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**PRELIMINARY RELIABILITY PREDICTION
FOR THE FFTF CONCEPTUAL
BUILDING ELECTRICAL POWER SYSTEM,
SYSTEM 12**

O. B. MONTEITH

AUGUST 1968

**AEC RESEARCH &
DEVELOPMENT REPORT**

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FOR THE FFTF CONCEPTUAL
BUILDING ELECTRICAL POWER SYSTEM

By

O. B. Monteith
Reactor and Plant Technology Department
FFTF Project

August 1968

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PRELIMINARY RELIABILITY PREDICTION
FOR THE FFTF CONCEPTUAL
BUILDING ELECTRICAL POWER SYSTEM,
SYSTEM 12

Oscar B. Monteith

INTRODUCTION

This report contains a preliminary reliability analysis of the FFTF Building Electrical Power System. Results of the analysis are preliminary because they are based on a conceptual design of the system (contained in the Conceptual System Design Description dated December 8, 1967) and on other systems of the FFTF which influence the design of the power system but are not yet fully defined. The purpose of this analysis is to obtain an early prediction of the Building Power System reliability and to explore analytical methods which can be used on a system of this complexity.

A suitable technique for predicting system reliability is not easily evolved. There are many equipment redundancies and alternative sources of power that are not amenable to conventional reliability analysis methods. In addition, each component can be repaired or replaced to restore the system in event of a failure.

The analytical method employed in this report is to combine elements in the reliability block diagram into progressively fewer and less complex arrangements, until a single logic block represents the assembly or a subsystem. The combinations are accomplished for series and parallel elements in the diagram. Complications arise because of the repairability of the components, and the conditional redundancies that exist.

Each major bus of the Building Electrical System is analyzed and a prediction is made of the availability of power to the bus, the mean-time-between-failure of power to the bus, and the mean-time-to-restore the power in event of failure. Failure rates for the system components were obtained from references in most cases, and in others engineering estimates are employed. The repair times of the various components were established from operating experience, engineering estimates, and some literature data.

ASSUMPTIONS

In the preparation of this analysis simplifying assumptions have been made; some of which are stated, others implied. A list of the more important assumptions follows:

1. The Building Electrical Power System is as described in the Conceptual System Description dated December, 1967.
2. Only single failures have been considered. Multiple failures, and dependent or secondary failures have not been included.
3. Components are operated in their useful life phase where the failure rate is constant and the distribution of the times between failures can be expressed by exponential distributions.
4. The distribution of repair times to restore the equipment from failed condition can be expressed by an exponential distribution.
5. Component failure rates and repair times have been estimated based on published data and engineering judgements.
6. Repairs and testing do not alter the original design, nor add other faults.
7. The system and components perform exactly as designed and there are no design deficiencies.
8. The time required to switch a failed component from service and readjust loads is not included in the availability calculations. This switching will be effected at the control console and the time to respond will be minimal.
9. It is assumed that the operating policy will be to initiate reactor shutdown in event of loss of either normal source of power to the Emergency Power Busses.

SUMMARY AND CONCLUSIONS

This reliability analysis predicts the availability, mean-time-between-failure, and the mean-time-to-restore electrical power to the various busses that make up the FFTF Building Electrical Power System.

A summary of the analysis results follows:

The 2.4 kV system busses 5, 6, 7, 8, and 9 (4 out of 5 busses)

Availability of power = 0.999999785

Mean-time-between-failure = 73,000,000 hr

Mean-time-to-restore = 15.6 hr

The 480 V system busses 13, 14, 15, 16, 17, 18, 19, and 20 (each bus)

Availability of power = 0.999999867

Mean-time-between-failure = 130,000,000 hr

Mean-time-to-restore = 17.5 hr

The Emergency Power Busses 11 and 12 (each bus)

Availability of power = 0.999999999999565

Mean-time-between-failure = 15,100,000,000,000 hr

Mean-time-to-restore = 6.6 hr

The 125 V dc busses (each of 3 busses)

Availability of power = 0.999999966

Mean-time-between-failure = 54,000,000 hr

Mean-time-to-restore = 1.83 hr

The 24 V dc busses (each of 2 busses)

Availability of power = 0.999999983

Mean-time-between-failure = 109,000,000 hr

Mean-time-to-restore = 1 hr

The "Zero Time Outage" Busses (each of 2 busses)

Availability of power = 0.9999999519

Mean-time-between-failure = 106,000,000 hr

Mean-time-to-restore = 5.12 hr

The 120 V Instrument & Control Busses (each of 2 busses)

Availability of power = 0.9999558

Mean-time-between-failure = 100,000 hr

Mean-time-to-restore = 4.4 hr

The Station Service dc Busses (each of 2 busses)

Availability of Power = 0.999999966

Mean-time-between-failure = 55,000,000 hr

Mean-time-to-restore = 1.88 hr

The preliminary examination of System 12 analyzed here reveals no significant reliability shortcomings. There are no suggestions to be gleaned from this analysis for changes in equipment configurations to improve reliability. Any improvements to be achieved would seem to be in the area of materials and methods of construction and these are beyond the scope of this document.

As a result of the planned operating procedure involving the emergency power busses, an expected unavailability of the FFTF as a result of failures in this equipment is predicted to be 0.76 hr per 1000 hr of operation. This is to be compared with the unavailability goal of 1 hr per each 1000 hr of operation allocated to System 12.

SYSTEM OPERATIONAL REQUIREMENTS

SYSTEM FUNCTIONS AND BOUNDARIES

The Building Electrical Power System, System 12, provides equipment, circuits, and systems to receive the primary power, transform the voltage to the levels required by the various FFTF loads, and distribute the power via safe, protective and reliable circuitry. System 12 receives the primary power at 13.8 kV and distributes it at 2400 V, 480 V, and 120 V ac; and 125 and 24 V dc (see Figure 1). The distribution at all voltage levels is redundant in that no single insulation or equipment failure can cause the complete loss of a reactor function or major building service. Standby power, both ac and dc, is provided in System 12 for emergency operation of the FFTF in event of failure of the normal power source.

System 12 receives power from the Primary Electrical Power System, System 11, and interfaces with nearly all other systems of the FFTF. In addition to providing power for process and service loads, it also supplies electrical heating for sodium piping and vessels. The electrical controls for some loads are included in System 12, in other cases the controls are included with the using FFTF system.

ANTICIPATED OPERATIONAL CONDITIONS

The Building Electrical Power System will use methods, components, and materials that have been proven reliable and safe in operation from long experience in industry. In some

FIGURE 1. System 12 Functional Block Diagram

cases electrical equipment will be subjected to environments of high temperature, high radiation, dry inert gases, or sodium vapors which are not encountered in the usual electrical application. In these cases, design study and development effort will be required to establish the required design. No problems are anticipated in providing these components.

