Decision Scheduling for Power System Maintenance in Preventive Intervals using the Markov Method

Sutisna, Rukmi Sari Hartati, Ida Bagus Gede Manuaba, and Ida Bagus Alit Swamardika

***Abstract*—Power system maintenance optimizes the cost of energy generation. In this case, preventive maintenance schedule plays an importance role. Maintenance oriented to the P-F curve affects the prediction of long-term scheduling. This study proposed a long-term preventative maintenance strategy in a transmission network using the Markov method. Furthermore, we identified scheduling in effective maintenance (EM), preventive maintenance (PM), corrective maintenance (CM), and High-Performance endPoint (HPeP) for an operational duration of 20 years. Finally, we tested a transmission model with 30 buses and two power sources as input with duration of 20 years. The Markov model was used to determine the reliability of each bus and estimate the reliability value at steady-state within 20 years of system operation. The test results show that several bus systems had several preventive maintenance periods from 18 to 20 years. The simulation results exhibit a 98.3% positive correlation between the duration of the operation.**

***Index Terms*—Markov; maintenance; preventive; reliability; scheduling.**

I. INTRODUCTION

MAINTENANCE scheduling activation affects long-term reliability systems, resulting a synergistic maintenance strategy with the asset life cycle curve. The life cycle of company assets generally passes through several intervals, which are serially described in a D- I-P-F (Design-Installation-Potential-Failure) curve, as shown in [1], [2], [3]. In the P-F interval, the predictive, preventive, and corrective maintenance characteristics are the main approaches to maintaining the reliability of the power system. However, the P-F curve is also discussed in reliability- centred maintenance (RCM). Some researchers confirm that RCM consists of four sessions, namely: corrective maintenance (CM), preventive maintenance (PM), predictive maintenance (PdM), and proactive maintenance (PoM) [4]. In other cases, the power system maintenance schedule is the primary key to maintaining system reliability. Several researchers proposed algorithm-based system reliability,prediction approaches, such as machine learning [5], fuzzy logic and AHP [6], and Monte Carlo [7]. The current method is combining direct observation in the field and projection using a mathematical model approach. However, researchers generally predict maintenance schedules using a high-level mathematical model approach. In this case, high anxiety of decision-makers has maintained the use of conventional and numerical techniques.

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RCM is essential to power system operational management [8], [9]. RCM is generally an analytical process to determine system failure management strategies, including predictive maintenance, costs, and work safety [10]. Some researchers also offer Modes and Effects Analysis (FMEA) [11], [12]. RCM and FMEA have the same main goal of continuously maintaining the system with maximum reliability. The mathematical models for optimizing system reliability in the short-term are used in the predictive maintenance of power systems with the branch-and-bound (BB) method, in which the results are compared with the particle swarm optimization (PSO) method [13]. Meanwhile, the predictive maintenance in the long-term uses the PSO-TS method. The result shows that the model and algorithm have good potential for long-term distribution system maintenance scheduling in the smart grid [14]. To the best of our knowledge, Markov method has not been used for reliability analysis in the P-F interval.

The Markov method is one of the stochastic models for estimating transitions in complex systems with memoryless transition networks [15]. The method uses a decision state model with two conditions, good and bad, or work and failure, generally used to predict a dynamic system. The Markov model assumes that information in the future is strongly influenced by system units that apply in the present. In the study of the maintenance strategy model on the power system, the Markov model proved not to cause random fluctuations as the Monte Carlo simulation did. However, the simulation experienced many repetitions [16]. The Markov model is also optimized for distribution system analysis based on the failure state [17]. Therefore, it is essential to conduct a study using the Markov method to get a detailed picture of the reliability system in a long-term scenario. The novelty of this paper is the Markov method for engineering optimization which was absent in [17]. Still, this study mainly discusses power system management oriented to the D-I-P-F curve [18]. Furthermore, the Parallel-and-mesh network study was conducted in [19], leading to the use of FMEA method in [10] and the RCM method in [17].

Many studies discuss non-series-parallel networks in a transmission system using sampling techniques with the highest reliability criteria. However, studies related to the completion of reliability analysis with the inclusion-exclusion method approach, which involves all channels in the system, have not been found in various literature.

This study uses the Markov method to propose the power system in reliability in long-term scheduling (20 years). This study is focused on simulation using the Matlab program; therefore, the output of this research is a model. The research object of this study is a power system model in the form of a line diagram from IEEE with 30 Bus systems with two power sources. It was chosen because the proposed model is planned to be implemented on a power system with more than 20 Bus units and two source systems.

