Prognostics and Health Management on MASTER-T Radar Maintenance Using Failure Mode Effect and Criticality Analysis Method to Predict Critical Failures and Extend Life

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Abstract

The readiness of military defense radar is absolute in effort to maintain Indonesia air sovereignty from potential threats that may enter and endanger the security of citizens and residents throughout Indonesia territory. Currently, the radar health condition monitoring system has not been integrated in a whole system integrated manner between the subsystems each other, it causes a relatively long time to identify critical failures that may arise in the related subsystems. Prognostics and health management (PHM) takes the current state of the system as a starting point, combined with structural characteristics, parameters, environmental conditions, and historical data of objects, to monitor the equipment working status with various knowledge, algorithms, and models based on advances in sensor acquisition technology. PHM on MASTER-T radar maintenance is proposed using the method of failure mode effect and criticality analysis (FMECA) which aims to predict critical failures, thus preventing fatal damage that can result in system breakdown. Predictive maintenance is added to conventional maintenance, thereby minimizing idle time when repairs must be made with the radar system inactive. The application of this method obtains a risk priority number (RPN) which is used as a reference in determining critical components that must be repaired immediately.

Keywords
Prognostics and Health Management, Military radar, FMECA, and RUL.

1. Introduction
The radar system operation in monitoring the air situation becomes very crucial in the presence of a sovereignty threat, it means the level of radar readiness must be maintained and system performance must always be monitored (Wang et al. 2020). The radar system is a complex electronics information system that has an important role in national air defense (Lyu et al. 2020). Nowadays, the advancement of radar related to technological developments, the level of

digitization, integration, and artificial intelligence is growing rapidly, this poses a challenge in the overall maintenance activities of the radar system. When the radar has problems, the level of air defense security cannot be controlled (Roux and Van Vuuren 2008). In Indonesia, the Man-less Advanced Solid-State Tactical Efficient Radar type-T (MASTER-T radar) is a military ground radar that plays an important role as an early warning detection system for threats in the sovereignty airspace of Negara Kesatuan Republik Indonesia (NKRI).

The advantages of the MASTER-T radar are it has surveillance radius of 440 km from the epicenter, capable of performing electronic warfare, and directs fighter pilots or interceptors. This radar has a compact design, full solid-state, and is equipped with a BITE system that provides information when failures arise within the system and radar performance. The BITE system aims to assist technicians in maintenance and localizing failures that occur in the radar system (Zhang and Ma 2012). PHM through the BITE system is applied to the radar subsystem, and this system still has weaknesses because it has not been integrated with other subsystem in a whole integrated manner, such as communication systems, energy systems, and remote-control rooms.

PHM is a series of processes for predicting future system reliability and monitoring system health by assessing the extent to which deviations or system degradation occur from normal operating condition real-time, in support of the appropriate action decision-making process (Biggio and Kastanis 2020). The benefits of PHM on a system are to predict critical failures, determine RUL, and extend the life of the system. Prognostics is part of the RUL process step by estimating the possibility of errors in a system with ongoing degradation rates, load history, and anticipating future operational and environmental conditions (Pecht and Kang 2018). The use of PHM continues to grow in the maintenance mode of a more complex system to replace conventional maintenance systems or periodic inspections with condition-based maintenance (Lyu et al. 2020). A condition-based maintenance system will provide a longer period from one maintenance to the next, and unlike general maintenance which must stop the operation of the system.

The development of PHM makes it possible to answer BITE system problems that have not been integrated into a system capable of providing real-time system diagnosis information (Zhang and Ma 2012; Prisacaru et al. 2017; Zhang et al. 2020). The application of PHM on the MASTER-T radar can not only inform technicians about the health status of the radar system accurately. Furthermore, radar health management should be able to provide comprehensive information such as the condition of system integrity, system safety and reliability (Moradi and Groth 2020; Wileman and Perinpanayagam 2013b). PHM makes it easy to locate faults in subsystems without stopping other subsystems, lower maintenance costs, shorten maintenance time, and maintain the excellency of radar support capabilities (Lyu et al. 2020). The failure parameters on the radar will be identified by BITE in each subsystem, then collected in an integrated monitoring system, with a priority calculation of the criticality level to determine which problems or failures must be addressed first in order to avoid the impact of fatal damage to the entire radar system.

