

IN-38

7037

88

DOE/NASA/20370-23
NASA TM-102378

Model 0A Wind Turbine Generator FMEA

William E. Klein
National Aeronautics and Space Administration
Lewis Research Center
Plum Brook Station

and

Vincent R. Lalli
National Aeronautics and Space Administration
Lewis Research Center

Work performed for

U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division

Prepared for the
1990 Annual Reliability and Maintainability Symposium
cosponsored by the ASME, ASQC, IIE, IEEE, SOLE,
IES, AIAA, SSS, and SRE
Los Angeles, California, January 23-25, 1990

(NASA-TM-102378) MODEL 0A WIND TURBINE
GENERATOR FMEA Final Report (NASA) 8 p
CSCL 10A

N90-12074

Unclass
0237037

68/38

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Printed in the United States of America

Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes¹

Printed copy: A02

Microfiche copy: A01

¹Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication, NTIS-PR-360 available from NTIS at the above address.

Model 0A Wind Turbine Generator FMEA

William E. Klein
National Aeronautics and Space Administration
Lewis Research Center
Plum Brook Station
Sandusky, Ohio 44870

and

Vincent R. Lalli
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division
Washington, D.C. 20545
Under Interagency Agreement AB29-79ET20370

Prepared for the
1990 Annual Reliability and Maintainability Symposium
cosponsored by the ASME, ASQC, IIE, IEEE, SOLE,
IES, AIAA, SSS, and SRE
Los Angeles, California, January 23-25, 1990

Model OA Wind Turbine Generator FMEA

William E. Klein; National Aeronautics and Space Administration; Lewis Research Center; Plum Brook Station; Sandusky, Ohio 44870

Vincent R. Lalli; National Aeronautics and Space Administration; Lewis Research Center; Cleveland, Ohio 44135

Abstract

This report presents the results of Failure Modes and Effects Analysis (FMEA) conducted for the Wind Turbine Generators. The FMEA was performed for the functional modes of each system, subsystem, or component. The single-point failures were eliminated for most of the systems. The blade system was the only exception. The qualitative probability of a blade separating was estimated at Level D-remote.

Many changes were made to the hardware as a result of this analysis. The most significant change was the addition of the safety system. Operational experience and need to improve machine availability have resulted in subsequent changes to the various systems which are also reflected in this FMEA.

Introduction

The NASA Lewis Research Center conducted research and development of large horizontal axis wind Turbine Generators for the Department of Energy as one phase of the overall Wind Energy Program. Wind turbines ranging in size from 100 to 3200 kW were designed and built as part of this program. The object of the program was to develop wind turbines which would generate electricity at a cost which is competitive with alternative generating methods, particularly oil.

This paper describes some of the changes that resulted from using the Failure Modes and Effects Analysis (FMEA) as a systems safety and reliability analysis tool for the 200 kW, MOD OA Wind Turbine Generators (WTG). Reference 1 further describes the logic for this approach. This analysis was originally done by the Reliability and Quality Assurance Office at NASA Lewis Research Center. Later, the government contracted with W.L. Tanksley and Associates to revise and update their analysis.

The complete FMEA resulted in several modifications to the original MOD OA WTG design. These included changes to the microprocessor (hardware and software), the safety system, the yaw system, the drive train, the supervisory system and the electrical system. The analysis was limited to a level of detail that would assure safe, reliable, machine operation. The MOD OA portion of the program has now been completed and the machines have been removed.

Machine Description

A photograph of one MOD-OA machine, located on Culebra Island, Puerto Rico, is shown as Fig. 1. Nearly identical machines were located in Clayton, New Mexico, Block Island, Rhode Island, and Oahu, Hawaii. The blades measured 125 ft, tip-to-tip. The hub center was 100 ft above ground level. The blades rotated at 40 rpm. The blades were mounted on the rotor hub, as shown in the cutaway drawing included as Fig. 2. The pitch actuator pitched the blades through a set of bevel gears located inside the hub. The hub was attached to a low-speed shaft which was connected to a speed increaser gearbox. A fluid coupling, attached to the 1800 rpm output shaft of the gearbox helped dampen out power oscillations. A high-speed shaft then transmitted power to V-belts which drove a synchronous alternator. The machine was housed in an 8-ft diameter nacelle.



FIGURE 1. - MOD OA WIND TURBINE AT CULEBRA ISLAND, PUERTO RICO.