The test was carried out with a variation of the reactance and resistance in the transmission line represents load dynamics; thus, it is assumed that each bus system has a failure rate per year. Model analysis Reliability identification includes CM, PM, EM, and HPeP. CM is the operational condition of the system after passing the steady state. PM is the system operating time before reaching the steady state. EM refers to the scenario with a change from a transition state to a steady state. Meanwhile, HPeP presents it from the point where the system has lost its best performance for the first time. This grouping is obtained by extracting the estimated data using the Markov algorithm. EM refers to how the system was changed from transition-state to steady-state. And the CM refers to the operational condition of the system after passing the steady-state, PM is the operating period of the system before going to the steady state, and HpeP refers to the transient-state condition. The first state of the system is the condition where the system decreases reliability to its lowest point for the first time.

II. Literature Review

A. Maintenance Interval in D-I-P-F Curve

The D-I-P-F Curve is an industry benchmark from production to system maintenance. Point *D* is design, *I* is installation, *P* is potential failure, and *F* is functional failure. In this case, *F* describes that an item (or the equipment containing it) is unable to meet a specified performance standard.

Treatment strategies are divided into two main categories: reactive maintenance and proactive maintenance [20]. Reactive maintenance consists of corrective and emergency maintenance. Meanwhile, proactive maintenance consists of preventive and predictive maintenance [21], [22]. Some researchers have classified system maintenance into four types referred to as the D-I-P-F curve, which are categorized into PM and CM [23]. Based on the approaches, maintenance is classified into the planned and corrective maintenance approach and the immediate and corrective approaches [21]. Referring to the European standards, there are two main maintenance strategy concepts: PM and CM [21].

B. Literacy Reliability Studies

The degraded components in the distribution system was optimized with 30 buses [17] using RCM which was built with the Markov model to get predictions of operational costs [24], maintenance costs for energy, generated [25], or energy purchases. Unfortunately, Hajivand et al. [17] did not classify the gradation characteristics of system performance. Therefore, this article proposes a more detailed analysis, especially the trend of system reliability characteristics on each Bus system. There is an operational duration influenced by initial load and reliability (See Fig. 1). It is expected that the decision for maintenance strategy is made with better programming from the results of this study. The Literacy Reliability studies proposed and showed the Markov method position. The Markov method plays a role in solving problems in the Inclusion-Exclusion method [26], [27]. These studies are generally part of the FMEA studies [28] and RCM [29].

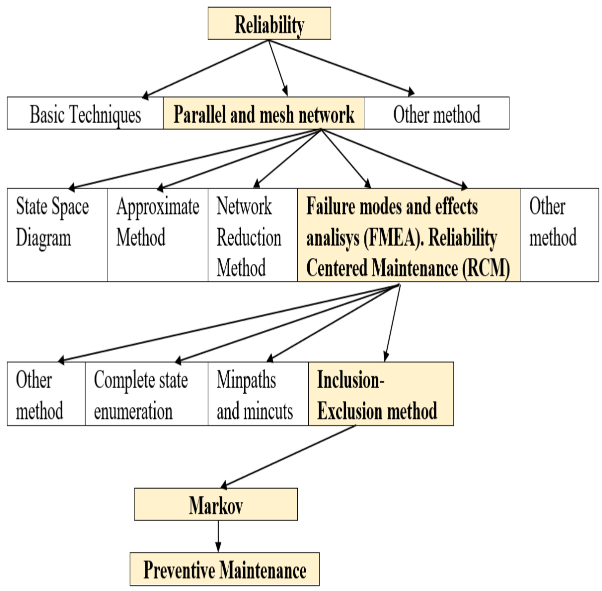


Fig. 1: Literacy Reliability Studies

C. Model Markov

The Markov process is a stochastic system in which the future state depends on the previous state [31]-[32]. Hence the discrete stochastic parameter process is defined as $\{X(t); t = 0, 1, 2, ...\}$, and the continuous parameter stochastic process $\{X(t); t \geq 0\}$ was defined as Markov process. Suppose it has a Markovian property as equation (1) with the probability expressed as equation 2 and represented as a conditional probability of the system being in state x_n at time t_n, given the state x_{n-1} at time t_{n-1}. In that case, it is called one-step transition probability. It can be defined in the k-step transition probability as equation (3) or equation (4), while equation (5) is Markov Chain with discrete state space. Thus, the final form of the Markov procedure was expressed as in equation (6). Where the p^n is a vector of state probabilities at time tn. In matrix form, P^0 is the initial state probabilities vector at time t_0, and P^n is the n-step transition matrix.