PHM in the BITE system becomes important for diagnosing the type of error through a sensor device that functions to monitor the degradation of each subsystem on the MASTER-T radar. Error monitoring at the subsystem level can be done using the FMECA method to identify events from the start and provide guidance parameters for system performance degradation. The FMECA method analyzes the impact of failure on the subsystem to its critical level, so that technicians can understand in detail the risk of damage that may occur (Suharjo et al. 2019). The presentation of information on the radar system condition is processed using the PHP programming language as an interface building machine that connects the equipment with the technicians. The GUI is designed in such a way to make it easier for technicians to gain parameter information data to help performing the next action. PHP has the probability characteristics and supports advanced word according to function requirements as well as data transplantation into other operating systems for maintenance and information management (Ren et al. 2021). The system parameter information data presented is expected to cover the entire system. This becomes a framework for integrating the BITE system on the radar through PHM in diagnosing the health of the overall subsystem, it is necessary to design based on RUL in order to determine the overall health condition level and the timing of the next maintenance action.

1.1 Objectives

The purpose of this study is to design the application of PHM on the MASTER-T radar system with an online web-based simulation that serves to provide prognostics information in predicting the occurrence of the critical failures in the subsystem to maintain the performance of the equipment. PHM is expected to produce a continuous-based maintenance framework under actual conditions, thereby minimizing idle time when stopping the radar system in the event of a system breakdown. The priority of critical failures refers to the calculation of RPN using the FMECA method and the extension of life through the prognostics of the predicted RUL

2. Materials and Methods

The materials and methods used in this study include radar, PHP programming techniques, PHM as the basis for designing the framework, and FMECA as a method for analyzing priority critical failures. The design of the condition-based maintenance framework can be explained as follows.

2.1 Radar Technology and Capabilities

Radar stands for Radio Detecting and Ranging, is a technology to determine the presence of objects and their distance to electromagnetic wave signal transmitters. The working principle of radar is that the radio wave signal emitted through the transmitter into the air will hit the object and bounce back to the radar equipment, the reflected wave signal (echo) is received and processed by the receiver. The echo is processed and calculated by a computer to determine the presence of a target, its distance, direction, and altitude from the radar. the principle of calculating the reflected signal is by applying the Doppler Effect so that the movement of the detected object can be known. The data is processed and displayed on the operator's monitor screen. The complexity of the complex radar components makes the need for accurate monitoring equipment (Wileman and Perinpanayagam 2013a).

The MASTER-T military radar has advantages such as 440 km surveillance radius from epicenter, electronic warfare capability, and directing fighter pilots or interceptor in combat tactics. This military radar has a compact design, full solid-state, and BITE system that provides information when failures arise within the radar system performance. MASTER-T radar technology is equipped with mission control system for the radar operator's activities in conducting air situation monitoring strategies, a long-distance communication system to communicate with fighter pilots and operators at other radar stations, and a power supply system to provide stable energy power needed by radar system operations. Figure 1 shows the relationship of radar principles to the electronic systems that compose radars in general.

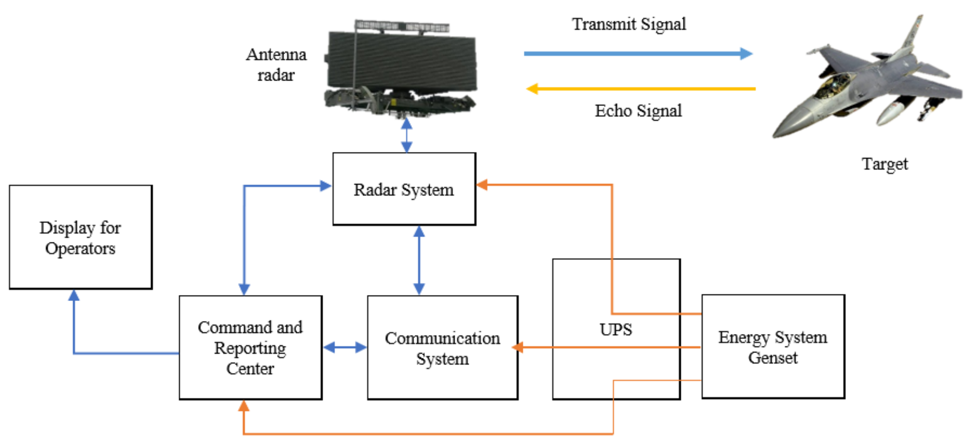

Figure 1. Block diagram radar principle (figure adapted from Suharjo et al. 2019)