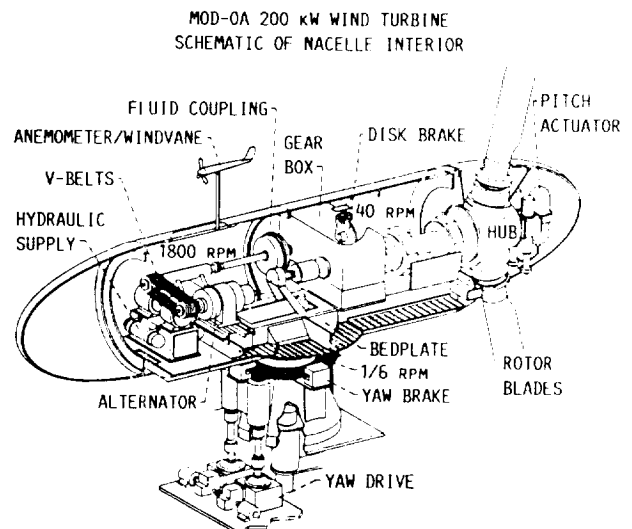


FIGURE 2. - CUTAWAY DRAWING OF TOWER MOUNTED EQUIPMENT.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

nacelle, mounted on a turntable bearing located on top of a truss tower. A dual yaw drive system kept the machine aligned with the wind.

The wind turbine was controlled by a microprocessor, two closed loop servo systems, and a safety system. It continually monitored machine status and wind conditions. When the wind speed reached 12 mph, the microprocessor signaled the pitch controller to start pitching the blades, gradually increasing rotor speed. When the alternator reached synchronous speed, the alternator was synchronized with the utility grid. After synchronization, the blades remained in the full power position, generating increasing power as the winds increased until the full output of 200 kW was reached at a wind speed of 24 mph. As winds increased further, the blades gradually feathered, spilling some of the wind, to maintain the 200 kW output.

If the wind speed dropped below 10 mph, the machine was shut down. If the wind speed increased above 40 mph, the machine was shut down to avoid high-blade loads. When the wind speed dropped back to 35 mph, the machine was restarted. The microprocessor also monitored several noncritical variables to shut the machine down if necessary.

The first closed loop servo system regulated the pitch of the blades. Blade pitch regulated machine speed from initial blade rotation until synchronization with the utility grid and regulated the power generated after synchronization. The second closed loop servo measured the difference between the actual wind direction and the nacelle direction to keep the machine aligned with the wind. The machine operated with the blades downwind and was kept aligned within 15° of the wind direction.

The safety system, as the name implies, measured several operating variables, shutting the machine down if any of these variables went out of limits. These variables included overspeed, overcurrent, pneumatic and hydraulic pressures, several overtemperatures, and high vibration. The Safety System shutdown signal directly shut the machine down, regardless of what the microprocessor or servo controllers were doing.

The machines were modified as operating experience was accumulated. The most prominent modifications were:

1. Different blade materials
2. Different rotational speeds
3. Control system upgrades with two servo loops
4. Incorporating several safety functions in the microprocessor loop.

The FMEA was used to study these changes and upgraded to include the final design.

Combined FMEA Procedure

Numerous reliability, quality assurance and system safety techniques were considered. A FMEA, preliminary hazards analysis, and operations hazard analysis are very similar and many of the form entries are the same. The modified FMEA was chosen to be the main tool for listing and analyzing each component for the various possible failure modes. On some previous projects, one person or team has simultaneously reviewed the hardware for a system safety and a reliability analysis, see Ref. 2. The results have been listed on a sample FMEA form, see Fig. 3. Each system was studied for possible failure modes, causes, and effects on the machine reliability as well as on personnel safety. The necessary corrective action was then determined independently. This combined FMEA technique works quite well and saves a significant number of manhours.

There is one drawback to this technique. It is easy to list failures that are not safety problems, but it is also easy to overlook safety problems which are not caused by equipment failures. Some examples of safety problems which could have been overlooked are the three listed below:

1. Personnel getting caught in rotating machinery.
2. Electrical shock hazards due to exposed terminals.
3. Operating errors.

These safety-related items can also be handled using the combined FMEA method. The reviewer has to make a conscious effort to consider each of the hazards as a possible failure mode. Hazards would be categorized as follows:

1. Lack of proper safeguards in the design.
2. Lack of operator training to follow procedures.
3. Lack of human engineering causing operator error.

This FMEA was primarily directed at identifying those critical failure modes that could be hazardous to life or could result in major damage to the system. The analysis was organized by systems to help limit the number of similar entries for similar events that could occur. The system was analyzed so that no major damage should occur because of a single-point failure or a single failure following an undetected failure. The analysis was qualitative in nature and was used to determine the cause and effect for each failure mode and what could be done to correct the problem.