Other operational considerations will enhance rather than detract from the system reliability. Thus, a basic design requirement is that "wiring and equipment shall be installed in such a manner as to prevent induced interference between separate systems that might result in erroneous signals." Adequate switching will be provided for maintenance of major components without necessitating a total outage of any function or service. There is ample system capacity as a result of the designed 30% additional capacity for future growth, plus that which results from the diversity of the loads. Several other design requirements listed in the Conceptual System Design Description for System 12, will aid in providing a reliable and operational design.

The anticipated interferences and interactions between System 12 and other FFTF systems are not new design problems, and the use of proven design techniques will reduce the adverse effects of electromagnetic interference, voltage surges and transients. The reliability analysis of System 11,⁽²⁾ the Primary Electrical Power System, discusses the problem of lightning strokes and other surges which occur on the BPA System and which are conducted into System 12 via System 11. Components of System 12 that are exposed to direct lightning strokes will have adequate protection.

The operational plans for the emergency power bus present a need for special consideration. Present planning indicates that the standard operating procedure will be to initiate

shutdown of the FTR in the event that the emergency power sources are activated. Thus, any failure in the two normal sources of power to the emergency busses will activate the emergency power supplies and cause reactor shutdown which results in reactor unavailability. The emergency power busses will need to be investigated for failures which can cause reactor unavailability.

MISSION PROFILES AND DUTY CYCLES

System 12 will be required to provide continuous power to the FFTF. The approximate duty cycle of the reactor is such that during each three month period three weeks are available during refueling which will permit shifting of loads for preventive maintenance.

SYSTEM GOALS AND REQUIREMENTS

A requirement for the FFTF systems is that a failure in System 12 will not cause an unsafe condition at the reactor. In the actual conceptual system design a single failure of any equipment in System 12 will not result in a reactor unsafe condition. This is accomplished by the use of equipment and power source redundancies that are specified in the conceptual design.

A goal for System 12 has been established through the allocation of reactor unavailability to the various systems that make up the FFTF. Based on past experience with Hanford production reactors, an arbitrary goal for unavailability of the FFTF reactor, as a result of System 12 equipment failures, is established at less than 1 hr per 1000 hr of operation.

RELIABILITY ANALYSIS

The building Electrical Power System is a combination of several subsystems with various interconnections. The conceptual design of System 12 is shown in Figures 2 through 6 of the Conceptual System Design Description.

It is the interconnections, combinations of the subsystems, and component repair capability which complicate the reliability analysis of the Building Electrical Power System. Thus, the 13.8 kV system supplies the 2.4 kV and 480 V systems; the 480 V system supplies the 120 V system, and 125 V dc and 24 V dc systems. An emergency power source is capable of supplying the emergency power bus in the event of the total loss of all normal power. Batteries will supply the dc busses in the event of total power failure. In addition, a number of equipment and subsystem redundancies are employed. All of the components are repairable either by replacement, or with/on-the-spot repairs in which the system restoration time varies from 1 to 168 hr.

Presented in this report is a reliability analysis for each of the busses that make up System 12. The results of the analysis yield the availability of electrical power to the bus, the mean-time-between-failure (MTBF) of power to the bus, and the mean-time-to-restore (MTTR) the power in event of failure.

The reliability analysis is developed from a reliability block diagram that represents the equipment supplying power to a bus. Each piece of equipment is represented in the diagram, and these blocks are then combined in accordance with the logical relations that establish the success of the path, or paths. The diagram is simplified by successive reductions until one block represents the assembly or sub-assembly. Some of these reductions are of series combinations, some are parallel combinations, and others follow from conditional probability arguments (Figure 7).

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FIGURE 2. One Line Diagram of 13.8 kv Feeders,
with 24 kv and 480 Volt Switchgear

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FIGURE 3. One Line Diagram of Instrument and Control, and Direct Current Power Systems

FIGURE 4. One Line Diagram of 480 Volt Alternating Current Power System

FIGURE 5. Electrical Site Plan

NOTES

1. ALL LOADS ARE APPROXIMATE

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FIGURE 6. One Line Diagram of 2.4 kV System

FIGURE 7. *Example of Analysis Method*

The analytical method employed in this report is to combine elements in the reliability block diagram into progressively fewer and less complex arrangements, until a single logic block represents the assembly or subsystem. This technique is outlined in Chapters 7 and 8 of Reliability Engineering,⁽³⁾ by the Staff of ARINC Research Corporation, edited by W. H. Von Alven. An example follows. Part (a) is the system and Part (b) is the first reduction wherein the series elements A and B are combined. The two parallel combinations of (b) are then combined to give two series elements in (c). The final combination of the two series elements in (c) gives the single block (d) which represents the system.

Table I is a list of the equipment failure rates and the time to restore for the components that make up System 12. Included in the list is the reference from which the various values were obtained.

In addition to availability, MTBF, and MTTR power to the busses; a calculation is made to determine the same numerical values for power to any connected load. It is significant to note that availability and MTBF of power to any load is lower than for the bus, because the equipment connecting the load to the bus is a series logic path which becomes the dominant factor in the values.

In each of the reliability diagrams a block is included which represents the logical position in the diagram for System 11 which is the Primary Electrical Power System. The values of availability, MTBF, and MTTR for System 11 are not included in this analysis of System 12 since the concern here is to evaluate the System 12 equipment. This has been done by assuming the block for System 11 is a perfect component without failure.

TABLE I. Equipment Failure Rates and Time to Restore

	Failures Per Million Hours	Reference	Time to Restore, hr	Reference
13.8 kV Circuit Breaker	0.65	4	1	4,*
13.8 kV Cable	3.8/1000 ft	4	48	4,*
13.8 kV Bus	1.8	5	8	*
13.8/2.4 kV Transformer	0.60	4	168	*
2.4 kV Circuit Breaker	0.65	4	1	*
2.4 kV Cable	3.8/1000 ft	4	48	4,*
2.4 kV Bus	1.8	5	8	*
13.8/.480 kV Transformer	0.94	4	168	*
600 V Cable	2.7/1000 ft	4	48	4,*
480 V Circuit Breaker	2.3	4	1	*
480/120 V Transformer	0.94	4	8	*
480 V Bus	1.8	5	8	*
Cable Joints & Terminations	0.24	4	24	4,*
Diesel Start = 0.998			5	
Run	59	6,7,8	5	6,7,8
Turbine Start = 0.999			4	
Run	100	6,7,8	4	6,7,8
1500 kVA 480 V Generator	10	4,*	168	*
480 V Voltage Regulator	5	*	4	*
120 V Circuit Breaker	2.5	*	1	*
125 V dc Power Supply	20	*	4	*
125 V dc Battery	100	*	4	*
75 HP 125 V dc Motor	5	4,*	80	4,*
60 kVA Synchronous Motor	5.9	4,*	78	4,*
Clutch	3.0	8	4	*
24 V dc Power Supply	20	*	4	*
24 V dc Battery	50	*	4	*
24 V dc dc Circuit Breaker	2.0	*	1	*
125 V dc dc Circuit Breaker	2.0	*	1	*