2.2 Built-in Test Equipment

BITE works as a system that ensures the reliability of equipment performance by measuring the monitored system parameters, then controlling the operation of the system accurately (Pandu and Sreenivasu 2016). BITE can provide information about the problem findings in the system to assist in system integration, equipment testing, and maintenance (Pecht et al. 2001; Dai and Yu 2020). BITE technology on the MASTER-T radar monitors the condition of the radar electronic system including Aerial Assembly (AA), Beam Steering Unit (BSU), Power Distribution Cabinet (PDC), Radar Signal Generation and Radar signal Receiver (RSG-RSR), Space Time Management (STM), Signal Processing (SP), Data Processing (DP), Transmitter (Trans), Secondary Surveillance Radar (SSR), and Radar Control and Monitoring Display (RCMD). BITE technology in other subsystems, namely the communication system, CRC, and power supply units are available in each of these systems. BITE is very helpful in providing information on system conditions and problems by section. Figure 2 shows the failure parameters on the radar subsystems, CRC, Communication, UPS unit, and Genset unit. The failure parameters of each subsystem are indicated by color indicators and their descriptions ranging from normal, warning, minor, marginal, to critical.

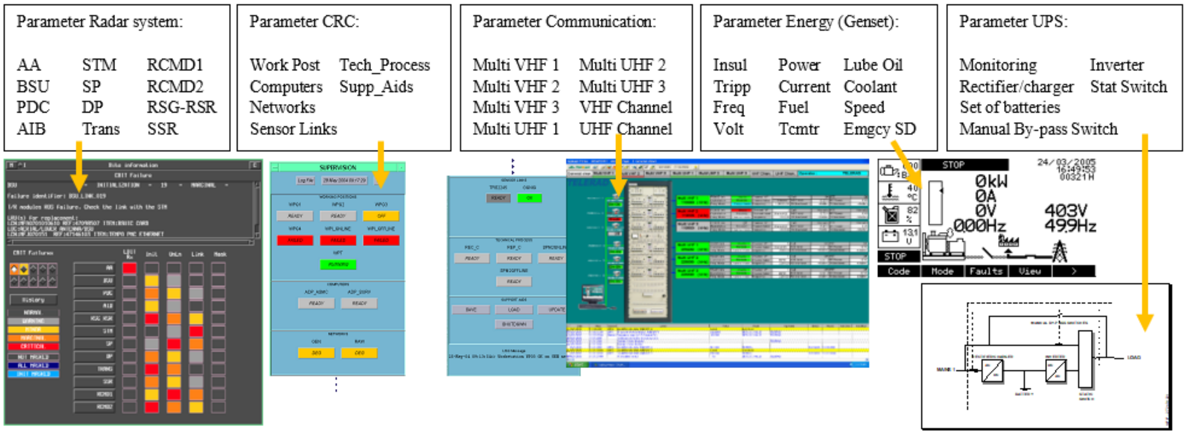

Figure 2. BITE parameter on MASTER-T radar subsystem

2.3 Failure Mode Effect and Criticality Analysis

The FMECA method takes a step further than the general failure analysis, each failure mode will be calculated in severity, potential problems are seen in more detail and get more accurate results. FMECA is a method that can be used to prevent various forms of component failure, predict problems, and find optimal and economical solutions. With this method, it is possible for the system to identify potential failures in the system, subsystems, and components, depending on the database it has. This method gives priority search of all potential problems to determine possible actions or preventive measures. The FMECA method is well accepted for analyzing the reliability and safety of equipment, because the data will be presented and easy to use (Ohring and Kasprzak 2014).

FMECA not only identifies but also investigates potential failure modes and their causes. When properly applied, it can help identify failures with the highest criticality values based on probability and severity (Suharjo et al. 2019). The FMECA method identifies the severity behavior (Severity index), the occurrence probability (Occurrence index), and the level of detection by technicians (Detection index). These identifications are used to calculate the risk priority number (RPN) with the calculation shown in Equation 1.

$$RPN = S \times O \times D \quad \text{(Eq. 1)}$$

- Severity index (S). Severity classification is assigned to each failure mode of each subsystem and entered FMECA matrix based on the consequences in each part of the radar system.
- Detection index (D**).** The detection index measurement is used to define and analyze the system's ability to detect and report problems with each system component and failure mode. In the FMECA matrix, information about the detection of problems in each component of the subsystem will be provided.
- Occurrence index (O) and calculation. Measurement of occurrence index or the frequency value of the repeated failure in a subsystem is done to find out how often failure modes occur in each component of the system.