The FMEA was determined for the functional modes of each system, subsystem, or component. The electrical and electronic portions of the FMEA were limited to the package level, showing only constant high level output or zero output. Wiring harnesses, cables, and electrical connectors were considered to be part of the output or input and were not considered separately.

The level of detail in the mechanical portion of the FMEA varies. For catalog, off-the-shelf components, only expected types of failures were considered. A remote-operated valve was considered to be in the failed open or failed closed position only. Pressure containment and distribution systems were considered as having failed when the system pressure had dropped below the minimum safe operating level. A hand valve was considered part of the containment system and could fail if the improper position would not be detected. The more likely failures, particularly those having severe consequences, were considered for possible redesign or the addition of redundant components.

Many changes were made to the hardware as a result of this analysis. The most significant change was the addition of the Safety System. Operational experience and the need to improve machine availability resulted in additional changes to the various systems.

Results

While performing the FMEA, it soon became obvious that the worst possible failure would be significant overspeed, since this could result in throwing a blade. The consequences of all of the other failures were relatively minor by comparison. Based on this conclusion, disk brakes were added to the high-speed shaft very early in the design to stop the rotor, even if the blades remained in the full power position. The brakes were designed to activate if electrical power was lost. It would also have been desirable to have the brakes activate upon loss of brake actuation pressure, but only one machine was converted before the end of the program. The brakes were applied for two main conditions:

1. Overspeed due to failures
2. To hold the blades still for maintenance

The analysis pointed out a number of items that were to be considered as primary safety devices. The reliability of these systems had to be maximized. Factors to be considered in attaining maximum reliability were: Redundancy, minimum electrical path, quality of components and periodic verification of system operation. These items included the following:

| ITEM | FAILURE MODE | CAUSE | EFFECT | CORRECTIVE ACTION | REMARKS |
|---|---|--|--|---------------------------------------|---------------------------------|
| 1. ALARM CIRCUIT "A" (DWG. 1016F11, SHEETS 1 & 3; 1016F12). | 1A. INADVERTENT REMOVAL OF SIGNAL TO SSR1. | 1. ELECTRONIC FAILURE. | 1A. NO START OR EMERGENCY SHUTDOWN. REMOVING SIGNAL FROM SOLID STATE RELAY 1 (SSR1) DE-ENERGIZES RELAY K1 WHICH DE-ENERGIZES RELAY K2. DE-ENERGIZING K2 OPENS CB2, REMOVES THE GENERATOR FIELD, FEATHERS BLADES AND TURNS OFF THE PITCH HYDRAULIC PUMP. | 1. NONE REQUIRED-REPAIR AS NECESSARY | 1B. PERIODIC CHECKOUT REQUIRED. |
| | 1B. CIRCUITS FAIL TO REMOVE SIGNALS WHEN SAFETY SENSORS SIGNAL PROBLEM. | | 1B. LOSE PRIMARY SAFETY SYSTEM. THE FOLLOWING SENSORS ACT DIRECTLY AND REMAIN ACTIVE: VS1A - VIBRATION PS1A - FEATHER BOTTLE PRESSURE PS2A - BRAKE BOTTLE PRESSURE OSS1 - OVERSPEED SWITCH OSS2 - OVERSPEED SWITCH HHP - PITCH PUMP PRESSURE | | |
| 2. EMERGENCY SHUTDOWN RESET PB 6. (DWG. 1016F12). | 2A. FAILS OPEN. | 2. SWITCH ELECTRICAL OR MECHANICAL FAILURE | 2A. NO RESET IN THE EVENT OF AN EMERGENCY SHUTDOWN. | 2. NONE REQUIRED-REPAIR AS NECESSARY. | |
| | 2B. FAILS CLOSED. | | 2B. NO EFFECT UNTIL EMERGENCY SHUTDOWN OCCURS. LOGIC GATES LATCH UP AND WILL NOT RESET. IF BOTH CONTACTS FAIL CLOSED, SHUTDOWN WILL NOT LATCH EXCEPT THROUGH MICROPROCESSOR. | | |

FIGURE 3. - SAMPLE PAGE FROM MOD 0A WIND TURBINE FMEA.

- a. 45 rpm overspeed
- b. Low-speed shaft vibrations
- c. Emergency feather pressure
- d. Rotor brake pressure
- e. Yaw error signal
- f. Alternator overcurrent
- g. Alternator reverse current

The next problem that surfaced resulted from the basic design of the machine. The Safety System was located in the control building at ground level. Most of the sensors were located in the machine nacelle on top of the tower. Since the machine must yaw to stay in alignment with the wind, the signals were routed through slip rings. The FMEA analysis revealed some potential failures in the slip rings (shorts or opens, depending on circuitry) that could override or bypass a Safety System shutdown signal. As a result, several redundant sensors were added in the nacelle that acted totally within the nacelle and did not rely on the slip rings for a shutdown signal path. In fact, they were designed to shut the machine down regardless of what signals the microprocessor was sending to the machine. These sensors included overspeed, low-speed shaft vibration switches, low-blade emergency feather pressure, and low-rotor brake pressure.