Table 1 shows the characteristics indicating the parameters of each bus in the system. In this study, the conductor reactance (X) in the network can be neglected. The R_{Based} value can be assumed to be the same as $|Z_B|$. However, some channels, such as the equation (11) to equation (16) of the Bus system, do not have a conductor, meaning that the line has no resistance value.

$$P\{X(t_n) \geq x_n | X(t_1) = x_1, X(t_2) = x_{n-1}\} \quad (1)$$

$$Px_{n-1}, x_n = P\{X(t_n) = x_n | X(t_{n-1}) = x_{n-1}\} \quad (2)$$

$$Px_n, x_{n+k} = P\{X(t_{n+k}) = x_{n+k} | X(t_n) = x_n\} \quad (3)$$

$$Px_{n-k} = P\{X(t_n) = x_n | X(t_{n-k}) = x_{n-k}\} \quad (4)$$

$$p_{ij} = P\}X(t_n) = j | X(t_{n-1}) = i\} \quad (5)$$

$$p^{(n)} = p^{(0)} P^{(n)} \quad (6)$$

In calculating the impedance, the assumption of 20 kV for V-based was defined, and MVA-based is 500 MVA. These values assume the system was operating at 100% capacity of the conductor capacity or operating under full load conditions. By using equation (3), the length of the conductor between Bus 1 and Bus 2 is obtained by using the value of $R_{Real} = 0.015\Omega$ and $R_{20} = 0.1887\Omega//$km, then the value of the transmission conductor length (L) is 0.081413 km. While the delivery failure rate from Bus 1 to Bus 2. This procedure for determining the conductor length applies to the following 30 buses. Meanwhile, the failure value on Bus 1 is calculated using equation (10), with $\lambda_L = 0.2$ and $L = 0.081413$, the value of the failure rate per year on Bus 2 is 0.016283 (fault/year).

D. IEEE 30 Bus System

The model used in this study is a single-line diagram with 30-buses released by the IEEE. The model has line parameters as Edge, $R(p.u)$, and $X(p.u)$, as shown in Table 1. The 41 edges with load profiles for R and X of each edge were defined in Table 1. The power line diagram model includes 30-buses, where Bus-1 was the source system. The rest were bus Bus-2 to Bus-30 as the load Bus, except Bus_13 as a reactive power source.

For all analyses on this system $V_i^{min}, V_i^{max}, \phi_i^{min}$, and ϕ_i^{max} for bus i are considered to be 0.9 p.u., 1.1 p.u., -45 degrees and 45 degrees, respectively. For the calculation process purpose, the Per Unit (p.u) value is calculated using equation (7), where *Av* is the actual value of the resistance (ohms), and Bv is the base value of the same dimension. The absolute base value of impedance $|Z_b|$ was calculated using equation (8), where Vb is the absolute base value of the system voltage (kV), and Sb is the absolute base value of the apparent power (MVA). The reliability of the system in a given year is represented as $R(t)$, then $R(t)$ is calculated using equation (9), where λ is the failure rate per year, and t is the time (year). The failure rate (λ) is calculated using equation (11), where L is failure per unit length per year. The standard SPLN 59: 1985 was used to determine the value of L to be 0.2 times/km/year. In comparison, the value of L is the length of the conductor (km). This failure rate value is intended to determine the reliability value of the transmission length system per km/year. Therefore, the greater the failure value, the worse the system. However, based on the SPLN standard 59: 1985, the feasibility of an acceptable transmission system failure is determined 0.2 times of fault/km/year or every fault per km for every 5 years, then the system is considered work properly.

$$p.u = \frac{Av}{Bv} \quad (7)$$

$$|Z_b| = \frac{|V_b|^2}{|S_b|}(\Omega) \quad (8)$$

$$R(t) = e^{-\lambda t} \quad (9)$$

$$\lambda = \lambda_L.L \quad (10)$$

$$L = \frac{R_{Real}}{R_{20}} \quad (11)$$

$$R_{real} = R_{(p.u)}.R_b(\Omega) \quad (12)$$

$$R_{20} = \rho_{20}\frac{l}{A} \quad (13)$$

$$Z = \sqrt{(X^2 + R^2)} \quad (14)$$

III. METHODOLOGY

Equation (15) shows the Markov Chain transition probability metric in the dimensions of the state i to state j from the reliability value calculated using the equation (9) and based on data from Table 1. The value of *Rn* is the reliability of the system in the dimensions of two states j and i, in parallel. It can be assumed that condition j is a failed condition or a non-failure condition in the future, while condition i is a failed condition or a non-failure condition in the present. In comparison, Equation (16) represents the steady-state (π) of reliability. Since the steady-state value for each system (π_n) of the reliability in the line (raw) is the same, equation (16) is a metric form of the Steady-State Probabilities of a multi-state system (π). Through Markov, as in equation (6), the steady-state probability of the system in two states is expressed as P_{ST}.

