Reliability Block Diagram Simulation Techniques Applied to the IEEE Std. 493 Standard Network

Wendai Wang, James M. Loman, *Member, IEEE*, Robert G. Arno, Pantelis Vassiliou, Edward R. Furlong, and Doug Ogden

***Abstract*—This is one of a series of papers discussing the application and accuracy of different analysis techniques supporting the determination of industrial and commercial power system reliability and availability. There is a need recognized in the power industry to identify and utilize a standard tool, or a set of tools, to analyze the reliability of power systems. Historically, the results of applying different reliability methodologies and tools varied significantly, and comparisons were difficult. The Reliability Analysis Techniques Working Group of the Gold Book (IEEE Std. 493–1997) developed a standard network to enable comparison of analytical techniques. This paper describes the approach of simulations via reliability block diagrams as applied to the Gold Book standard network. Reliability indexes of the load points are presented, and are compared with ones obtained from other techniques in the series to determine the accuracy.**

***Index Terms*—Availability, industrial, interruptions, network reliability, power system, reliability, simulations.**

I. INTRODUCTION

THE Power Reliability Enhancement Program (PREP) of the U.S. Army Corps of Engineers sponsored a survey effort to determine the various reliability/availability (R/A) analysis software tools available for utility, commercial, and industrial electrical and mechanical R/A analysis [1]. The research indicated that users were utilizing a wide variety of tools and techniques with different analysis results. Furthermore, the only recommended methodology presented in IEEE Std 493 since 1980 was the "series and parallel" reliability methodology and the minimal cut-set method which estimated the frequency and duration of load point interruptions [2].

The different approaches identified in [1] include:

- Zone Branch;
- Reliability Block Diagram;
- Event Tree;
- Monte Carlo (and Discrete Event Simulations);
- Boolean Algebra;
- FMECA;
- Cut Set.

These analytical approaches are applied to the IEEE Gold Book standard network in a series of papers to determine the accuracy of their results and how closely they can verify operational anomalies [3]–[5].

Other approaches applicable to R/A analysis of industrial and commercial power systems are the following:

- Path Set;
- Fault Tree;
- Markov Model;
- Petri Nets.

This paper addresses the simulation approach as applied through a reliability block diagram (RBD). Results are compared with ones from other papers.

II. IEEE GOLD BOOK STANDARD NETWORK

A standard network is required to enable comparisons between different methodologies. After examination of various actual industrial and commercial power system network configurations, the single-line diagram of the Gold Book standard network was defined [3], as shown in Fig. 1. The equipment reliability data corresponding to each labeled component of the network is listed in Table I.

Two independent 15-kV primary distribution feeders, as shown in Fig. 1, supply the standard network. There are four diesel engine generators at the facility, where two out of four generators are required to meet the network load demands at all times. The reliability indexes of the load points, as shown in Fig. 1 (Outputs A, B1, B2, C, D, E, F, G1, G2, H, and I), are evaluated by the methodology of simulation via RBD in this paper.

The following assumptions are to be used by any reliability methodology applied to the Gold Book standard network.

- Failure and repair times are exponentially distributed.
- Actual cable lengths are indicated on the drawings; modify failure rate accordingly. *Example:*

$$\begin{aligned}&\text{actual cable failure rate}\\&=\text{cable failure rate per rated length}\\&\quad\times\text{actual cable length indicated on the drawing.}\end{aligned}$$

- "M" denotes manual operation and is allocated 15 min for activation.
- Required generators are two out of four.

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W. Wang and J. M. Loman are with the GE Global Research Center, Niskayuna, NY 12309 USA (e-mail: wang@research.ge.com; loman@research.ge.com).

R. G. Arno is with Alion Science and Technology, Rome, NY 13440 USA (e-mail: rarno@alionscience.com).

P. Vassiliou and D. Ogden are with ReliaSoft Corporation, Tucson, AZ 85710 USA (e-mail: Pantelis.Vassiliou@ReliaSoft.com; Doug.Ogden@ReliaSoft.com).

