rates, installation rates and number of spares have been taken and are recommended for maintaining these two typical drive systems.

SLIP ENERGY RECOVERY DRIVE

OPTIMIZATION OF REPAIR RATE AND SPARE FOR ACHIEVING Ass ≈ 0.95

ASSUMPTION: 1. Five times repairs can be carried out on subsystem at a cost equal to cost of Subsystem 2. Cost of installation rate is equal to the cost of Sub system

MOTOR PROTECTION CIRCUIT λ=0.175 C=1 UNIT									MOTOR SPARE=0 λ=0.00625 C=30 UNITS						RECTIFIER & FILTER CKT. SPARE=0 λ=0.024 C=2 UNIT						3Φ LINE COMMUTED INVERTER λ=0.276 C=2 UNIT								COMPARATOR λ=0.0482 C=.5 UNIT								CONTROL AND FIRING CIRCUIT λ=1.617 C=1 UNIT									3Φ AUTO TRANSFORMER λ=0.037 C=10 UNIT					TACHOGENERATOR SPARE=0 λ=.0023 C=0.2 U				TOTAL COST	Ass OF SYSTEM
SPARES			REPAIR RATE			COST	Ass	1-Ass / COST	REPAIR RATE			COST	Ass	1-Ass / COST	REPAIR RATE			COST	Ass	1-Ass / COST	SPARES		REPAIR RATE			COST	Ass	1-Ass / COST	SPARES		REPAIR RATE			COST	Ass	1-Ass / COST	SPARES			REPAIR RATE			COST	Ass	1-Ass / COST	REPAIR RATE		COST	Ass	1-Ass / COST	REPAIR RATE	COST	Ass	1-Ass / COST		
0	1	2	μ_1	μ_2	μ_3				μ_1	μ_2	μ_3				μ_1	μ_2	μ_3				0	1	μ_1	μ_2	μ_3				0	1	μ_1	μ_2	μ_3				0	1	2	μ_1	μ_2	μ_3				μ_1	μ_2									
0	-	-	5	-	-	3	.9661	.0113	1	-	-	44	.9937	.00014	2	-	-	4.8	.9881	.0024	0	-	3	-	-	5.2	.9156	.0162	0	-	5	-	-	1.5	.9904	.0064	0	-	-	8	-	-	3.6	.8248	.0486	5	-	30	.9926	.00024	1 -	0.44	.9997	.0006	92.54	0.7040
																																					0	-	-	-	10	-	4	.8547	.0363										92.94	0.7295
																																					0	-	-	-	-	12	4.4	.8759	.0282										93.34	0.7476
																																					-	1	-	8	-	-	4.6	.964	.0078										93.54	0.8228
																					0	-	-	4	-	5.6	.9356	.0115																										93.94	0.8407
																					0	-	-	-	8	7.2	.9665	.0046																										95.54	0.8685
0	-	-	-	10	-	4	.9827	.0043																																																96.54	0.8834
																																					-	1	-	-	10	-	5	.9768	.0046										96.94	0.8951
																													0	-	-	10	-	2	.9969	.0013																				97.44	0.9008
																					-	1	3	-	-	7.2	.992	.0011																										97.44	0.9245
																																					-	1	-	-	-	12	5.4	.9826	.0032										97.84	0.9301
0	-	-	-	-	15	5	.9884	.0023																																																98.84	0.9354
																																					-	-	2	8	-	-	5.6	.9923	.0013										99.04	0.9447
															-	5	-	6	.9952	.0008																																				100.24	0.9514
-	1	-	5	-	-	4	.9968	.0008																																																99.24	0.9595
																																					-	-	2	-	10	-	6.0	.9934	.0011										99.64	0.9606

REVERSIBLE D.C. MOTOR DRIVE

OPTIMIZATION OF REPAIR RATE AND SPARES FOR ACHIEVING $A_{SS} \approx 0.96$

ASSUMPTIONS: 1. five times repairs can be carried out on sub.system at a cost equal to cost of Subsystem. 2. Cost of installation is equal to the cost of Sub system

TRANSFORMER $\lambda = .02$, $C = 10U$ (with protection)

Repair rate μ_1	μ_2	Cost	Ass	1-Ass/Cost
2	–	22	.9901	.0004

FILTER CIRCUIT $\lambda = .042$, $C = 0.5U$

μ_1	μ_2	μ_3	Spare 0	Spare 1	Cost	Ass	1-Ass/Cost
2	–	–	0	–	1.1	.979	.0191
–	5	–	0	–	1.5	.9916	.0055
–	–	10	0	–	2	.9952	.0021
2	–	–	–	1	1.7	.9995	.0002