$$\overbrace{0123\cdots n}^{to state j}$$

$$P = \begin{cases} 0 \\ 1 \\ 2 \\ 3 \\ \cdots \\ n \end{cases} \begin{bmatrix} R_00 & R_01 & R_02 & R_03 & \cdots & R_0n \\ R_10 & R_11 & R_12 & R_13 & \cdots & R_1n \\ R_20 & R_21 & R_22 & R_23 & \cdots & R_2n \\ R_30 & R_31 & R_32 & R_33 & \cdots & R_3n \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ R_n0 & R_n1 & R_n2 & R_n3 & \cdots & R_nn \end{bmatrix} \quad (15)$$

$$\Pi = \begin{bmatrix} \pi_0 & \pi_1 & \pi_2 & \cdots & \pi_k \\ \pi_0 & \pi_1 & \pi_2 & \cdots & \pi_k \\ \pi_0 & \pi_1 & \pi_2 & \cdots & \pi_k \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \pi_0 & \pi_1 & \pi_2 & \cdots & \pi_k \end{bmatrix} \quad (16)$$

$$P_{ST} = \begin{bmatrix} \pi_0 & \pi_1 \\ \pi_0 & \pi_1 \end{bmatrix} \quad (17)$$

TABLE I: Branch Bus parameter

Egde	$R_{(p.u)}$	$X_{(p.u)}$	$\|Z\|_{(p.u)}$	Egde	$R_{(p.u)}$	$X_{(p.u)}$	$\|Z\|_{(p.u)}$	Egde	$R_{(p.u)}$	$X_{(p.u)}$	$\|Z\|_{(p.u)}$
e_1	0.019	0.058	0.061	e_{15}	Nan	0.256	0.256	e_{29}	0.012	0.024	0.026
e_2	0.045	0.185	0.191	e_{16}	Nan	0.140	0.140	e_{30}	0.100	0.202	0.225
e_3	0.057	0.174	0.183	e_{17}	0.695	0.256	0.284	e_{31}	0.115	0.179	0.213
e_4	0.013	0.038	0.040	e_{18}	0.695	0.130	0.146	e_{32}	0.132	0.270	0.301
e_5	0.047	0.198	0.204	e_{19}	0.695	0.199	0.220	e_{33}	0.189	0.329	0.379
e_6	0.058	0.176	0.186	e_{20}	0.695	0.200	0.298	e_{34}	0.254	0.380	0.457
e_7	0.012	0.041	0.043	e_{21}	0.695	0.192	0.199	e_{35}	0.109	0.209	0.236
e_8	0.046	0.116	0.125	e_{22}	0.695	0.219	0.243	e_{36}	0.000	0.396	0.396
e_9	0.027	0.082	0.086	e_{23}	0.695	0.129	0.144	e_{37}	0.220	0.415	0.470
e_{10}	0.012	0.042	0.044	e_{24}	0.751	0.068	0.076	e_{38}	0.320	0.603	0.682
e_{11}	0.000	0.208	0.208	e_{25}	0.751	0.209	0.229	e_{39}	0.240	0.453	0.513
e_{12}	0.000	0.556	0.556	e_{26}	0.751	0.085	0.090	e_{40}	0.064	0.200	0.210
e_{13}	0.000	0.208	0.208	e_{27}	0.751	0.075	0.083	e_{41}	0.017	0.060	0.062
e_{14}	0.000	0.110	0.110	e_{28}	0.751	0.150	0.167				

A. *Reliability parameter*

The reliability parameters are focused on identifying the values of CM, PM, transient-state, HPeP, steady-state point, and EM. HPeP is calculated using Equation (19) with illustration of the use of parameters in the system reliability analysis. The CM or wear out is the operational condition of the system after passing steady-state. PM or useful life is the operational time of the system before it reaches a steady-state. HPeP refers to the lowest point at which system performance drops for the first time. Steady-state refers to the endpoint of the period PM to CM. EM refers to the condition in the system where there is a change from a transition-state to steady-state. EM is calculated using equation (18), where $R(n)$ is year reliability (n), while $R(n+1)$ is year reliability $(n+1)$. The correlation between the operational duration of the Bus unit and the system reliability value is calculated using the correlation equation (20), where R_{yx} is the correlation coefficient of the operational period (x) and the steady-state reliability of the system (Y).

$$EM = \Delta R(n) = R(n) - R(n+1) = 0 \quad (18)$$

$$HPeP = R(n) = \pi_j(0)P^n \quad (19)$$

$$R_{yx} = \frac{\Sigma(x-\bar{x}).(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2.(y-\bar{y})^2}} \quad (20)$$

IV. RESULTS AND DISCUSSION

A. *Line Failure rate on reactants and resistance*

The system reliability rate value is determined based on the partial data in the Table 1. Since some lines, such as $e11$ to $e16$, have no conductor, meaning that the line has a value of R = 0 Ω, the failure rate per year (λ) for each Bus system is calculated using equation (10), as shown in Figure 2. The failure rate per year has the same characteristics as the line resistance value (ohm). Using Markov approach, the steady state of the system can be identified based on the PM duration of each Bus system. The colour of the Bus system is a steady state sign of the PM duration, and there are seven transmission lines $(e_{32}, e_{33}, e_{20}, e_{34}, e_{37}, e_{38}, e_{39})$ with reliability values above 10%. In addition, the average failure rate is 0.057, meaning that the system works with acceptable reliability.