E. R. Furlong is with GE Industrial Systems, Edison, NJ 08817 USA (e-mail: Ted.Furlong@indsys.ge.com).

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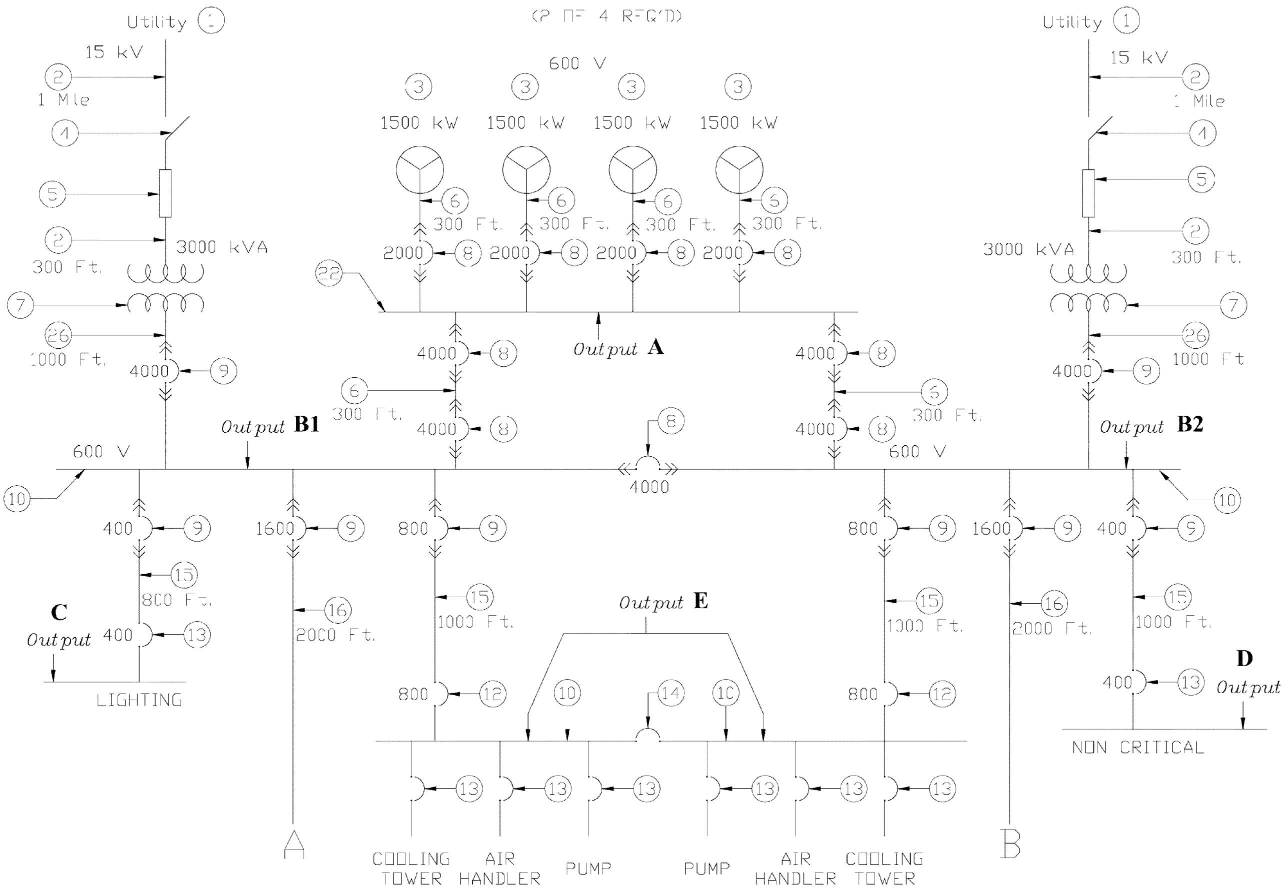

Fig. 1. One-line diagram of IEEE Gold Book standard network.

- The UPSs are redundant.
- The PDU transformers are redundant.
- Terminations and splices, while normal for all systems, are not included on the drawings, and are not included in the calculations.
- The assumed breaker failure modes are 50% open and 50% short.

One of the key reliability indexes for industrial and commercial customers is the frequency and duration of load point interruptions within their facility.

The following reliability indexes are evaluated:

- frequency of load point interruptions (interruptions per year);
- annual duration of load point interruptions (hours per year);
- average duration of load point interruptions (hours per interruption);
- availability level of power supply to the load point.

III. METHODOLOGY

Generally, system reliability depends on the: 1) reliability and maintainability of its components (including failure and repair time distributions, failure modes and effects, and environment effects); 2) system design (configuration or topology, dependency, and failure detection); and 3) system behavior (operational characteristics, switching procedure, and maintenance services).

A reliable equipment data source is key to an accurate analysis. Data sources such as the IEEE Gold Book and the PREP database, partly shown in Table I, provide the user with the necessary data to evaluate the reliability of power system network configurations. These two equipment reliability data sources are based on extensive surveys over many years. An understanding of component reliability and maintenance actions provides the necessary background to determine the availability value of the reliability approach. If actual data recorded from the facility or vendor are available, it is better to proceed with analysis using these data. However, component reliability information (equipment data) is not a topic of this series of papers. This study focuses on, having component reliability information, and from the component reliability information, creating the system level reliability model, based on system design and behavior.

Since industrial and commercial power systems are complex (large number of components or equipment, redundant networks, complicated operation) and repairable, reliability analysis becomes difficult. In general, no closed-form solutions to system reliability quantities of interest exist.

Usually, there are two steps to find the system reliability indexes: 1) constructing the system reliability model and 2) analyzing the model.

A system reliability model accommodates the system configuration and its behaviors. Of course, the answer relies on how accurately the system configuration and its behaviors are understood, and what assumptions are made and adopted. It also relies on what modeling method and tool are used.