* Estimate based on Hanford Experience and engineering judgment

ANALYSIS OF THE 2.4 kV SYSTEM, BUSES B5 THROUGH B9

The 2.4 kV system is made up of five busses, each supplied from the 13.8 kV system through a circuit breaker, cable, and 13.8 kV/2.4 kV, 5 MVA transformer. Its major load is the FFTF Heat Transport System, System 50. The 2.4 kV system supplies four primary coolant loop pump motors, four secondary coolant loop pump motors, 16 heat dump blower motors, and three sodium heating loads. These loads are connected to four of the five busses, with the fifth bus energized but supplying no load. In event of power loss to any one of the four loaded busses, the fifth bus can be switched to pick up the load of the power deficient bus.

This arrangement of busses and loading constitutes a form of redundancy. However, in the reliability context it is not pure operational redundancy, and it is not pure standby redundancy. For this analysis the combination described above is being considered as a four out of five operational redundancy with the knowledge that this is an approximation, and that the error is small.

The reliability block diagram of the 2.4 kV system is shown in Figure 8 and the results of the analysis are as follows:

For four out of five 2.4 kV busses

Availability of power = 0.999999785

(unavailability = 0.215×10^{-6})

Mean-time-between-failure = 73,000,000 hr

Mean-time-to-restore = 15.6 hr

For any 2.4 kV load

Availability of power = 0.999878

(unavailability = 122×10^{-6})

Mean-time-between-failure = 290,000 hr

Mean-time-to-restore = 35.5 hr

FIGURE 8. Reliability Block Diagram 2.4 kV System

FIGURE 8. (Contd)

$$A_{2.4\text{kV}} = \left([1 - (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4)^2] \left\{ 5 [1 - (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14})] \right\}^4 - 4 [1 - (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14})] \right\}^5$$

$$\begin{aligned} \odot_{2.4\text{kV}} &= (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4) [2 (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)] \\ &\quad [1 - (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4)] \\ &\quad + 20 \left\{ [1 - (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14})] \right\}^3 \\ &\quad (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14}) \left\{ \lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12} + \lambda_{13} + \lambda_{14} \right\} \end{aligned}$$

$$\tau_{2.4\text{kV}} = \frac{(1 - A_{2.4\text{kV}}) \odot_{2.4\text{kV}}}{A_{2.4\text{kV}}}$$

Math Model for 2.4 kV System Bus (Figure 8)

ANALYSIS OF THE 480 V SYSTEM, BUSES B13 THROUGH B20

The normal 480 volt system comprises eight busses each supplied from the 13.8 kV system through a circuit breaker, cable, and 13.8 kV/480 V, 1.5 MVA transformer. After providing for the loads of the heat transport system, System 12 supplies the remaining FFTF electrical loads by the 480 V system as a normal source. The conceptual design of these busses includes approximately 40% overcapacity for the anticipated requirements. In addition, there is a diversity of loads which yields further available capacity. The planned operation of the 480 V system provides for switching of the loads from a failed bus to an adjacent bus, through bus-tie breakers. In the event that switching is required, some noncritical loads may be disconnected to carry both loads adequately on one bus.

The conditions of operation and bus arrangement noted above are representative of operational redundancy. Though the 480 V system does not meet all the requirements for operational redundancy, it is a satisfactory approach for this analysis. A rigorous analysis would be more complicated and time consuming than the results would warrant.

The reliability block diagram of one 480 V bus is shown in Figure 9. All of the busses, B13 through B20 are considered to be identical. The results of the analysis are as follows:

For one 480 V bus

Availability of power = 0.999999867
(unavailability = 0.133×10^{-6})

Mean-time-between-failure = 130,000,000 hr

Mean-time-to-restore = 17.5 hr

For any 480 V load

Availability of power = 0.9999182
(unavailability = 81.8×10^{-6})

Mean-time-between-failure = 183,000 hr

Mean-time-to-restore = 15 hr

FIGURE 9. Reliability Block Diagram 480 Volt System

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FIGURE 9. (Contd)

$$A_{480V} = [1 - (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4)^2][1 - (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14})(\lambda_{15}\tau_{15} + \lambda_{16}\tau_{16} + \lambda_{17}\tau_{17} + \lambda_{18}\tau_{18} + \lambda_{19}\tau_{19} + \lambda_{20}\tau_{20} + \lambda_{21}\tau_{21})]$$

$$\begin{aligned} \frac{1}{\mathcal{C}_{480V}} &= (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4) [2 (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)] 1 - (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4) + (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14}) \\ &\quad (\lambda_{15}\tau_{15} + \lambda_{16}\tau_{16} + \lambda_{17}\tau_{17} + \lambda_{18}\tau_{18} + \lambda_{19}\tau_{19} + \lambda_{20}\tau_{20} + \lambda_{21}\tau_{21}) \\ &\quad \frac{\lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12} + \lambda_{13} + \lambda_{14} (1 - (\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14}))}{\lambda_9\tau_9 + \lambda_{10}\tau_{10} + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13} + \lambda_{14}\tau_{14}} \\ &\quad + \frac{\lambda_{15} + \lambda_{16} + \lambda_{17} + \lambda_{18} + \lambda_{19} + \lambda_{20} + \lambda_{21} [1 - (\lambda_{15}\tau_{15} + \lambda_{16}\tau_{16} + \lambda_{17}\tau_{17} + \lambda_{18}\tau_{18} + \lambda_{19}\tau_{19} + \lambda_{20}\tau_{20} + \lambda_{21}\tau_{21})]}{\lambda_{15}\tau_{15} + \lambda_{16}\tau_{16} + \lambda_{17}\tau_{17} + \lambda_{18}\tau_{18} + \lambda_{19}\tau_{19} + \lambda_{20}\tau_{20} + \lambda_{21}\tau_{21}} \end{aligned}$$

$$\tau_{480V} = \frac{(1 - A_{480V}) - \mathcal{C}_{480V}}{A_{480V}}$$

Math Model for 480 Volt System Bus (Figure 9)

ANALYSIS OF THE EMERGENCY POWER BUSES, B11 AND B12

The emergency power busses supply critical reactor auxiliaries and building service loads which include the pony motors for the primary and secondary sodium pumps, selected ventilation equipment, instrument and control systems, and others that are listed in the CSDD for System 12. There are two separate sources of power for the emergency busses; (a) normal power is provided from the 13.8 kV system by redundant paths of circuit breaker, cable, and 13.8 kV/480 V, 1.5 MVA transformer, and (b) emergency power from a redundant combination of a 1500 kVA diesel driven generator and a 1500 kVA gas turbine driven generator.