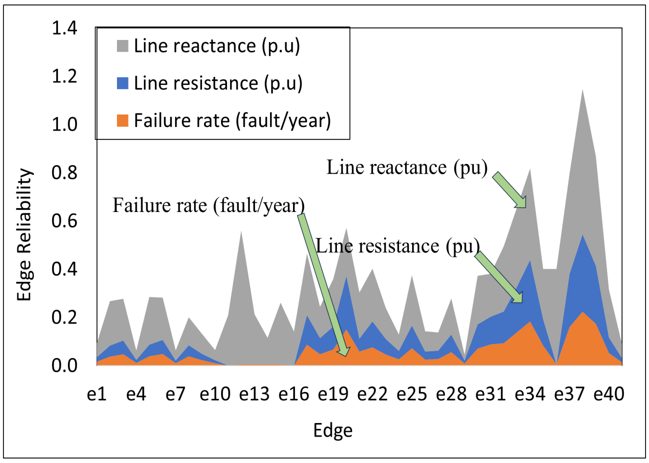


Fig. 2: Failure rate, line reactance, and line resistance

B. *IEEE-Power System Architecture with 30 Bus*

Figure 3 shows the result of simulation using the Markov method with Equation (15) to Equation (16) and data shown in Table 1. The variation of the transient was shown in different colours, representing the system bus steady-state transient. The red colour indicates the steady-state value of the bus system with the shortest operating duration of 11 years, while the green colour represents the steady-state transient of the bus system with the most extended active period of 20 years. Figure 3 allows the user immediately knows which bus system will be down earlier and which bus system has a long operational duration, so maintenance decisions can be carried out optimally based on the position of the bus system.

C. *Steady State Analysis*

Table 2 shows the result of the Transition of Steady-State Matrix analysis on 28 buses with two power sources and an operational period of 20 years. The values of CM, PM, HPeP on each bus are based on the characteristics of system requirements over 20 years. Moreover, the values of CM, PM, and HPeP on each bus system are based on the characteristics of system requirements over 20 years. Table 2 shows the values of HPeP, CM, and PM from each bus. This result is highly dependent on the system workload profile. The analysis results show that the HpeP point occurs at Bus 1 to Bus 30, and there are also eight cycles of the PM period starting from the first year to the 20^{th} year. Therefore,