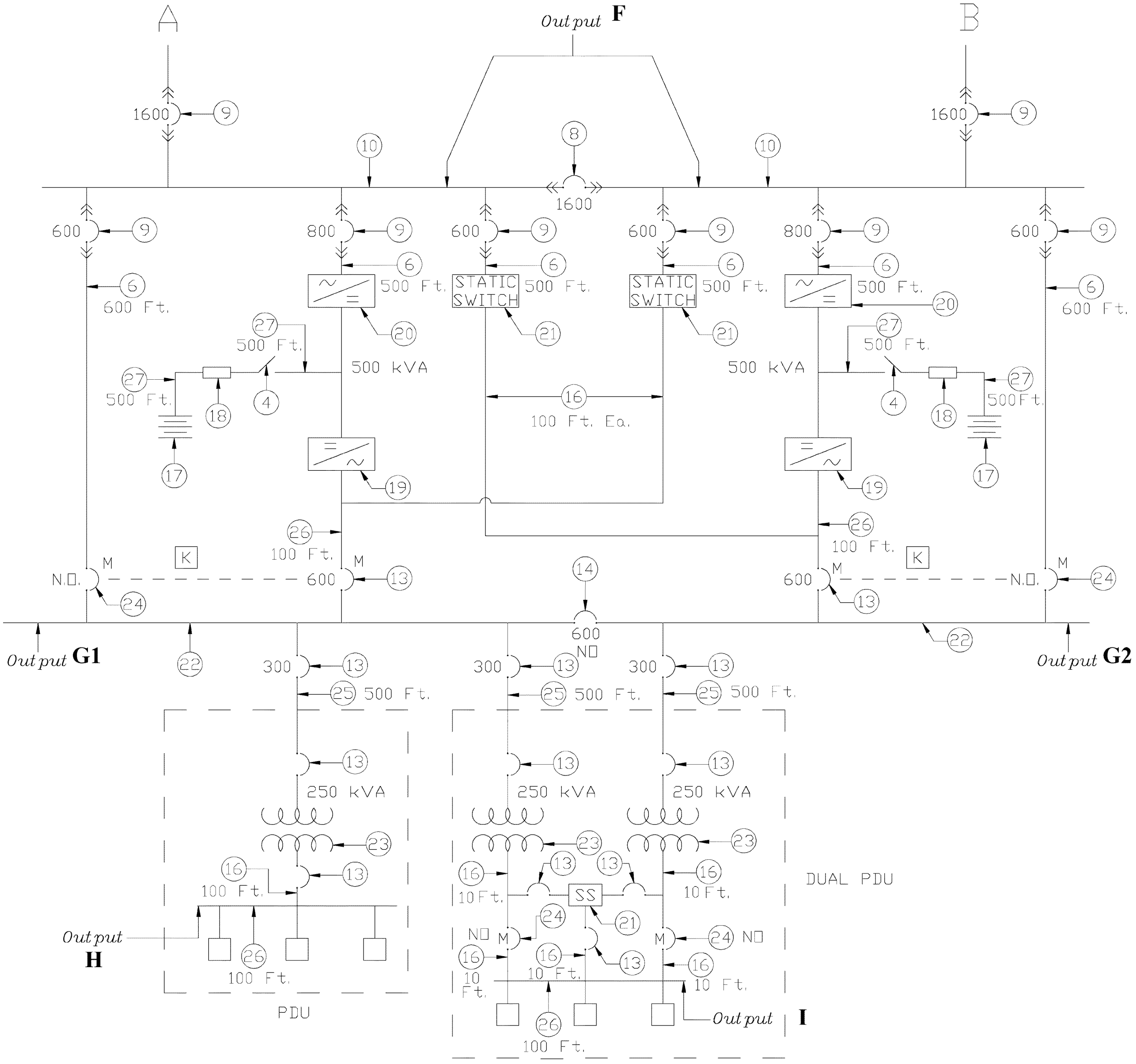

Fig. 1. (*Continued.*) One-line diagram of IEEE Gold Book standard network.

The RBD method has been found to be a practical reliability modeling method for industrial and commercial power systems [6]. It is a graphical presentation of a system diagram in reliability-wise or functional logic; i.e., connecting subsystems or components according to their function or reliability relationship. The virtue of RBD is that it is easy to read. It is readily understood by customers who purchase the critical power systems, by the people who sell the systems, by engineers who design and test the systems, and by managers who make decisions on the systems. With knowledge of the system design (such as a one-line drawing), engineers can easily construct, verify, and modify the RBD, and also communicate with those of different disciplines.

RBD has traditionally been used for nonrepairable systems with mathematics—structure function—behind it. With the structure function, the system reliability indexes can be obtained analytically. However, the structure function can only be applied to certain system configuration and system behaviors. For example, it does not capture inter- and sequence-dependent behavior and repair. For complex repairable systems, the structure function that can be obtained through the RBD becomes intractable. On the other hand, the RBD approach opens up degrees of freedom in model construction. Without being worried about the analysis, one can easily model the behavior of the most complex repairable systems, just by connecting components using the functional logic.

Many analysis methods (approximations) have been used to solve the reliability model. When an exact computation is intractable, simulation methods (discrete event simulations) can be employed to obtain solutions to complex repairable systems constructed using an RBD approach. Simulation technique provides a powerful tool that enables engineers and managers to study system behavior and performance, and to understand how internal and external factors impact system reliability [6].