This analysis is based on the failure of either path of the normal primary power, and therefore the turbine unit is considered a redundant source for the diesel unit connected to the failed bus.

The switchover from normal power to emergency power is automatically actuated by loss of normal power. There is approximately 5 to 20 sec delay in restoring power in the event of switchover as this period is required to start the diesel and gas turbine drives and bring them up to speed.

A complication to the reliability analysis of this equipment combination is the standby mode of the diesel and gas turbine drives, and their expected starting unreliability. To facilitate the analysis, a starting reliability was determined for the diesel and turbine based on successes in a number of starts, and the expected number of starts to be required of this equipment in the FFTF. The combination of diesel and turbine driven generators are then considered as redundant equipment. This reliability model is an approximation and the error involved is not easily determined.

The reliability block diagram of the emergency power busses, B11 and B12 is shown in Figure 10. The two busses are considered to be identical for this analysis. The results of the analysis are as follows:

For the emergency bus

Availability of power = 0.999999999999565

(unavailability = 4.35×10^{-13})

Mean-time-between-failure = 15,100,000,000,000 hr

Mean-time-to-restore = 6.6 hr

For any load on the emergency bus

Availability of power = 0.9999833

(unavailability = 16.7×10^{-6})

Mean-time-between-failure = 244,000 hr

Mean-time-to-restore = 4.1 hr

The planned operation of the emergency system will be to start both diesels and the turbine drives in the event of a failure in either of the normal primary power sources. The turbine drive will then act as a redundant source to whichever diesel is required to supply the emergency bus. The second diesel will be started as a precaution. The analysis presented above does not consider the case of both normal primary sources failing since this is a multiple failure. However, the capacity of the emergency generators is such that any one of the three generator sources can supply the total emergency shutdown load. An approximation to establish the availability of a one-out-of-three combination of the three emergency generator sources yields the following:

A = 0.999999992 for one out of three emergency
generator sources

This is the availability of power from the generators alone, without considering power from the normal primary sources.

FIGURE 10. Reliability Block Diagram
Emergency Power Busses

FIGURE 10. (Contd)

$$A_{EB} = 1 - \left\{ 1 - [1 - (\lambda_1^{\tau_1} + \lambda_2^{\tau_2} + \lambda_3^{\tau_3} + \lambda_4^{\tau_4})^2] [1 - (\lambda_9^{\tau_9} + \lambda_{10}^{\tau_{10}} + \lambda_{11}^{\tau_{11}} + \lambda_{12}^{\tau_{12}} + \lambda_{13}^{\tau_{13}} + \lambda_{14}^{\tau_{14}}) (\lambda_{15}^{\tau_{15}} + \lambda_{16}^{\tau_{16}} + \lambda_{17}^{\tau_{17}} + \lambda_{18}^{\tau_{18}} + \lambda_{19}^{\tau_{19}} + \lambda_{20}^{\tau_{20}} + \lambda_{21}^{\tau_{21}})] \right\} (\lambda_{22}^{\tau_{22}} + \lambda_{23}^{\tau_{23}} + \lambda_{24}^{\tau_{24}} + \lambda_{25}^{\tau_{25}}) (\lambda_{26}^{\tau_{26}} + \lambda_{27}^{\tau_{27}} + \lambda_{28}^{\tau_{28}} + \lambda_{29}^{\tau_{29}})$$

$$\frac{1}{Q_{EB}} = (\lambda_{22}^{\tau_{22}} + \lambda_{23}^{\tau_{23}} + \lambda_{24}^{\tau_{24}} + \lambda_{25}^{\tau_{25}}) (\lambda_{26}^{\tau_{26}} + \lambda_{27}^{\tau_{27}} + \lambda_{28}^{\tau_{28}} + \lambda_{29}^{\tau_{29}}) \left\{ \left[1 - [1 - (\lambda_1^{\tau_1} + \lambda_2^{\tau_2} + \lambda_3^{\tau_3} + \lambda_4^{\tau_4})^2] [1 - (\lambda_9^{\tau_9} + \lambda_{10}^{\tau_{10}} + \lambda_{11}^{\tau_{11}} + \lambda_{12}^{\tau_{12}} + \lambda_{13}^{\tau_{13}} + \lambda_{14}^{\tau_{14}}) (\lambda_{15}^{\tau_{15}} + \lambda_{16}^{\tau_{16}} + \lambda_{17}^{\tau_{17}} + \lambda_{18}^{\tau_{18}} + \lambda_{19}^{\tau_{19}} + \lambda_{20}^{\tau_{20}} + \lambda_{21}^{\tau_{21}})] \right] \left[\frac{[1 - (\lambda_1^{\tau_1} + \lambda_2^{\tau_2} + \lambda_3^{\tau_3} + \lambda_4^{\tau_4})^2] [1 - (\lambda_9^{\tau_9} + \lambda_{10}^{\tau_{10}} + \lambda_{11}^{\tau_{11}} + \lambda_{12}^{\tau_{12}} + \lambda_{13}^{\tau_{13}} + \lambda_{14}^{\tau_{14}})]}{[1 - [1 - (\lambda_1^{\tau_1} + \lambda_2^{\tau_2} + \lambda_3^{\tau_3} + \lambda_4^{\tau_4})^2] [1 - (\lambda_9^{\tau_9} + \lambda_{10}^{\tau_{10}} + \lambda_{11}^{\tau_{11}} + \lambda_{12}^{\tau_{12}} + \lambda_{13}^{\tau_{13}} + \lambda_{14}^{\tau_{14}})]} \right] \right\} \frac{(\lambda_{15}^{\tau_{15}} + \lambda_{16}^{\tau_{16}} + \lambda_{17}^{\tau_{17}} + \lambda_{18}^{\tau_{18}} + \lambda_{19}^{\tau_{19}} + \lambda_{20}^{\tau_{20}} + \lambda_{21}^{\tau_{21}})}{(\lambda_{15}^{\tau_{15}} + \lambda_{16}^{\tau_{16}} + \lambda_{17}^{\tau_{17}} + \lambda_{18}^{\tau_{18}} + \lambda_{19}^{\tau_{19}} + \lambda_{20}^{\tau_{20}} + \lambda_{21}^{\tau_{21}})}$$