The RPN as an alternative calculation in critical analysis and reference value in the priority action plan for maintenance. The RPN value is the product of the Detection Index (D) * Severity Index (S) * Occurrence Index (O). Each on a scale of 1 to 10, it means the highest RPN value is 10x10x10 = 1000. Failure with a high RPN value indicate that the failure cannot or is difficult to detect by inspection, is very severe and the occurrence is almost certain. Failure mode can be mapped on the criticality matrix using severity code as one axis and the probability level code on the other. In quantitative assessment, the total of criticalities is calculated for each failure mode of each item and the criticality number of items is calculated for each component.

2.4 Weibull Distribution

Weibull probability distribution is used to calculate the probability of equipment failure in the system, so that the period between failure and the next can be estimated (McCool 2012). The Weibull distribution is applied in this study because it can see the range of failures that occur until an equipment cannot operate or is damaged. There are two forms of Weibull distribution which are distinguished by their parameters. The Cumulative Distribution Function (CDF) can be expressed in closed form. The three-parameter version of the Weibull distribution CDF can be written as in Equation 2.

$$F(x) = 1 - exp\left[-\left(\frac{x-\gamma}{\eta}\right)^{\beta}\right];\ \ x > \gamma \qquad \text{(Eq. 2)}$$

The probability density function (pdf) is a description of information about a continuous random variable *x*, it is a positive continuous function defined over the range of random variable (McCool 2012). The pdf has the property that is integral between two points, is the probability that an observed *X* will have value between x_1 and x_2. The pdf of the two parameter Weibull distribution is shown in Equation 3.

$$f(x;\, \eta, \beta) = \frac{dF(x)}{dx} = \frac{\beta}{\eta}\left[\frac{x}{\eta}\right]^{\beta-1}.exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \qquad \text{(Eq. 3)}$$

The Reliability Function *R(x)* is commonly known as the survival function in biomedical applications which expresses the probability that a device or subject will exceed a predetermined value (McCool 2012). The reliability function of the Weibull distribution with two parameters can be seen in Equation 4.

$$R(x) = Prob\ [X > x] = exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right];\ \ x > 0 \qquad \text{(Eq. 4)}$$

2.5 Management Information System

Management information system is an internal control planning system that includes the use of documents, technology, procedures, people, and other important matters by the management administration. The development of the world technology has led to innovative and optimize the role of information means that affects operations (Gunawan 2020; Wu and Tang 2020). Information technology these days uses a lot of internet network connections or some other similar way in collecting data quickly, so that can help operators to take immediate action correctly based on the information data received. One of the programming languages in easy designing web-based information management is PHP, which is a very powerful open-source general-purposes programming language in term of web development (Andress and Linn 2017; Laverdiere and Merlo 2018). The presented information data uses a GUI which can be integrated with the framework using a combination of JavaScript and Bootstrap based on the system parameter hierarchy (Maw et al. 2018). The GUI works as represent the equipment's internal and external information that is displayed to the operator and technicians.

2.6 Prognostics and Health Management

PHM is a new engineering approach that enables real-time health assessment of a system under actual operating conditions as well as prediction of its future state based on up-to-date information by combining various disciplines including sensing technology, failure physics, machine learning, modern statistics, and reliability engineering. PHM has its roots in the aerospace industry, and is currently being explored for application in various sectors including the manufacturing and digital equipment industries (Lall et al. 2012; Sutharssan et al. 2015; Kim et al. 2017). PHM becoming a trend and opening opportunities for equipment health monitoring technology for longer usage (Bektas et al. 2020; Calabrese et al. 2019). PHM calculates the remaining life of the equipment and formulates a scientific maintenance plan based on the information collected, with a view to eliminating errors in advance to ensure completion of training and combat missions (Lyu et al. 2020). The results that can be gained from PHM information help localize errors and failures that must be handled so that errors or problems do not have a fatal impact on the system or the activities being carried out.

3. Result and Discussion

This section explains the research data dan their discussion which contains about the hierarchical design on the MASTER-T radar for each item, integrating BITE in MASTER-T radar, predictive maintenance innovation offers for the system, and designing PHM simulations in monitoring the status of radar conditions and prioritizing critical failures that must be followed up immediately.

3.1 PHM Hierarchical Design on the MASTER-T Radar

The design of PHM on the MASTER-T radar shows the hierarchical level of system health and condition monitoring, so that it can determine the extent to which the critical failure relationship of a subsystem or component affects other subsystems. Information data on radar system items is disassembled form the highest level to the level of solid-state component or module items, so that detailed information is gained in accordance with local BITE information which is generally reported on each subsystem status monitoring screen on the radar. The subsystem data on MASTER-T radar is calculated up to fourth level of the whole radar system as shown in Figure 3.