TABLE I
EQUIPMENT RELIABILITY DATA FOR GOLD BOOK STANDARD NETWORK CONFIGURATION

REF#	ITEM DESCRIPTION	PREP, ITEM #	MTTR (hours)	Failure rate, failure/year
1	Single Circuit Utility Supply, 1.78 failures/unit year, A =0.999705, Gold Book p. 107	NA	1.32	1.956
2	Cable Arial, ≤ 15kV, per mile	32	1.82	0.04717
3	Diesel Engine Generator, Packaged, Standby, 1500kW	98	18.28	0.1235
4	Manual Disconnect Switch	187	1.0	0.00174
5	Fuse, 15kV	117	4.0	0.10154
6	Cable Below Ground in conduit, ≤ 600V, per 1000 ft	47	11.22	0.00201
7	Transformer, Liquid, Non Forced Air, 3000kVA	208	5.0	0.00111
8	Ckt. Breaker, 600V, Drawout, Normally Open, > 600 Amp	68	2.0	0.00553
9	Ckt. Breaker, 600V, Drawout, Normally Closed, >600 Amp	69	0.5	0.00185
10	Switchgear, Bare Bus, 600V	191	7.29	0.00949
11	Ckt. Breaker, 600V Drawout, Normally Closed, < 600 Amp	67	6.0	0.00021
12	Ckt. Breaker, 600V, Normally Closed, > 600 Amp, Gold Book p. 40	63	9.6	0.0096
13	Ckt. Breaker, 3 Phase Fixed, Normally Closed, ≤ 600 Amp	61	5.8	0.0052
14	Ckt. Breaker, 3 Phase Fixed, Normally Open, > 600 Amp	62	37.5	0.00343
16	Cable, Above Ground, Trays, ≤ 600V, per 1000 ft., Gold Book p.105		10.5	0.00141
18	Fuse, 0 - 5kV	115	4.0	0.00137
21	Static Switch, 0 -- 600 Amp, <= 600V	210	2.0	0.00105
22	Switchgear, Insulated Bus, ≤ 600V	194	2.4	0.0017
23	Transformer, Dry, Isolation, < 600V	132	21.26	0.00284
24	Ckt, 3 Phased Fixed, Normally Open	60	18.67	0.00011
25	Cable, Above Ground, In Conduit, <=600V, per 1000ft	18	8.0	0.00007
26	Bus Duct, Gold Book p.206, per Circuit foot		12.9	0.000125
27	Cable, Insulated, DC, per 1000ft	49	2.0	0.00728

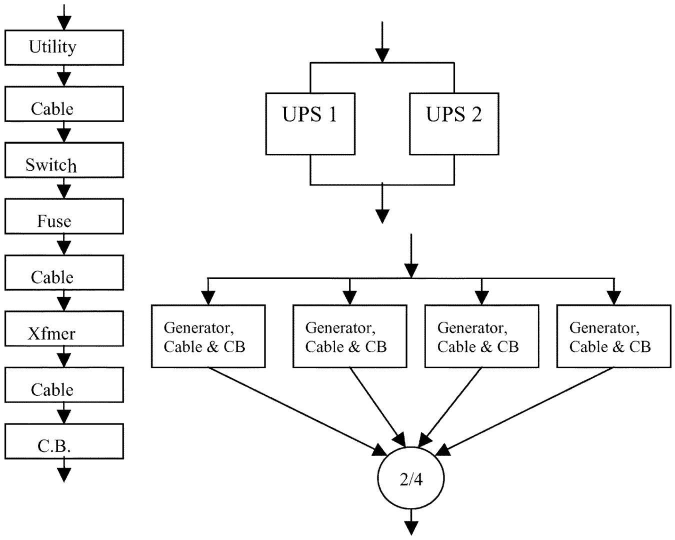

Fig. 2. Examples of RBDs.

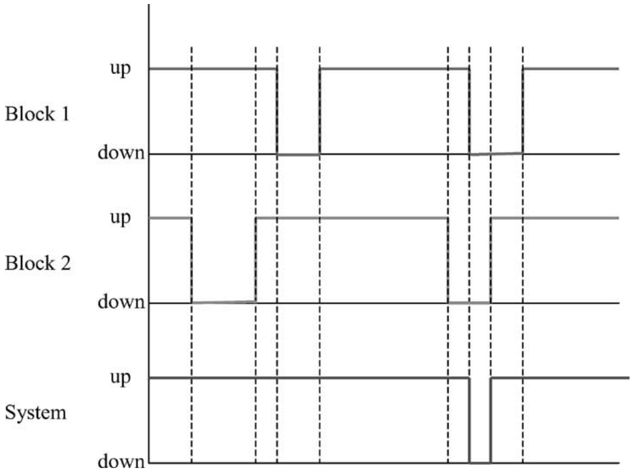

Fig. 3. A simulated "history" of a two-unit-parallel system.