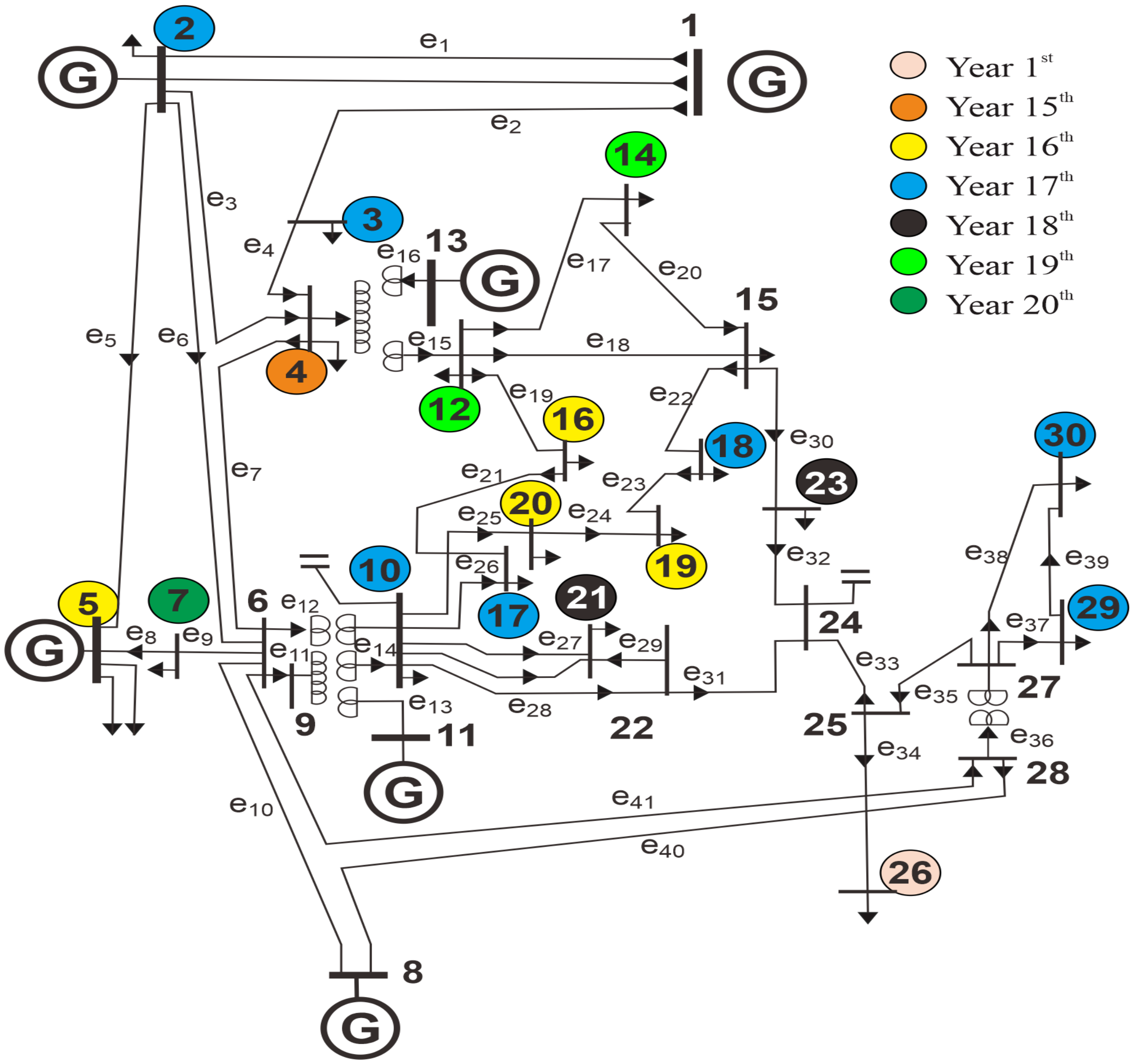


Fig. 3: Maintenance time indicator of each bus

to get a broad perspective on the results and more simply understand, the discussion in this study is divided into two main parts. The first part discusses the analysis results of the maintenance scheduling on a single bus. Meanwhile, the second part discusses maintenance scheduling on multibus. The analysis results start from the maintenance schedule in the initial year to the final year. Maintenance scheduling in the first to 20^{th} years is also presented in Table 3.

D. Preventive to Corrective Analysis

Figure 4 shows the reliability change on Bus 26 as the first system bus to fail. Based on the HPEP point, Bus 26 experienced the lowest reliability decline in the 11^{th} year, i.e., 0.53 $p.u$. There was a fluctuation in reliability, though insignificant. The PM duration on Bus 26 has a duration of 11 years. This condition means that the PM cycle on Bus 26 occurred in the 11^{th} year or that the Transient-state time (T-s) for Bus 26 was 11 years. The characteristics of the constraints on Bus 26 are in the numerical form as shown in Equation (21), where Y Bus 26 is the reliability value ($p.u$), and x is the operational period (years). Equation (21) forms the determinant coefficient (R^2) = 0.999.

Figure 5 shows the reliability change on Bus 24 as the second system bus to fail. Based on the HPEP point, Bus 24 experienced the lowest reliability decline in the 13^{th} year. The reliability value of Bus 24 started at 0.83 $p.u$, then there was a significant decrease in the 5^{th} year. It gradually decreased and reached the lowest value of 0.63 in the 13th year, and then the value of 0.63 did not change until the 20^{th} year. This condition means that on Bus 24, the HPEP and PM values are simultaneous in the 13^{th} year or that the Transient-state (T-s) time for Bus 24 is 13 years. The characteristics of the constraints on Bus 24 are in the numerical form areas as shown in Equation (22), where Y Bus 24 is the reliability value ($p.u$), and x is the operational period (years). Equation (22) forms with the determinant coefficient $(R^2) = 0.99$.

Figure 6 shows the reliability change on Bus 29 as the third system bus to fail. Based on the HPEP point, Bus 29 experienced the lowest reliability decline in the 13^{th} year, and it was only an early symptom. Then, there was an increase in reliability and then dropped back to the lowest reliability point in the 15^{th} year. This condition means that the system ultimately failed in the 15^{th} year. The Bus 29 characteristics experienced the best performance decline

TABLE II: The transition of Steady-State Matriks 28 Buses and two sources system in 20 years estimation