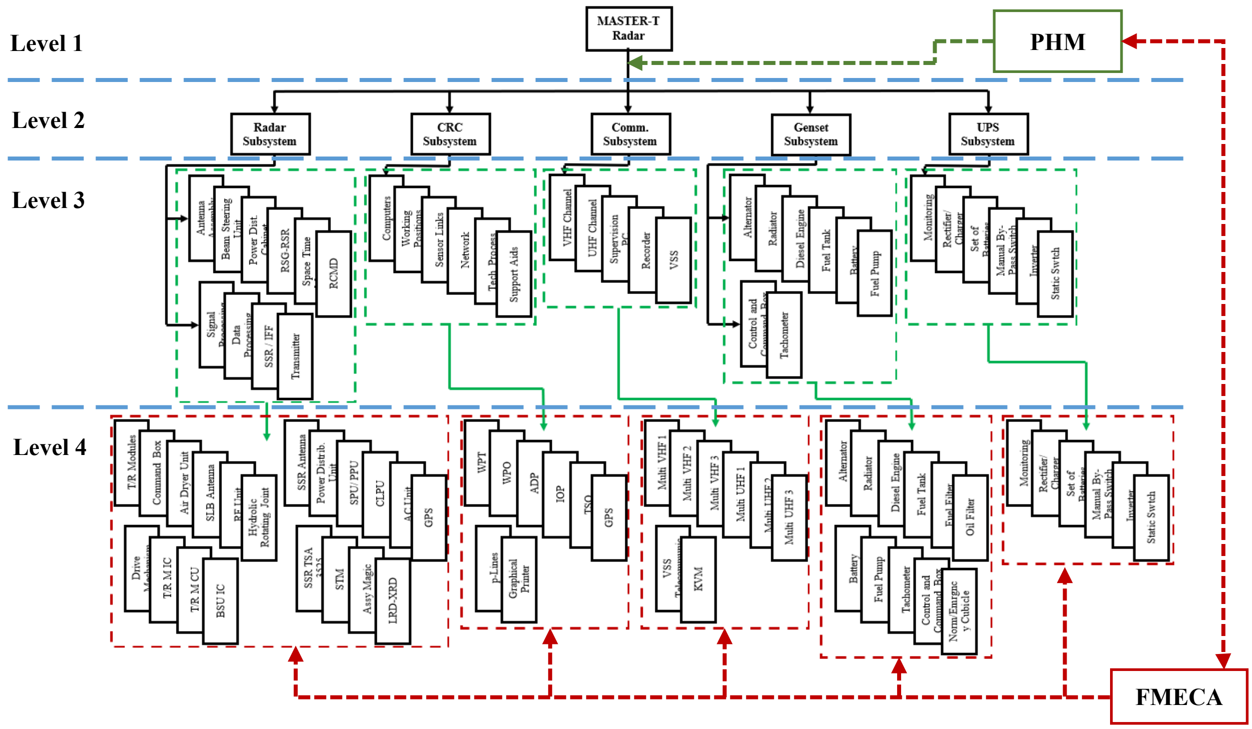

Figure 3. PHM design hierarchy for MASTER-T radar (figure adapted from Ren et al., 2021)

From Figure 3 explain that Level 1 is the overall radar system, level 2 is the five major parts of the radar subsystem, level 3 is the sub-subsystem that builds on each larger subsystem, and lastly the level 4 is the sub-sub-subsystem in each part or is a solid-state module of electronic and electrical equipment of the radar system. The fourth level subsystem health data management is calculated using the FMECA method to gather the RPN priority as described in the text. The results of the FMECA method are become input for the radar system PHM in predicting critical failures, maintenance priorities, and overall radar system health information in relation to RUL. There are 300 items from all radar systems that have been assessed in this study.

3.2 BITE System Integration on the Whole System

The BITE system on the radar as a health status monitoring for each subsystem, namely the radar subsystem, CRC subsystem, communication subsystem, genset subsystem, and UPS are integrated. The BITE integrated system will make it easier for technicians to observe the overall radar system health status, so that they are immediately aware of possible failures, reduce the time needed to carry out inspections on related subsystems, and speed up decision making in maintenance or repair actions if necessary. The BITE system is integrated with the PHM implementation through the FMECA method to obtain critical failures prediction information, then sorted by critical priority, and prognostics predictions to determine efficient maintenance or repair action times based on the detected RUL subsystem. Figure 4 shown proposed the BITE system integration for MASTER-T radar by using PHM through FMECA method.