A. Constructing the Reliability Block Diagram

An RBD presents a logical or function relationship of the system components. It is a graphic representation of the components and how they are reliability-wise (functionally) related (connected). A block physically represents a component or subsystem. The logic diagram is arranged to indicate which combinations of component failures result in the failure of the system, or which combinations of components working properly keep the system operating. Therefore, RBDs are based on system design, operation and maintenance procedures, and analysis of component failure effects. A block in an RBD also represents

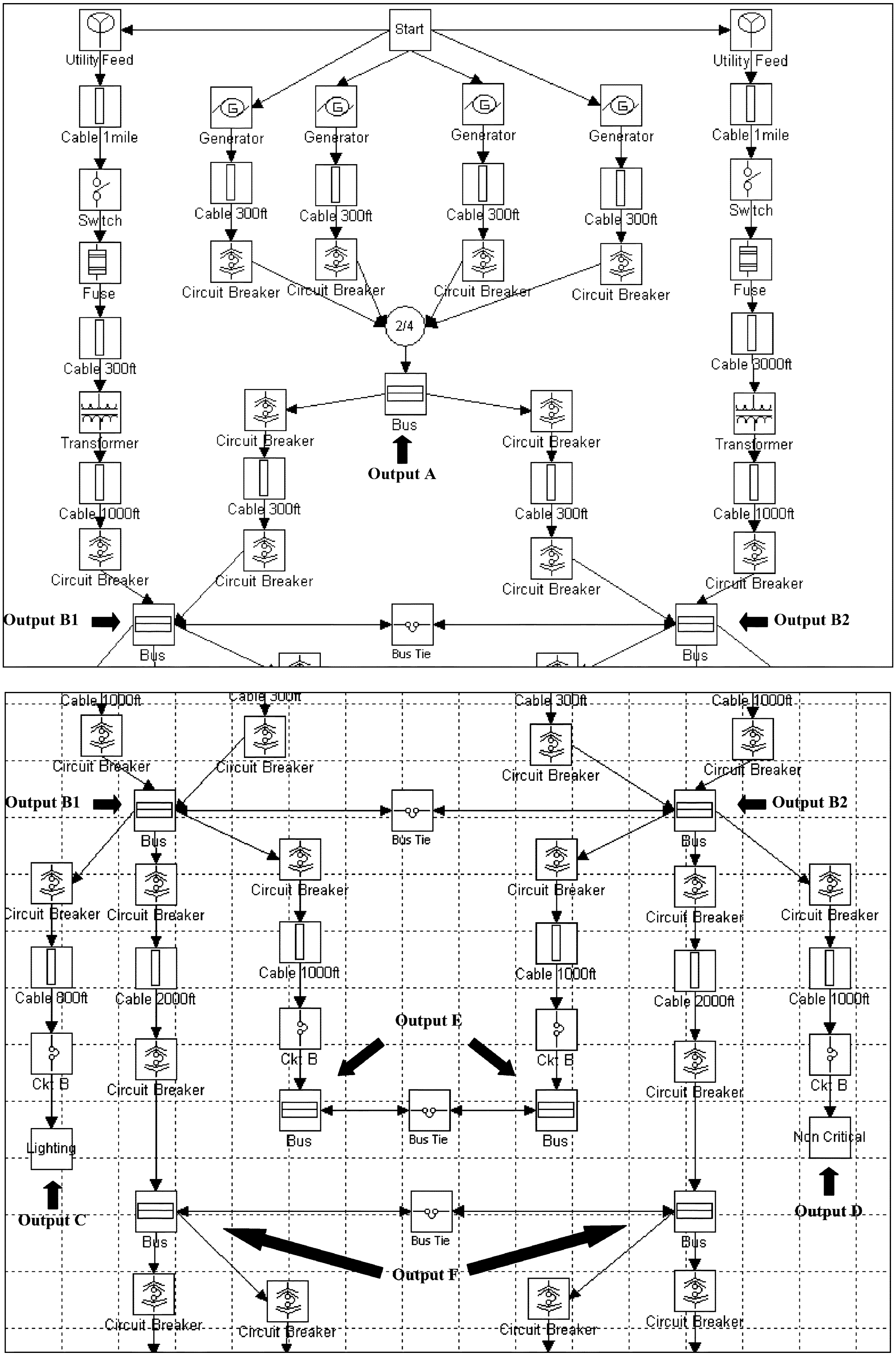

Fig. 4. RBD of the IEEE Gold Book standard network.