Math Model for Emergency Bus (Figure 10)

$$\begin{aligned}
& \left(\frac{1}{\tau_{EB}} \text{ Contd} \right) \frac{[2 \left(1 - (\lambda_1^{\tau_1} + \lambda_2^{\tau_2} + \lambda_3^{\tau_3} + \lambda_4^{\tau_4}) \right) (\lambda_1^{\tau_1} + \lambda_2^{\tau_2} + \lambda_3^{\tau_3} + \lambda_4^{\tau_4})}{(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4) + (\lambda_{15}^{\tau_{15}} + \lambda_{16}^{\tau_{16}} + \lambda_{17}^{\tau_{17}} + \lambda_{18}^{\tau_{18}} + \lambda_{19}^{\tau_{19}} + \lambda_{20}^{\tau_{20}} + \lambda_{21}^{\tau_{21}}) (1 - (\lambda_9^{\tau_9} + \lambda_{10}^{\tau_{10}} + \lambda_{11}^{\tau_{11}} + \lambda_{12}^{\tau_{12}} + \lambda_{13}^{\tau_{13}} + \lambda_{14}^{\tau_{14}})) (\lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12} + \lambda_{13} + \lambda_{14}) + (\lambda_9^{\tau_9} + \lambda_{10}^{\tau_{10}} + \lambda_{11}^{\tau_{11}} + \lambda_{12}^{\tau_{12}} + \lambda_{13}^{\tau_{13}} + \lambda_{14}^{\tau_{14}}) [1 - (\lambda_{15}^{\tau_{15}} + \lambda_{16}^{\tau_{16}} + \lambda_{17}^{\tau_{17}} + \lambda_{18}^{\tau_{18}} + \lambda_{19}^{\tau_{19}} + \lambda_{20}^{\tau_{20}} + \lambda_{21}^{\tau_{21}}) (\lambda_{15} + \lambda_{16} + \lambda_{17} + \lambda_{18} + \lambda_{19} + \lambda_{20} + \lambda_{21})]} \\
& + \frac{[1 - (\lambda_{22}^{\tau_{22}} + \lambda_{23}^{\tau_{23}} + \lambda_{24}^{\tau_{24}} + \lambda_{25}^{\tau_{25}})] (\lambda_{22} + \lambda_{23} + \lambda_{24} + \lambda_{25})}{(\lambda_{22}^{\tau_{22}} + \lambda_{23}^{\tau_{23}} + \lambda_{24}^{\tau_{24}} + \lambda_{25}^{\tau_{25}})} \\
& + \frac{[1 - (\lambda_{26}^{\tau_{26}} + \lambda_{27}^{\tau_{27}} + \lambda_{28}^{\tau_{28}} + \lambda_{29}^{\tau_{29}})] (\lambda_{26} + \lambda_{27} + \lambda_{28} + \lambda_{29})}{(\lambda_{26}^{\tau_{26}} + \lambda_{27}^{\tau_{27}} + \lambda_{28}^{\tau_{28}} + \lambda_{29}^{\tau_{29}})} \}
\end{aligned}$$

$$\tau_{EB} = (1 - A_{EB}) \left(\frac{1}{\tau_{EB}} \right)$$

Math Model for Emergency Bus (Contd) (Figure 10)

ANALYSIS OF THE "ZERO TIME OUTAGE" BUSES

The "zero time outage" (ZTO) busses supply instrumentation and control loads which cannot tolerate momentary power loss. There are two such busses (each with the same arrangement) which have as their normal source the 480 V ac emergency power bus. In addition, each bus is connected to a synchronous alternator that is floating on the line and will deliver power through flywheel inertia in event of momentary outages. The alternator is also driven by a dc motor and clutch from the 125 V dc system. The dc drive will provide alternator power for extended outages.

This arrangement of sources of power and equipment configuration results in a complicated reliability block diagram. The most difficult of analysis is the provision that B11 can supply the 125 V dc system in event of power failure to B17, but the reverse flow of power, from B17 to B11 is precluded. To facilitate the present analysis, this connection of B11 to supply the 125 V dc system is omitted. As a consequence, the results of the analysis will be pessimistic because this connection provides an additional path for success.

The reliability block diagram of the ZTO bus is shown in Figure 11 and the results of the analysis are as follows:

For one ZTO bus

Availability of power = 0.9999999615
(unavailability = 0.0385×10^{-6})

Mean-time-between-failure = 106,000,000 hr

Mean-time-to-restore = 5.12 hr

For any load on the ZTO bus

Availability of power = 0.9999831
(unavailability = 16.9×10^{-6})

Mean-time-between-failure = 220,000 hr

Mean-time-to-restore = 3.93 hr

FIGURE 11. Reliability Block Diagram "Zero Time Outage" Busses

FIGURE 11. (Contd)

FIGURE 11. (Contd)

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FIGURE 11. (Contd)

$$A_{ZTO} = (A_V A_m + A_X A_k - A_V A_m A_X A_k) + A_D^2 [(A_C A_k + A_f A_m - A_C A_k A_f A_m) - (A_V A_m + A_X A_k - A_V A_m A_X A_k)]$$

$$\begin{aligned} \frac{1}{\odot_{ZTO}} &= \frac{1 - \bar{A}_D^2}{\frac{\bar{A}_w A_t}{\odot_t} + \frac{\bar{A}_t A_w}{\odot_w}} + \frac{\bar{A}_D^2}{\frac{\bar{A}_y A_z}{\odot_z} + \frac{\bar{A}_z A_y}{\odot_y}} \\ &+ \frac{2\bar{A}_d A_d}{\odot_d} (A_j A_k \bar{A}_c \bar{A}_f + A_j A_k \bar{A}_c \bar{A}_m + A_q A_m \bar{A}_c \bar{A}_f + A_q A_m \bar{A}_f \bar{A}_k) \\ \tau_{ZTO} &= \frac{\bar{A}_{ZTO}}{A_{ZTO}} \odot_{ZTO} \end{aligned}$$

where

$$\bar{A}_c = 1 - A_c = (\lambda_1 \tau_1 + \lambda_2 \tau_2 + \lambda_3 \tau_3 + \lambda_4 \tau_4)(\lambda_5 \tau_5 + \lambda_6 \tau_6 + \lambda_7 \tau_7 + \lambda_8 \tau_8)$$

$$\bar{A}_d = 1 - A_d = \lambda_9 \tau_9 + \lambda_{10} \tau_{10} + \lambda_{11} \tau_{11} + \lambda_{12} \tau_{12}$$