TWO CURRENT MONITORING CIRCUITS $\lambda = .024$, $C = 0.5U$

μ_1	μ_2	μ_3	Spare 0	Spare 1	Cost	Ass	1-Ass/Cost
2	–	–	0	–	2.2	.9765	.0106
–	5	–	0	–	3	.9904	.0031
–	–	8	0	–	3.6	.994	.0016
2	–	–	–	1	3.4	.9997	.00008

TWO COMPARATOR $\lambda = .0480$, $C = 1$ UNIT

μ_1	μ_2	μ_3	Spare 0	Spare 1	Cost	Ass	1-Ass/Cost
2	–	–	0	–	2.4	.954	.019
–	5	–	0	–	3	.9808	.0063
–	–	10	0	–	4	.9934	.0016
2	–	–	–	1	3.4	.9983	.0005

TWO TRIGGER UNIT $\lambda = 1.617$, $C = 1$ UNIT

μ_1	μ_2	μ_3	Spare 0	Spare 1	Spare 2	Cost	Ass	1-Ass/Cost
–	–	[illegible]	0	–	–	8.5	.76[illegible]	.0284
3	–	–	–	1	–	9.2	.9202	.0096
–	10	–	–	1	–	10	.9541	.0046
–	–	15	–	1	–	10.3	.9[illegible]55	.0032
8	–	–	–	–	2	11.2	.92[illegible]6	.0043

THYRISTOR BRIDGE $\lambda = .084$, $C = 2$ UNIT

μ_1	μ_2	μ_3	Spare 0	Spare 1	Cost	Ass	1-Ass/Cost
2	–	–	0	–	4.8	.9596	.0024
–	5	–	0	–	6	.9834	.0027
–	–	8	0	–	7.2	.9895	.0014
2	–	–	–	1	[illegible]	.9983	.0002

MOTOR STARTER $\lambda = .0025$, $C = 5U$

μ_1	μ_2	Cost	Ass	1-Ass/Cost
2	–	1.2	.9927	.0010

MOTOR $\lambda = 0.0625$, $C = 20$ UNIT

μ_1	μ_2	Cost	Ass	1-Ass/Cost
1	–	44	.9937	.0001

TACHOGENERATOR $\lambda = .0023$, $C = 0.2U$

μ_1	μ_2	Cost	Ass	1-Ass/Cost
1	–	.44	.9997	.0006

System Cost	System Ass
82.74	.6595
88.14	.7958
88.54	.8091
89.14	.8319
89.94	.8439
91.14	.8646
91.94	.8877
92.94	.8991
93.44	.9025
94.24	.9137
94.64	.9318
95.24	.9352
96.44	.9410
96.14	.9445
95.94	.9499
95.34	.9550
94.94	.9635

CHAPTER VI

C O N C L U S I O N

Reliability is a serious concern to the system analyst. When the system is at design stage the reliability should be spelled out so that required reliability may be achieved by various means. In case of maintained systems the availability gives the better idea about systems performance. With this in view the availability analysis of SCR controlled drives was undertaken.

The reason for low reliability of SCR controlled drives is electronic control circuitry. The reliability of drives can be improved to a very large extent by improvement in this department only. However, as most of the commercial drives are maintained systems, effects of repair, installation of subsystem and their spares have been considered. It has been seen that availability increases considerably at a very marginal increase in cost. The calculation of SS availability has been done by a symbolic method. The SS availability for the complete system has been calculated and it has been found to be very low. Now in order to improve it either repair rate has to be increased drastically or spares have to be provided in case of subsystems having very low SS availability. It has been observed that increase in repair rate for increasing SS availability should be done by keeping cost factor in mind. At a certain stage the cost of higher

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repair rate will increase the cost of providing spare whereas the SS availability with extra spare, and low repair rate will be much more than SS availability with higher repair rate. The installation rate has small effect on SS availability. The excercise has been carried out to optimize the repair rate and number of spares for achieving desired SS availability at minimum cost.

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APPENDIX B

SLIP POWER CONTROL DRIVE

S.No.	Sub System	Installation Rate for 10^4 hr	Cost of Sub-System
1.	Motor Protection Circuit	10^4	1 unit
2.	Motor	1.5×10^3	20 unit
3.	Rectifier and filter circuit	0.5×10^4	20 unit
4.	3Ø line commuted invertors	0.25×10^4	2 unit
5.	Comparator	0.5×10^4	0.5 unit
6.	Control and firing circuit	10^4	1 unit
7.	3Ø auto transformer	2×10^3	10 unit
8.	Tachogenerator	10^4	0.2 unit