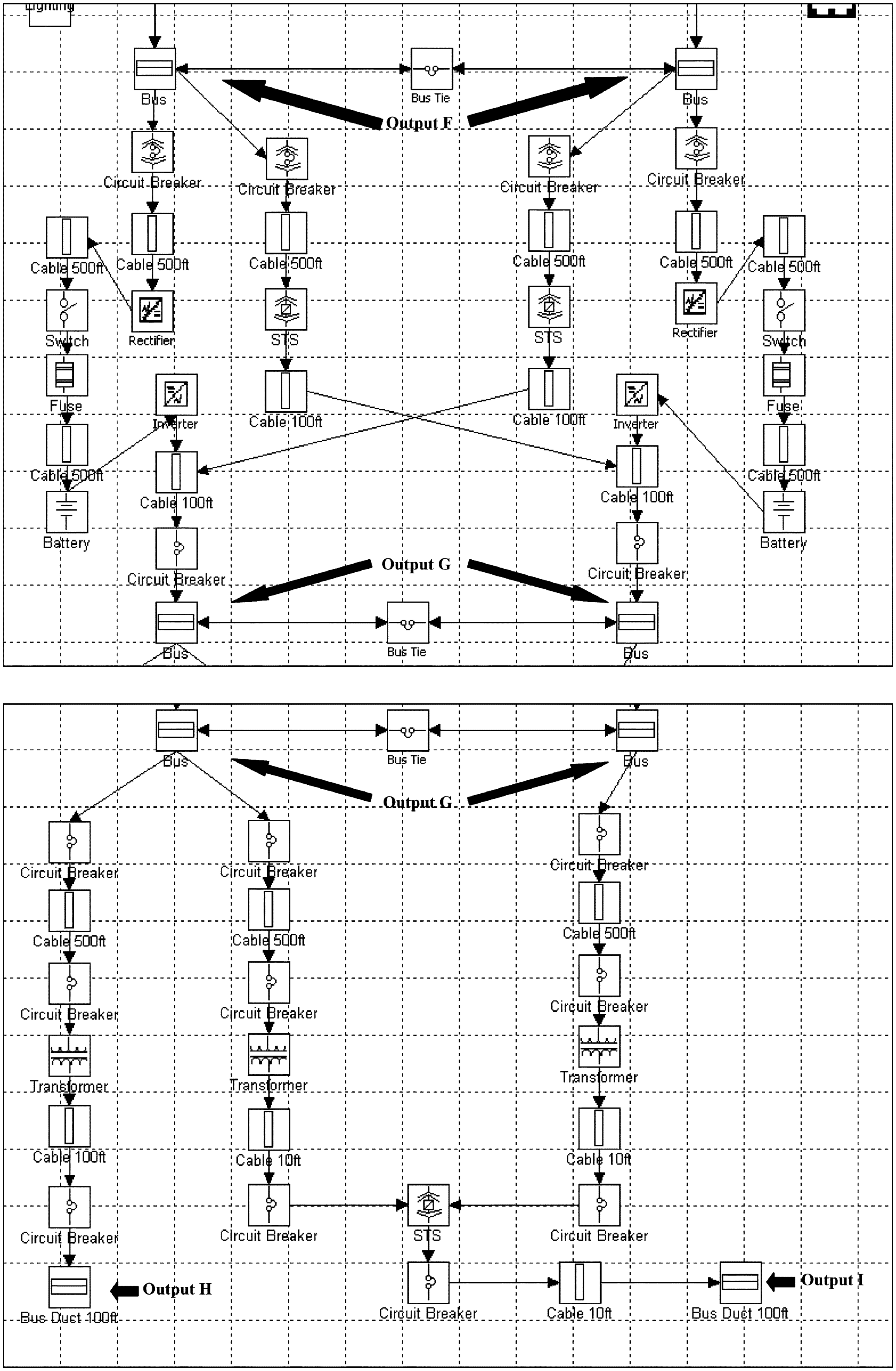

Fig. 4. (*Continued.*) RBD of the IEEE Gold Book standard network.

TABLE II
RELIABILITY INDEXES AT OUTPUT LOAD POINTS

Output Location	Frequency of Interruptions, 1/yr	Average Interruption, hrs	Annual Down Time, hrs	Inherent Availability
A -- Generator Bus	0.018244077	2.037723563	0.0371424	0.99999576
B -- Main Switchgear Bus	0.018781976	4.372200422	0.0820812	0.99999063
C -- Lighting Bus	0.022393451	4.388099240	0.0982872	0.99998878
D -- Non-Critical Bus	0.022319450	4.394270450	0.0981120	0.99998880
E -- Mechanical Switchgear	0.023668803	9.423628664	0.2230296	0.99997454
F -- Switchboard Bus	0.015863339	4.830980165	0.0766500	0.99999125
G – UPS Output Bus	0.011206145	10.147775420	0.1137048	0.99998702
H -- Single PDU Output	0.035461812	8.445709521	0.2995044	0.99996581
I -- Dual PDU Output	0.014409536	5.750544601	0.0828696	0.99999054

* Results are based on 10 000 simulations only for each load point

TABLE III
ANALYSIS RESULTS FROM DIFFERENT METHODS

Frequency of Interruptions, 1/yr	RBD	Zone-Branch	GO	Cut Set
A -- Generator Bus	0.018244077	2.106450	-	0.015530000
B -- Main Switchgear Bus	0.018781976	2.248535	-	0.017895008
C -- Lighting Bus	0.022393451	2.253936	-	0.020696008
D -- Non-Critical Bus	0.022319450	2.253960	-	0.012315000
E -- Mechanical Switchgear	0.023668803	2.276470	-	0.023841493
F -- Switchboard Bus	0.015863339	-	-	-
G – UPS Output Bus	0.011206145	-	-	-
H -- Single PDU Output	0.035461812	-	-	-
I -- Dual PDU Output	0.014409536	-	-	-