$$\bar{A}_f = 1 - A_f = \lambda_{17} \tau_{17} + \lambda_{18} \tau_{18}$$

$$\begin{aligned} \bar{A}_j = 1 - A_j &= (\lambda_{19} \tau_{19} + \lambda_{20} \tau_{20} + \lambda_{21} \tau_{21} + \lambda_{22} \tau_{22} + \lambda_{23} \tau_{23} \\ &+ \lambda_{24} \tau_{24})(\lambda_{25} \tau_{25} + \lambda_{26} \tau_{26} + \lambda_{27} \tau_{27} + \lambda_{28} \tau_{28} \\ &+ \lambda_{29} \tau_{29} + \lambda_{30} \tau_{30} + \lambda_{31} \tau_{31}) \end{aligned}$$

$$\bar{A}_k = 1 - A_k = \lambda_{45} \tau_{45} + \lambda_{46} \tau_{46} + \lambda_{47} \tau_{47} + \lambda_{48} \tau_{48}$$

$$\bar{A}_m = 1 - A_m = \lambda_{53} \tau_{53} + \lambda_{54} \tau_{54} + \lambda_{55} \tau_{55} + \lambda_{56} \tau_{56}$$

$$\bar{A}_q = 1 - A_q = 1 - A_j [1 - (\lambda_{49} \tau_{49} + \lambda_{50} \tau_{50} + \lambda_{51} \tau_{51} + \lambda_{52} \tau_{52})]$$

$$\bar{A}_t = 1 - A_r = 1 - A_m (1 - \bar{A}_q \bar{A}_f)$$

Math Model for ZTO Bus (Figure 11)

$$\bar{A}_v = 1 - A_v = \bar{A}_q \bar{A}_f$$

$$\bar{A}_w = 1 - A_w = 1 - A_k (1 - \bar{A}_c \bar{A}_j)$$

$$\bar{A}_x = 1 - A_x = \bar{A}_c \bar{A}_j$$

$$\bar{A}_y = 1 - A_y = 1 - A_f A_m$$

$$\bar{A}_z = 1 - A_z = 1 - A_c A_k$$

$$\frac{1}{\odot_d} = \lambda_d = \lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12}$$

$$\frac{1}{\odot_t} = \lambda_t = (\lambda_{53} + \lambda_{54} + \lambda_{55} + \lambda_{56}) \left(\bar{A}_v \frac{\tau_q + \tau_f}{\tau_q \tau_f} \right)$$

$$\tau_f = \frac{\lambda_{17} \tau_{17} + \lambda_{18} \tau_{18}}{\lambda_{17} + \lambda_{18}}$$

$$\tau_q = \bar{A}_q \odot_q$$

$$\frac{1}{\odot_q} = (\lambda_{49} + \lambda_{50} + \lambda_{51} + \lambda_{52}) + \bar{A}_j \left(\frac{\tau_g + \tau_h}{\tau_g \tau_h} \right)$$

$$\tau_g = \frac{\lambda_{19} \tau_{19} + \lambda_{20} \tau_{20} + \lambda_{21} \tau_{21} + \lambda_{22} \tau_{22} + \lambda_{23} \tau_{23} + \lambda_{24} \tau_{24}}{\lambda_{19} + \lambda_{20} + \lambda_{21} + \lambda_{22} + \lambda_{23} + \lambda_{24}}$$

$$\tau_h = \frac{\lambda_{25} \tau_{25} + \lambda_{26} \tau_{26} + \lambda_{27} \tau_{27} + \lambda_{28} \tau_{28} + \lambda_{29} \tau_{29} + \lambda_{30} \tau_{30} + \lambda_{31} \tau_{31}}{\lambda_{25} + \lambda_{26} + \lambda_{27} + \lambda_{28} + \lambda_{29} + \lambda_{30} + \lambda_{31}}$$

$$\frac{1}{\odot_w} = (\lambda_{45} + \lambda_{46} + \lambda_{47} + \lambda_{48}) + \bar{A}_c \bar{A}_j \left(\frac{\tau_c + \tau_j}{\tau_c \tau_j} \right)$$

$$\tau_c = \frac{\tau_a \tau_b}{\tau_a + \tau_b}$$

$$\tau_a = \frac{\lambda_1 \tau_1 + \lambda_2 \tau_2 + \lambda_3 \tau_3 + \lambda_4 \tau_4}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4}$$

Math Model for ZTO (Contd)(Figure 11)

$$\tau_b = \frac{\lambda_5 \tau_5 + \lambda_6 \tau_6 + \lambda_7 \tau_7 + \lambda_8 \tau_8}{\lambda_5 + \lambda_6 + \lambda_7 + \lambda_8}$$

$$\tau_j = \frac{\tau_g \tau_h}{\tau_g + \tau_h}$$

$$\frac{1}{Q_z} = (\lambda_{45} + \lambda_{46} + \lambda_{47} + \lambda_{48}) + \frac{\bar{A}_c}{\tau_c}$$

$$\frac{1}{Q_y} = (\lambda_{17} + \lambda_{18} + \lambda_{53} + \lambda_{54} + \lambda_{55} + \lambda_{56})$$

ANALYSIS OF THE 125 V dc AND 24 V dc BUSES

The dc power systems contain three 125 volt dc busses and two 24 volt dc busses. Each of the busses is supplied from the normal 480 volt system and is automatically switched to the emergency bus if the normal supply fails. A third source for the dc busses is provided by batteries that are paralleled with the busses and are kept in the charged state by the normal power and a dc power supply. The load on the dc systems include critical instruments, emergency lights, and controls.

The sources of power and equipment arrangements are the same for the 125 V dc and the 24 V dc systems. The only difference occurs in the dc power supply and the battery. It is possible to use a lower voltage circuit breaker for the 24 volt dc system but the effect on the reliability analysis is insignificant.