Alignment of the machine with the wind was also important. The direction of the nacelle was compared to the wind direction to keep the machine aligned with the wind. The FMEA pointed out the need for a redundant yaw error signal, which was added.

There was concern that an intruder would go up into the nacelle and get caught in the rotating machinery. The only access route up into the nacelle was by using an open elevator-type device. When the elevator was not being used, the power was turned off from inside the control room and interlocked with the safety system.

Conclusions

The performance of the FMEA for the 200 kW Wind Turbine Generator accomplished several objectives. As is usually the case with this type of tool, the act of performing a systematic, detailed review of the design was very useful. The FMEA indicated the need for a number of design changes:

1. Disk brakes on high speed shaft
2. Primary safety devices
 - a. Overspeed
 - b. Vibration
 - c. Feather pressure
 - d. Brake pressure
 - e. Yaw error
 - f. Alternator over/reverse current
3. Redundant sensors
4. Intruder alarm

The final FMEA also gave project management personnel a qualitative indication of the degree of program and safety risk that they were accepting with this design.

Since this was an evolutionary R&D project, there were a large number of changes proposed for the machine. With the completed FMEA, it was easy to review the safety and reliability implications of each proposed change. By using this technique, it was shown that the increased safety and reliability risk of some of the proposed changes did not justify the change. Most of the proposed changes did not increase the risk and in some cases, decreased the risk. Finally, the FMEA was revised to reflect all approved changes.

In summary, the FMEA performed for this project served several very useful functions. The benefits far outweighed the cost of performing the FMEA.

References

1. Klein, W.E., 1980, "Modified Aerospace Reliability and Quality Assurance Methods for Wind Turbines," NASA TM-79284.
2. Lalli, V.R., 1980, "Photovoltaic Power System Reliability Considerations," NASA TM-79291.

| | | | | | |
|--|--|--|--|---|-------------------|
| 1. Report No. NASA TM-102378 DOE/NASA/20370-23 | | 2. Government Accession No. | | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Model 0A Wind Turbine Generator FMEA | | | | 5. Report Date October 1989 | |
| | | | | 6. Performing Organization Code | |
| 7. Author(s) William E. Klein and Vincent R. Lalli | | | | 8. Performing Organization Report No. E-5117 | |
| | | | | 10. Work Unit No. None | |
| 9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191 | | | | 11. Contract or Grant No. | |
| | | | | 13. Type of Report and Period Covered Technical Memorandum | |
| 12. Sponsoring Agency Name and Address U.S. Department of Energy Wind/Ocean Technology Division Washington, D.C. 20545 | | | | 14. Sponsoring Agency Code | |
| | | | | | |
| 15. Supplementary Notes Final Report. Prepared under Interagency Agreement DE-AB29-79ET20370. William E. Klein, Lewis Research Center, Plum Brook Station, Sandusky, Ohio and Vincent R. Lalli, Lewis Research Center. Prepared for the 1990 Annual Reliability and Maintainability Symposium, cosponsored by the ASME, ASQC, IIE, IEEE, SOLE, IES, AIAA, SSS, and SRE, Los Angeles, California, January 23-25, 1990. | | | | | |
| 16. Abstract This report presents the results of Failure Modes and Effects Analysis (FMEA) conducted for the Wind Turbine Generators. The FMEA was performed for the functional modes of each system, subsystem, or component. The single-point failures were eliminated for most of the systems. The blade system was the only exception. The qualitative probability of a blade separating was estimated at Level D-remote. Many changes were made to the hardware as a result of this analysis. The most significant change was the addition of the safety system. Operational experience and need to improve machine availability have resulted in subsequent changes to the various systems which are also reflected in this FMEA. | | | | | |
| 17. Key Words (Suggested by Author(s)) Design tradeoffs, Environmental analysis; Failure modeling; Reliability; Generator; Safety; Repairability; Serviceability; System engineering | | | | 18. Distribution Statement Unclassified - Unlimited Subject Category 38 DOE Category UC-60 | |
| 19. Security Classif. (of this report) Unclassified | | 20. Security Classif. (of this page) Unclassified | | 21. No of pages 6 | 22. Price* A02 |