Average Interruption, hrs	RBD	Zone-Branch	GO	Cut Set
A -- Generator Bus	2.037723563	1.460191	-	2.043786220
B -- Main Switchgear Bus	4.372200422	2.169794	-	4.595114239
C -- Lighting Bus	4.388099240	2.178369	-	4.743891002
D -- Non-Critical Bus	4.394270450	2.178373	-	7.387812026
E -- Mechanical Switchgear	9.423628664	2.273392	-	9.484818415
F -- Switchboard Bus	4.830980165	-	-	-
G – UPS Output Bus	10.147775420	-	-	-
H -- Single PDU Output	8.445709521	-	-	-
I -- Dual PDU Output	5.750544601	-	-	-

Annual Down Time, hrs	RBD	Zone-Branch	GO	Cut Set
A -- Generator Bus	0.0371424	3.074739	-	0.0317400
B -- Main Switchgear Bus	0.0820812	4.876143	-	0.0822296
C -- Lighting Bus	0.0982872	4.907155	-	0.0981796
D -- Non-Critical Bus	0.0981120	4.907215	-	0.0909809
E -- Mechanical Switchgear	0.2230296	5.172254	-	0.2261322
F -- Switchboard Bus	0.0766500	-	-	-
G – UPS Output Bus	0.1137048	-	-	-
H -- Single PDU Output	0.2995044	-	-	-
I -- Dual PDU Output	0.0828696	-	-	-

Inherent Availability	RBD	Zone-Branch	GO	Cut Set
A -- Generator Bus	0.99999576	0.999649	0.99999630	0.99999638
B -- Main Switchgear Bus	0.99999063	0.999443	0.99999123	0.99999061
C -- Lighting Bus	0.99998878	0.999440	0.99998769	0.99998879
D -- Non-Critical Bus	0.99998880	0.999440	0.99998768	0.99998961
E -- Mechanical Switchgear	0.99997454	0.999410	0.99998860	0.99997419
F -- Switchboard Bus	0.99999125	-	-	-
G – UPS Output Bus	0.99998702	-	-	-
H -- Single PDU Output	0.99996581	-	-	-
I -- Dual PDU Output	0.99999054	-	-	-

- Results are not available

the physical component working well, and the failure of this component is indicated by the removal of the corresponding block. If enough blocks are removed in an RBD to interrupt the connection between the input and output points, the system has failed. In other words, if there is at least one path connecting between input and output points, the system is still operating properly. For example, in the IEEE standard network, electric power to main switchgear B1 from the utility feeder requires all components between these two points; i.e., cable line (1 mile), disconnect switch, fuse, cable line (300 ft), transformer, cable line (1000 ft), and circuit breaker, working properly. If any of these components fails, no power feeds to the main switchgear (B1) from the utility (no path from utility to B1). Therefore, the RBD representing this function would be a series of blocks that represent these components, just like the actual physical connection, as shown in the left diagram of Fig. 2. If there are two UPSs in parallel, any one of them can fully power their load and failure of one UPS does not affect operation of the other UPS; an RBD of two blocks (UPS) in parallel will represent this configuration, as shown in the upper right diagram of Fig. 2.

Another simple example is that of generators in the IEEE standard network. There are four diesel generators at the facility where two out of four generators are required to meet the network load demands. When any one or two generators fail, the generator switchgear still has enough power input. It is a 2-out-of-4:G configuration, and looks like a parallel connection, as shown in the lower right diagram of Fig. 2.

It is easy for engineers to construct the RBD model of a power system—just by connecting all paths with components required in each path to the load point. Although the RBD may differ from physical connections in general, the RBD of an industrial and commercial power system is pretty similar to configuration on its one-line drawing with only a few exceptions such as k-out-of-n:G and standby designs.

B. Analyzing Complex Repairable System RBD

For a repairable system, which is the case of commercial and industrial power systems, an RBD model does not provide any computing method behind it. Only series or parallel structures can be calculated directly, which is network reduction method in current version of the Gold Book. Actually, that method can only handle the exponential case and steady-state (long-term) solutions. Several methods, such as merging, truncation, R-M, and decomposition, have been used to seek approximation of system reliability quantities [6].

Simulation provides the “exact” solutions to system reliability. Once the RBD of a system is determined, simulation is straightforward. The concept of simulation is simple: it’s just a series of numerical experiments on RBD. An “actual” realization of states is simulated on each block. During its course of a block, events (working or failing) are made to occur at times determined by random processes obeying failure or repair time distributions of the block (component). A system realization is then composed according to all blocks’ realizations and the RBD (system design). After having observed histories of many identical systems, estimates are made of the desired reliability indexes statistically. Fig. 3 shows an example of one trial of two blocks in parallel.