The reliability block diagram for the 125 volt dc system is shown in Figure 12. The diagram is the same for the 24 volt dc system with the 125 volt equipment replaced by 24 volt units. The results of the analysis are as follows:

For the 125 volt dc bus

Availability of power = 0.999999966

(unavailability = 0.034×10^{-6})

Mean-time-between-failure = 54,000,000 hr

Mean-time-to-restore = 1.83 hr

For any load on the 125 volt bus

Availability of power = 0.99999797

(unavailability = 2.03×10^{-6})

Mean-time-between-failure = 495,000 hr

Mean-time-to-restore = 1 hr

FIGURE 12. Reliability Block Diagram 125 Volt Direct Current System

FIGURE 12. (Contd)

FIGURE 12. (Contd)

$$A_{DC} = 1 - \bar{A}_f \left\{ 1 - A_k [(1 - \bar{A}_e)(1 - \bar{A}_q \bar{A}_w) + \bar{A}_e A_c A_{45}] \right\}$$

$$\begin{aligned} \bar{\mathcal{Q}}_{DC} = \bar{A}_f \left\{ 1 - A_k [(1 - \bar{A}_e)(1 - \bar{A}_q \bar{A}_w) + \bar{A}_e A_c A_{45}] \right\} & \left\{ \frac{A_f \lambda_f}{\bar{A}_f} \right. \\ & + \frac{A_k (A_e A_s + \bar{A}_e A_o) [\lambda_k + A_e (\bar{A}_w A_q \lambda_q + \bar{A}_q A_w \lambda_w)]}{1 - A_k (A_e A_s + \bar{A}_e A_o)} \\ & \left. + \frac{\bar{A}_e (\lambda_c + \lambda_{45}) + \lambda_e (A_j A_{45} \bar{A}_c + A_q \bar{A}_c + A_q \bar{A}_{45})}{1} \right\} \end{aligned}$$

$$\tau_{DC} = \bar{A}_{DC} \bar{\mathcal{Q}}_{DC}$$

where

$$\begin{aligned} \bar{A}_c = 1 - A_c = (\lambda_1 \tau_1 + \lambda_2 \tau_2 + \lambda_3 \tau_3 + \lambda_4 \tau_4) (\lambda_5 \tau_5 + \lambda_6 \tau_6 \\ + \lambda_7 \tau_7 + \lambda_8 \tau_8) \end{aligned}$$

$$\bar{A}_e = 1 - A_e = (\lambda_9 \tau_9 + \lambda_{10} \tau_{10} + \lambda_{11} \tau_{11} + \lambda_{12} \tau_{12})^2$$

$$\bar{A}_f = 1 - A_f = \lambda_{17} \tau_{17} + \lambda_{18} \tau_{18}$$

$$\bar{A}_k = 1 - A_k = \lambda_{47} \tau_{47} + \lambda_{48} \tau_{48} + \lambda_{49} \tau_{49}$$

$$\begin{aligned} \bar{A}_j = 1 - A_j = (\lambda_{19} \tau_{19} + \lambda_{20} \tau_{20} + \lambda_{21} \tau_{21} + \lambda_{22} \tau_{22} + \lambda_{23} \tau_{23} \\ + \lambda_{24} \tau_{24}) (\lambda_{25} \tau_{25} + \lambda_{26} \tau_{26} + \lambda_{27} \tau_{27} + \lambda_{28} \tau_{28} \\ + \lambda_{29} \tau_{29} + \lambda_{30} \tau_{30} + \lambda_{31} \tau_{31}) \end{aligned}$$

Math Model for 125 Volt Direct Current (Figure 12)

$$\bar{A}_O = 1 - A_O = 1 - A_C(1 - \lambda_{45}^T \lambda_{45})$$

$$\bar{A}_q = 1 - A_q = 1 - A_j(1 - \lambda_{46}^T \lambda_{46})$$

$$\bar{A}_s = 1 - A_s = \bar{A}_q[1 - \lambda_{45}^T \lambda_{45}(1 - \bar{A}_C \bar{A}_j)]$$

$$\bar{A}_w = 1 - A_w = 1 - \lambda_{45}^T \lambda_{45} (1 - \bar{A}_C \bar{A}_j)$$

$$\bar{A}_{45} = 1 - A_{45} = \lambda_{45}^T \lambda_{45}$$

$$\lambda_f = \lambda_{17} + \lambda_{18}$$

$$\lambda_k = \lambda_{47} + \lambda_{48} + \lambda_{49}$$

$$\lambda_q = (\lambda_{19}^T \lambda_{19} + \lambda_{20}^T \lambda_{20} + \lambda_{21}^T \lambda_{21} + \lambda_{22}^T \lambda_{22} + \lambda_{23}^T \lambda_{23} + \lambda_{24}^T \lambda_{24})$$

$$(\lambda_{25} + \lambda_{26} + \lambda_{27} + \lambda_{28} + \lambda_{29} + \lambda_{30} + \lambda_{31})$$

$$[1 - (\lambda_{25}^T \lambda_{25} + \lambda_{26}^T \lambda_{26} + \lambda_{27}^T \lambda_{27} + \lambda_{28}^T \lambda_{28} + \lambda_{29}^T \lambda_{29}$$

$$+ \lambda_{30}^T \lambda_{30} + \lambda_{31}^T \lambda_{31})] + (\lambda_{25}^T \lambda_{25} + \lambda_{26}^T \lambda_{26} + \lambda_{27}^T \lambda_{27}$$

$$+ \lambda_{28}^T \lambda_{28} + \lambda_{29}^T \lambda_{29} + \lambda_{30}^T \lambda_{30} + \lambda_{31}^T \lambda_{31})(\lambda_{19} + \lambda_{20}$$

$$+ \lambda_{21} + \lambda_{22} + \lambda_{23} + \lambda_{24})[1 - (\lambda_{19}^T \lambda_{19} + \lambda_{20}^T \lambda_{20}$$

$$+ \lambda_{21}^T \lambda_{21} + \lambda_{22}^T \lambda_{22} + \lambda_{23}^T \lambda_{23} + \lambda_{24}^T \lambda_{24})] + \lambda_{46}$$

Math Model for 125 Volt Direct Current System (Contd)(Figure 12)

$$\lambda_w = \bar{A}_j \bar{A}_c \left(\frac{\tau_a \tau_b}{\tau_a + \tau_b} + \frac{\tau_g \tau_h}{\tau_g + \tau_h} \right) + \lambda_{45}$$

$$\tau_a = \frac{\lambda_1 \tau_1 + \lambda_2 \tau_2 + \lambda_3 \tau_3 + \lambda_4 \tau_4}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4}$$

$$\tau_b = \frac{\lambda_5 \tau_5 + \lambda_6 \tau_6 + \lambda_7 \tau_7 + \lambda_8 \tau_8}{\lambda_5 + \lambda_6 + \lambda_7 + \lambda_8}$$

$$\tau_g = \frac{\lambda_{19} \tau_{19} + \lambda_{20} \tau_{20} + \lambda_{21} \tau_{21} + \lambda_{22} \tau_{22} + \lambda_{23} \tau_{23} + \lambda_{24} \tau_{24}}{\lambda_{19} + \lambda_{20} + \lambda_{21} + \lambda_{22} + \lambda_{23} + \lambda_{24}}$$

$$\tau_h = \frac{\lambda_{25} \tau_{25} + \lambda_{26} \tau_{26} + \lambda_{27} \tau_{27} + \lambda_{28} \tau_{28} + \lambda_{29} \tau_{29} + \lambda_{30} \tau_{30} + \lambda_{31} \tau_{31}}{\lambda_{25} + \lambda_{26} + \lambda_{27} + \lambda_{28} + \lambda_{29} + \lambda_{30} + \lambda_{31}}$$

$$\lambda_c = \bar{A}_c \left(\frac{\tau_a + \tau_b}{\tau_a \tau_b} \right)$$

$$\lambda_e = \bar{A}_e \left(\frac{2 (\lambda_9 + \lambda_{10} + \lambda_{11} + \lambda_{12})}{\lambda_9 \tau_9 + \lambda_{10} \tau_{10} + \lambda_{11} \tau_{11} + \lambda_{12} \tau_{12}} \right)$$