Bus Terminal	1	2	...	11	12	13	14	15	16	17	18	19	20
Bus_1	0.99	0.99	...	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Bus_2	0.98	0.97	...	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Bus_3	0.96	0.94	...	0.89	0.89	0.89	0.89	0.89	0.89	0.95	0.89	0.89	0.89
Bus_4	1.00	0.99	...	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Bus_5	1.00	0.99	...	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Bus_6	1.00	1.00	...	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bus_7	0.98	0.96	...	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Bus_8	1.00	1.00	...	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Bus_9	1.00	1.00	...	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bus_{10}	0.98	0.97	...	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Bus_{11}	0.99	0.99	...	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Bus_{12}	0.99	0.99	...	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Bus_{13}	0.99	1.00	...	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bus_{14}	0.91	0.85	...	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Bus_{15}	0.98	0.97	...	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Bus_{16}	0.93	0.88	...	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Bus_{17}	0.98	0.96	...	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Bus_{18}	0.91	0.85	...	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Bus_{19}	1.00	0.99	...	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98
Bus_{20}	0.91	0.85	...	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Bus_{21}	0.95	0.92	...	0.87	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Bus_{22}	0.92	0.88	...	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Bus_{23}	0.91	0.86	...	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Bus_{24}	0.83	0.74	...	0.64	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Bus_{25}	0.89	0.82	...	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Bus_{26}	0.73	0.62	...	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Bus_{27}	0.97	0.94	...	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Bus_{28}	0.98	0.97	...	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Bus_{29}	0.82	0.73	...	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Bus_{30}	0.91	0.86	...	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77

TABLE III: Criteria Bus

Priority Scala	Bus system	Total (Bus)
1	Bus_26	1
2	Bus_24	1
3	Bus_29	1
4	Bus_20	1
5	Bus_18, Bus_22, Bus_25, Bus_30	4
6	Bus_16, Bus_17, Bus_21, Bus_23, Bus_28	5
7	Bus_3, Bus_4, Bus_5, Bus_10, Bus_12, Bus_14, Bus_19	7
8	Bus_2, Bus_6, Bus_7, Bus_8, Bus_9, Bus_11, Bus_15, Bus_27	8

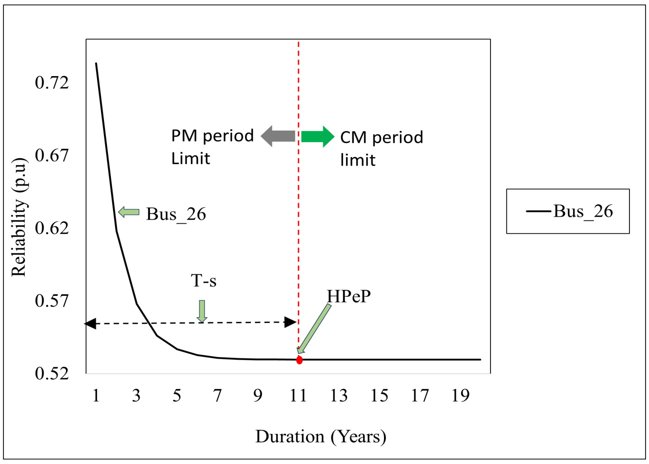


Fig. 4: Preventive to corrective maintenance transition in 11 year after used

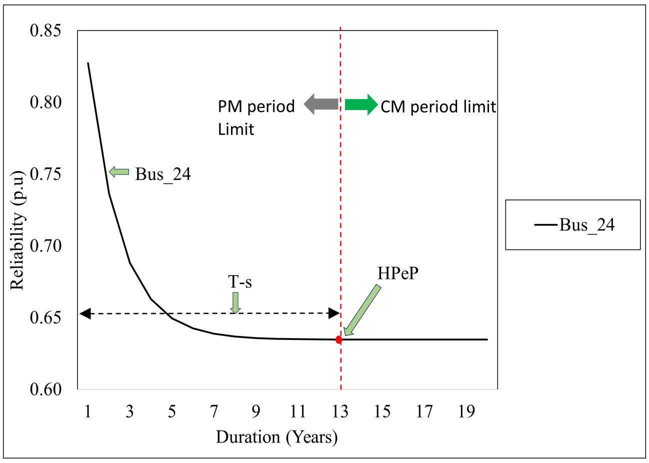


Fig. 5: Preventive to corrective maintenance transition in 13 year after used

HPeP period in the 13^{th} year, while the PM value occurred in the 16^{th} year. The reliability matrix value in Table 2 shows that Bus 29 in year 0 started with a reliability value of 0.82. There was a significant decrease from year 0 to year 6. It gradually decreased and reached the lowest value of 0.62 in year 13, meaning that the HPeP value for Bus 29 occurs in year 13. From the 15^{th} to 20^{th} year, the reliability value was constant at 0.63. This condition means that the PM cycle ended in the 16^{th} year or, in other words, that the Transient-state (T-s) time is 16 years. The characteristics