Life histories of two blocks are simulated, and then a system (failure-operation) history is assembled through examining the system states over the time. When a large number of experiments (system histories) have been created, all reliability indexes can be obtained easily and with satisfactory accuracy. Theoretically, an infinite number of trials would result in the true value of. Obviously, a computer program is needed to perform a large number of simulations to reach an acceptably accurate result. Fortunately, there are many reliability simulation software packages available of varying modeling capabilities, such as ReliaSoft’s BlockSim (used in the analysis in this paper), Relex’s RBD, IsographDirect’s AvSim+, ITEM’s RBD, Clockwork’s ENRiCO, ARINC’s Raptor, Data Solutions’ RBDA, and others. Among these software packages, ReliaSoft’s BlockSim is capable of handling and modeling a large, repairable system. Additionally, through it’s intuitive interface it can be easily used for industrial and commercial power systems. With simple drag and drop techniques, users can easily define a power system utilizing a RBD and, through a fast and efficient built-in simulation engine, required reliability indexes can be easily obtained.

IV. CASE STUDY—APPLY RBD AND SIMULATIONS TO THE IEEE NETWORK

This section performs the inherent availability analysis on the IEEE Gold Book Standard Network System, using the method described in this paper, and also shows the obtained results. To simplify the analysis, manual switches and maintenance paths are not included in this analysis. An RBD representing this standard network has been developed using BlockSim, as seen in Fig. 4, with input data of each block from Table I. Based on the equipment reliability data, the frequency and duration of interruptions for each load point being served by this power system have been evaluated (calculated through simulations) and listed in Table II.

V. CONCLUSION

The results of the analysis, through simulation on the RBD representing the IEEE Gold Book standard network, are obtained, which can then be compared to results obtained from other methods/tools, as seen in Table III.

Simulation via RBD is a practical and applicable technique in determination of industrial and commercial powers system reliability and availability. Primary advantages of this method include the following:

1) easily model large, repairable systems;
2) no restrictions on the failure, repair, and other time distributions in the system;
3) dependent relations between the failure, repair, and other events easily accounted for;
4) easy to construct, understand, modify, and incorporate any system additions;
5) all reliability indexes are obtainable;
6) solutions of reliability indexes to RBD are “exact” (accurate);
7) both long-term and short-term solutions easily obtained.

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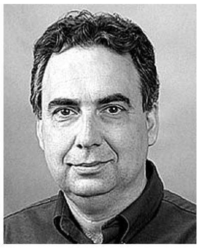
Wendai Wang received the B.S. and M.S. degrees in mechanical engineering from Shanghai Jiaotong University, Shanghai, China, and the Ph.D. degree in reliability engineering from the University of Arizona, Tucson.

He works in the area of electronic and photonics systems at the General Electric Global Research Center, Niskayuna, NY. He has more than 15 years working experience in reliability and maintainability engineering. His research interests include system reliability and availability reliability prediction, life testing, ALT/ADT, HALT/HAST, reliability data analysis, physics-of-failure, and probabilistic design.



James M. Loman (M'97) received the B.S. degree from Villanova University, Villanova, PA, the M.S. degree from the University of Notre Dame, Notre Dame, IN, and the Ph.D. degree from the University of Delaware, Newark, all in physics.

He is the Manager of the Advanced Photonics and Electronics Laboratory of the General Electric Global Research Center, Niskayuna, NY. He is the author of over 30 publications and patents. He has been a leader of GE's "Design for Reliability" initiative that has been an integral part of the well-known GE Six Sigma Quality initiative.

Dr. Loman is a Certified Six Sigma Master Black Belt and a Certified Reliability Engineer.

Robert G. Arno received the B.S. degree in electrical engineering from the State University of New York at Utica/Rome in 1982.

He has worked in the reliability field for 25 years, joining IIT Research Institute, Rome, NY, in 1977. His principal responsibilities include program management, electrical and mechanical system analysis and modeling, and data collection and analysis. He is currently with Alion Science and Technology, Rome, NY.

Mr. Arno is a Member of the Mohawk Valley Chapter of the American Society for Quality Control.

Pantelis Vassiliou received the M.S. degree in reliability engineering from the University of Arizona, Tucson.

He is with ReliaSoft Corporation, Tucson, AZ, where he directs R&D efforts to deliver state-of-the-art software tools for applying reliability engineering concepts and methodologies. He is the original architect of ReliaSoft's Weibull++, a renowned expert and lecturer on reliability engineering, and ReliaSoft's founder. He is currently spearheading the development of new technologically advanced products and services.

Edward R. Furlong received the B.S. degree from The University of Texas at Arlington, and the M.S. degree and the Ph.D. degree in mechanical engineering with an electrical engineering minor from Stanford University, Stanford, CA.

His field of research is advanced diagnostic systems for real-time control applications. He began his career with General Electric in 1998 when he joined the GE Corporate Research and Development Center. There, he developed laser-based diagnostics, active control systems, and advanced combustion systems for GE aircraft engines and power systems. He currently serves as a Technology Manager for GE Industrial Systems, Edison, NJ.

Doug Ogden currently serves as Vice President of Corporate Relations for ReliaSoft Corporation, Tucson, AZ, and is spearheading the adaptation of reliability programs, analysis software, and custom data acquisition systems for Fortune 500 companies worldwide.