Math Model for 125 Volt Direct Current System (Contd) (Figure 12)

For the 24 volt dc bus

Availability of power = 0.999999983

(unavailability = 0.017×10^{-6})

Mean-time-between-failure = 109,000,000 hr

Mean-time-to-restore = 1.85 hr

For any 24 volt dc load

Availability of power = 0.99999898

(unavailability = 2.02×10^{-6})

Mean-time-between-failure = 497,000 hr

Mean-time-to-restore = 1 hr

ANALYSIS OF THE 120 VOLT ALTERNATE CURRENT BUSES

There are two 120 volt ac busses that serve instrumentation and control loads and are associated with the "zero time outage" busses. However, they do not have the alternator source of the ZTO busses and are supplied by the 480 V ac emergency bus. The reliability diagram (Figure 13) for each of these 120 V ac busses is a series arrangement of circuit breaker, voltage regulator, and transformer connected to the emergency bus. In effect, this is a connected load of the 480 volt emergency bus with the additional components mentioned above.

For one 120 volt bus

Availability of power = 0.9999558

(unavailability = 44.2×10^{-6})

Mean-time-between-failure = 100,000 hr

Mean-time-to-restore = 4.4 hr

Math Model of 120 V Bus

$$\bar{A}_S = \lambda_1 \tau_1 + \lambda_2 \tau_2 + \lambda_3 \tau_3 + \lambda_4 \tau_4$$

$$\bar{Q}_S = \frac{1}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4}$$

$$\tau_S = \frac{\bar{A}_S \bar{Q}_S}{A_S}$$

FIGURE 13. Reliability Block Diagram 120 Volt Instrument and Control Busses

ANALYSIS OF THE STATION SERVICE

Power for the Station Service is utilized at 125 volts dc. The normal supply for the Station Service is redundant circuits each with a circuit breaker, cable, and 13.8 kV/480 V 300 kVA transformer. The 480 V is then converted to 125 V dc by a power supply. An alternative source for the Station Service is a 125 V battery which is floating on the bus and kept in the charged state by the dc power supply. The load on the Station Service includes the operating coils of the 13.8 kV, 2.4 kV, and 480 V switchgear, interlocks, relays, and substation lighting.

The reliability block diagram for the Station Service is shown in Figure 14, and the results of the analysis are as follows:

For the Station Service dc Bus

Availability of Power = 0.999999966

(unavailability = 0.034×10^{-6})

Mean-time-between-failures = 55,000,000 hr

Mean-time-to-restore = 1.88 hr

For any Load on the Station Service

Availability of power = 0.999998

(unavailability = 2×10^{-6})

Mean-time-between-Failure = 500,000 hr

Mean-time-to-restore = 1 hr

FIGURE 14. Reliability Block Diagram for Station Service

$$A_s = 1 - \left\{ (\lambda_{21}\tau_{21} + \lambda_{22}\tau_{22}) \left[1 - [1 - (\lambda_{23}\tau_{23} + \lambda_{24}\tau_{24} + \lambda_{25}\tau_{25})] [1 - (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4 + \lambda_5\tau_5 + \lambda_6\tau_6 + \lambda_7\tau_7 + \lambda_8\tau_8 + \lambda_9\tau_9 + \lambda_{10}\tau_{10})^2] \right] \right\}$$

$$\begin{aligned} \frac{1}{\tau_s} = (\lambda_{21} + \lambda_{22}) & \left\{ 1 - [1 - (\lambda_{23}\tau_{23} + \lambda_{24}\tau_{24} + \lambda_{25}\tau_{25})] \right. \\ & [1 - (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4 + \lambda_5\tau_5 + \lambda_6\tau_6 \\ & + \lambda_7\tau_7 + \lambda_8\tau_8 + \lambda_9\tau_9 + \lambda_{10}\tau_{10})^2] \\ & + (\lambda_{21}\tau_{21} + \lambda_{22}\tau_{22}) \left\{ (\lambda_{23} + \lambda_{24} + \lambda_{25}) + [2 (\lambda_1 \right. \\ & + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8 + \lambda_9 + \lambda_{10}) \\ & (\lambda_1\tau_1 + \lambda_2\tau_2 + \lambda_3\tau_3 + \lambda_4\tau_4 + \lambda_5\tau_5 + \lambda_6\tau_6 + \lambda_7\tau_7 \\ & + \lambda_8\tau_8 + \lambda_9\tau_9 + \lambda_{10}\tau_{10})] \left. \right\} \end{aligned}$$

$$\tau_s = \bar{A}_s \tau_s$$

Math Model for Station Service (Figure 14)

EFFECTS OF BUILDING ELECTRICAL POWER SYSTEM
FAILURES ON REACTOR AVAILABILITY

The emergency power busses represent the only significant equipment in System 12 that will have an effect on reactor availability. To determine reactor unavailability it is assumed that any failure in either of the two normal sources to the emergency busses will cause the reactor to be shutdown. The expected reactor downtime caused by failures in the emergency busses (per 1000 hours of operation) is:

$$\sum \lambda_i D_i (1000) = 0.76 \text{ hr}$$

where D_i is the component repair time plus the one hour required for the reactor to recover from a shutdown.

It is possible to operate the reactor and the FFTF with a failure in one of the normal sources of power to the emergency busses. However, present plans and procedures require that the reactor be shutdown automatically during such a condition. Any revisions in this procedure or changes in the conceptual configuration of System 12 equipment, will necessitate reevaluation of the above reactor unavailability.

NOMENCLATURE

A = Availability of component or system

$\bar{A}$ = Unavailability of component or system

$$A = 1 - \bar{A}$$

λ = Failure rate of component or system

Θ = Mean-time-between-failure of a component or system

$$\Theta = \frac{1}{\lambda} \text{ for the exponential distribution}$$

τ = Mean-time-to-restore a component or system that has failed

MTBF = Mean-time-between-failure

MTTR = Mean-time-to-restore

Legend for Block Diagrams

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