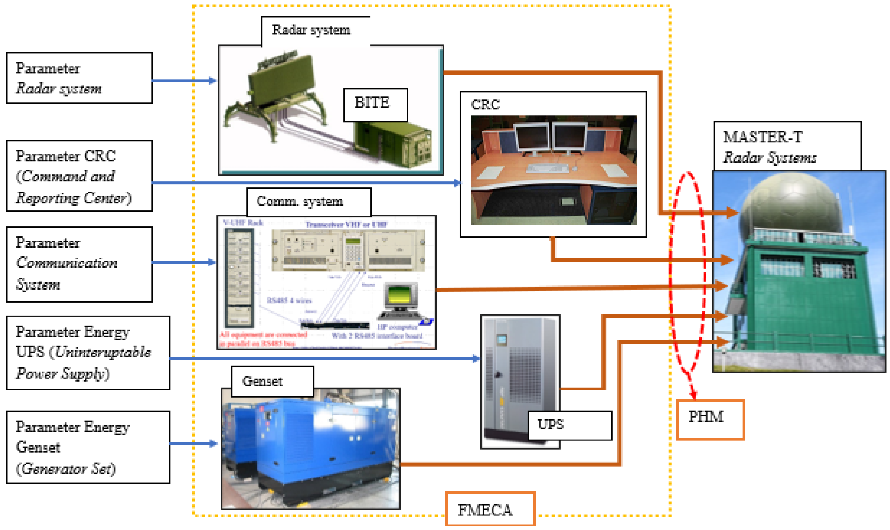

Figure 4. BITE system MASTER-T radar integration scheme (figure adapted from Lyu et al., 2020)

3.3 Predictive Maintenance Innovation

Radar systems need to get certain maintenance to maintain the readiness and operational performance level, therefore maintenance is needed that is adjusted to the situation and condition of the system. Two types of conventional maintenance are corrective and preventive maintenance, this already applied to the MASTER-T radar maintenance step. Predictive maintenance technique is a data-based maintenance strategy to assist technicians in managing the time of maintenance activities efficiently, so that maintenance frequency and costs can be relatively compromised (Ran et al. 2019). Predictive maintenance seeks to predict the useful life of equipment at a given time period step to indicate a point in the future at which maintenance should be performed. The result is lower maintenance costs because the equipment can be fully exploited without compromising efficiency and safety (Fink 2020). The implementation of predictive maintenance innovation that can be used on the MASTER-T radar.

Table 1. RPN calculation for MASTER-T radar items

NO	SUB/LOCATION	ITEM	S	O	D	CRIT	RPN
1	Genset - Engine	Diesel Engine	10	6	5	9	300
2	Radar - CBIT	Power Supply – LPS	7	7	6	5	294
3	Radar - CBIT	32 Logic Input Card – LID	7	7	6	4	294
4	Radar - SSR	EQ. Power Supply – 619	8	7	5	4	280
5	Radar - SSR	IFF TSA2525 – 620	8	7	5	8	280
6	Genset - Engine	Alternator	9	6	5	8	270
7	Radar - CBIT	Assy Magic Card – 472	7	6	6	6	252
8	Radar - CBIT	Thermostat – 916	7	6	6	4	252
9	Radar - CBIT	Circuit Breaker – 917	7	6	6	4	252
10	Radar - PDC	Command Box – 120	7	5	7	6	245
291	Radar - CBIT	Filter – 917	2	1	6	5	12
292	Radar - PDC	16 Logic Output Card – LOD	2	2	2	3	8
293	Radar - PDC	Encoder – 961	2	2	2	3	8
295	Radar - PDC	Flashing Light – 471	2	2	2	3	8
294	Radar - PDC	Overpressure Valve – 11	2	2	2	4	8
296	Radar - AA	Contactor – 918	3	2	1	2	6
299	Radar - PDC	Fan – 918	1	3	2	3	6
297	Radar - PDC	Switch – 917	3	2	1	2	6
298	Radar - PDC	Switch – 918	3	2	1	2	6

300	Radar - PDC	Switch – 915	2	1	2	3	4

The FMECA method using the MIL-STD-1629A form which is useful for providing a general description of each subsystem regarding the function, impact due to failure that may occur, severity, level of possibility or probability, criticality level, and occurrence time of operating failure (Dept of Defense USA 1977; Suharjo et al. 2019). Prognostics simulations with a combination of maintenance data and FMECA can provide clues about which systems and priority equipment that must be addressed immediately. Critical failures prediction can be known from the processing of RPN calculation data by the FMECA method combined with the diagnosis of problems that have been detected by BITE, thus locating the estimated problematic subsystem. Table 1 show RPN calculation of all radar items and then sorted from the highest value to the smallest.