APPENDIX-A

FAILURE DATA

S.No.	Component	Failure Rate for 10^6 hrs.
1.	Thyristors	0.500
2.	Transistors	0.610
3.	Diodes	0.203
4.	Resistors	0.600
5.	Variable resistors	3.000
6.	Capacitors	0.600
7.	Small transformers	0.200
8.	Pulse transformers	0.150
9.	Motors	0.625
10.	Tachogenerators	0.230
11.	Fuses	0.500
		Failure Rate Percent for 10^3 hrs.
12.	IC silicon, digital	0.01
13.	IC silicon, linear	0.03

Sources: 1. IEE Conf.Pub.No.53, pp.146-153
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APPENDIX C

REVERSIBLE ROLLER DRIVE

S.No.	Sub-System	Installation Rate for 10^4 hr	Cost of Sub-System
1.	Transformer with protection circuit	$2x10^3$	10 units
2.	Filter circuit	$0.5x10^4$	0.5 units
3.	Current monitoring circuits	10^4	0.5 units
4.	Comparator	10^4	0.5 units
5.	Trigger unit	10^4	1 units
6.	Thyristor bridge	$0.25x10^4$	2 units
7.	Motor starter	10^4	0.5 units
8.	Motor	$1.5x10^3$	20 units
9.	Tachogenerator	10^4	0.2 units

APPENDIX -D

INTREES GENERATION

All intrees of the digraph are generated by properly selecting and deleting the branches.

MORE NOTATION

Matrix B:

$$b_{ij} = \begin{cases} h, & \text{if h-branch of the digraph is connected between nodes i and j and is directed towards node i} \\ 0 & \end{cases}$$

Matrix b^i: at i-iteration is derived from matrix B^{i-1} by deleting the column(s) and row(s) in which entries corresponding to the branches of the set u^{i-2} are present. Initially $B^1 = B^2 =$ 'reduced matrix B' by deleting column corresponding to root node.

Matrix C^i: It consists of row(s) of B^i corresponding to the node in the set W^{i-1}. C^1 is a row vector consisting of the elements of the row of matrix B^1 corresponding to root node.

Matrix D^i: It is obtained from C^i by deleting the columns in which the entries corresponding to the branches belonging to the set Q^{i-1} are present $D^1 = C^1$.

u^i set of branches connected at iteration i.

W^i set of nodes from which the branches εu^i are coming out in the digraph.

Q^i set of branches selected to form a intree so far.

Q^i $Q^{i-1} \cup u^i$

F^i vector whose h-element $f_h^i = \sum_{j=1}^{y} b_{jh}^i$, where y is the number of the rows in the matrix B^i. All the elements of this set must be nonzero. If any element of this set is zero, corresponding choice will not give any intree. Zero entry indicates that the out-degree for one of the nodes becomes zero at this iteration.

V_h^i set of nonzero entries in the h-column of the matrix Di

R^i $[V_1^i, V_2^i, \ldots, V_1^i, V_1^i x V_2^i \ldots V_{l-1}^i x V_1^i, \ldots, V_1^i x V_2^i x V_3^i \ldots$ multiplication of sets taking (y-1) sets at a time]

z=(1,2), z' = (3,4), then zxz'= [(1,3),(1,4),(2,3),(2,4)
y≡ columns in the matrix Di
$|Q^i|$ ≡ Elements is the set nQ^i

An algorithm to determine the intrees of an oriented graph corresponding to a root node can be written as follows.

Algorithm

$h = 1,\ y^h = 1$

1. Find B^h
2. Calculate F^h, if any element of F^h is zero, go to step 9. Otherwise go to next step.
3. Find D^h and set R^h, say
   $R^h = (r_h^1, r_h^2, \ldots, r_h^{y^h} \ldots r_h^{m^h})$
4. IfRR^h is empty, go to Step 9. Otherwise go to next step.
5. Find set U^h which is equal to $r_h^{y^k}$
6. Find set W^h and Q^h
7. If $|Q^h| < m-1$ go to next step. Otherwise write Q^h which corresponds to an intree, and go to step 9.
8. $h \leftarrow h+1$ and $y^h = 1$, go to step 1.
9. h-h-1
10. If $h < 1$ stop. Otherwise go to next step.
    1. $y^h \leftarrow y^h + 1$
    2. If $y^h > m^h$ go to step 9. Otherwise go to Step 5.

For finding intrees, it is not necessary to draw the digraph corresponding to the transition matrix. Numbers are designated for the non-zero entries of the transition matrix, except the diagonal entries. Then B is defined as

$$b_{ij} = \begin{cases} h \text{ , if } a_{ij} \;\; 0 \text{ and it is designated by } h \\ 0 \text{ , otherwise} \end{cases}$$