From the RPN values in Table 1 it can be considered that the item that needs to be prioritized for maintenance is the genset diesel engine with the value of 300. While the item with the lowest priority is the Switch-915 on the radar PDC with an RPN value of 4. This will help the technicians in predicting the correct maintenance must be done soon.

3.4 PHM Framework Solution Based on FMECA for MASTER-T Radar

The projected calculation of the criticality level and the priority of the failure risk that must be handled first in the system is realized into a simulation system. A web-based simulation system is built as a research prototype to provide convenience in monitoring the system. Prognostics simulation to provide calculations regarding maintenance predictions that must be carried out before there is a fatal damage to the system, an illustration of the PHM framework can be seen in Figure 5.

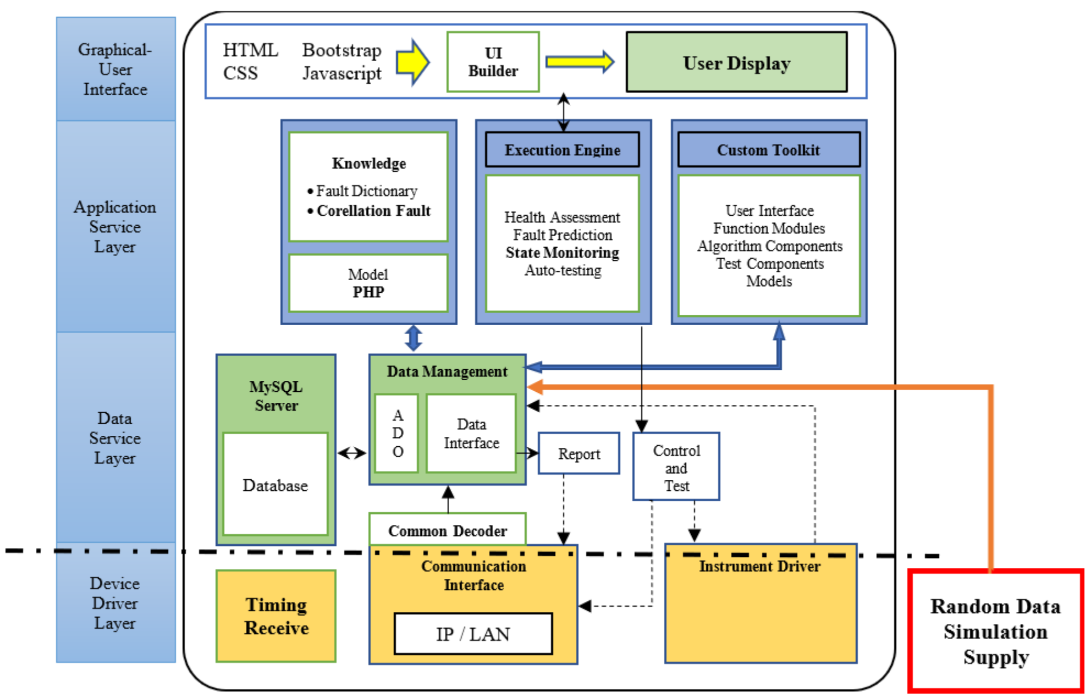

Figure 5. Proposed software architecture for radar PHM (figure adapted from Lyu et al., 2020)

Architecture software created for PHM radar is processed to combine calculated RPN values and random data values. PHP programming as a data processing engine is used to retrieve data for each radar system online and then display it in a PHM simulation which contains information on the health status of each radar subsystem. Online data retrieval is intended to facilitate data access for technicians at remote monitoring locations from each radar subsystem to a single location point. The user interface is built using HTML, CSS, Bootstrap and JavaScript so that it can produce user displays that are easily understood by technicians about the health status of all radar subsystems in one screen. The user display of the PHM simulation on the radar system can be seen in Figure 6.

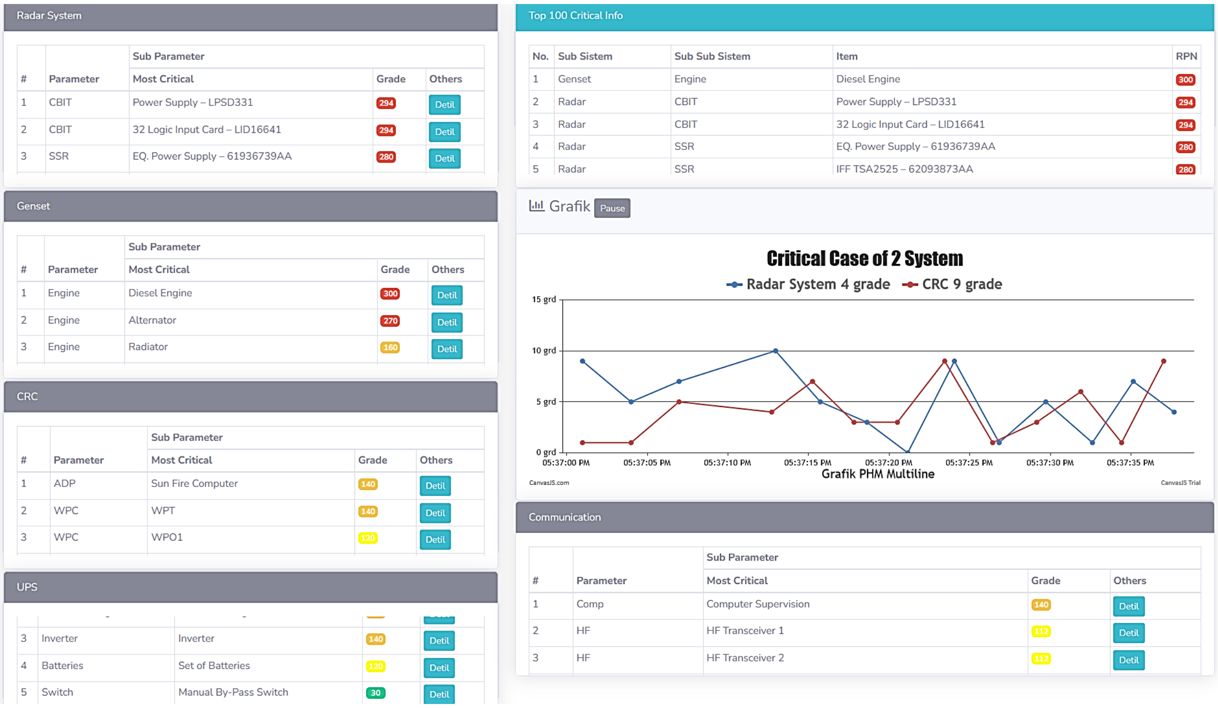

Figure 6. PHM simulation display on the MASTER-T radar system

From Figure 6 it can be understood that the main things that need to be considered by technicians on the PHM display screen are the "Top Critical Info" table and the Graphs of subsystem health conditions. The "Top critical info" table provides predictive information on priority critical items that need to be aware for checking according to the subsystem grouping. The subsystem health condition graph shows the subsystem health condition status in general as a consideration for radar system maintenance measures from time to time. The columns for each subsystem on the left side of the PHM display provide additional information on the priority of risks for each subsystem.

The PHM framework provides further information on the detected RUL subsystems or components, making it easier for technicians to take maintenance actions that will be carried out based on the remaining life time of the equipment before a critical failure occurs. The predictive maintenance built by PHM finally helps technicians in repairing the radar system in efficient manner time, effort, and cost, without interfering with the replacement of other equipment that does not experience significant problems, so the use of each equipment or subsystem can be used to its full potential, and the life of the system radar becomes longer.

4. Conclusion

PHM with FMECA method on MASTER-T radar maintenance develops a more advanced maintenance from conventional maintenance into predictive maintenance, able to predict potential critical failures to prevent fatal damage on the system. Prognostics on monitoring the entire radar system provides RUL information for each subsystem, so that it can determine equipment maintenance time before system breakdown occurs and extend its service life as a long-term goal. The simulation shown can make the difference to the overall health monitoring of the radar system more quickly to technicians and operators in the hope of helping make decisions about the series of maintenance actions that must be done immediately. The prototype of the health monitoring model that is designed can be used as an initial step to determine the maintenance and repair priority of the affected subsystems according to the order of the RPN value is that appear in the monitoring system. As an example, in the paper when diesel engine item that has an RPN value of 300 (the highest at certain time) is anticipated from failure, fatal damage to the radar system and the radar crew can be avoided, and the operational time of the radar system can continue to last longer. The FMECA method can provide priority calculations of critical failures that must be done immediately, the application of PHM as data management on the system health status can provide information on the right time to carry out maintenance to extend the service life.

Future Work

The development of the security of its information management system which still uses standard security and monitoring development data that is not yet fully from the system directly, and the development of PHM for system optimization on other radar systems is a development plan for future studies. Future work on this study is very open to many possible collaborations with other maintenance technologies.

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