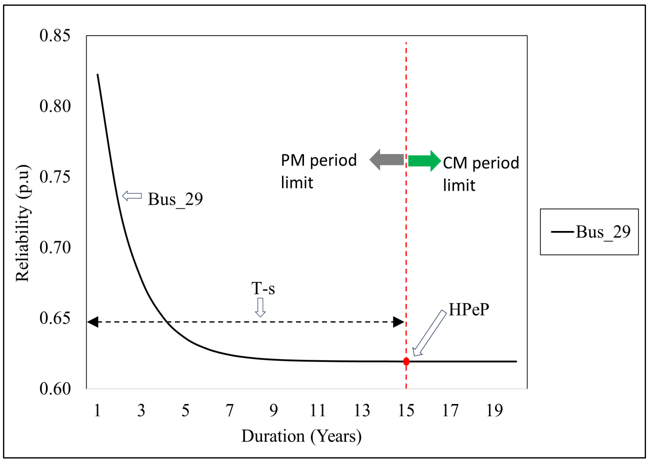


Fig. 6: Preventive to corrective maintenance transition in 15 year after used

of the constraints on Bus 26 are in the numerical form as shown in Equation (23), where Y Bus 29 is the reliability value ($p.u$), and x is the operational period (years). Equation (23) forms the determinant coefficient $(R^2) = 0.99$.

Figure 7 show the reliability change on Bus 20 as the third system bus to fail. Based on the HPEP point, Bus 20 experienced the end of the PM cycle in year 16. In the 0^{th} year, Bus 20 started with a reliability value = 0.9 $p.u$. The reliability value decreased significantly in the 16^{th} year. It gradually decreased to the lowest reliability value of 0.77 $p.u$ in the 16^{th} year, and then the reliability value was constant until the 20^{th} year. This condition means that Bus 20 has the same HPeP value as the PM value in the 16^{th} year. In other words, the Transient-state (T-s) time for Bus 20 is 16 years. The characteristics of the constraints on Bus 20 are in the numerical form as shown in Equation (24), where Y Bus 20 is the reliability value $(p.u)$, and x is the operational period (years). Equation (24) forms the determinant coefficient (R^2) =0.99.

$$Y_{Bus\_26} = -3(e^{-07})x^6 - 2(e^{-05})x^5 + 0.0005x^4 - 0.0077x^3 + 0.0609x^2 - 0.2436x + 0.921 \quad (21)$$

$$Y_{Bus\_24} = 1(e^{-07})x^6 - 1(e^{-05})x^5 + 0.0003x^4 - 0.0048x^3 + 0.0409x^2 - 0.1808x + 0.9707 \quad (22)$$

$$Y_{Bus\_29} = 1(e^{-07})x^6 - 1(e^{-05})x^5 + 0.0003x^4 - 0.0049x^3 + 0.0419x^2 - 0.187x + 0.9711 \quad (23)$$

$$Y_{Bus\_20} = 6(e^{-08})x^6 - 4(e^{-06})x5 + 0.0001x^4 - 0.0022x^3 + 0.0201x^2 - 0.1011x + 0.992 \quad (24)$$

Figure 8 shows the results of grouping the steady-state reliability of the Bus system in the 18^{th} year. Bus 16, Bus 17, Bus 21, and Bus 28 are systems where the lowest reliability value HPeP occurred in the 16^{th} year, although each Bus system started with a different initial reliability value. In addition, Bus 23 had the lowest reliability value HPeP occurring in the 15^{th} year. The whole Bus system in Figure 8 has different initial reliability values. Bus 28 had the highest initial reliability value. At the same time, Bus 23 had the lowest initial reliability value, but Bus 23 was the fastest periodic PM, i.e., in the 16^{th} year.

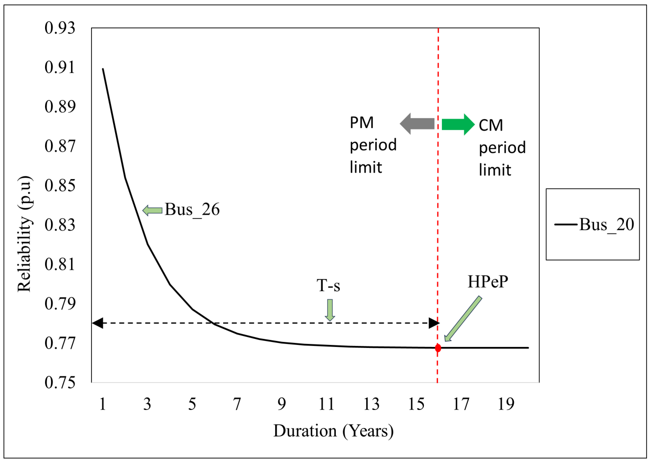


Fig. 7: Preventive to corrective maintenance transition in 16 year after used

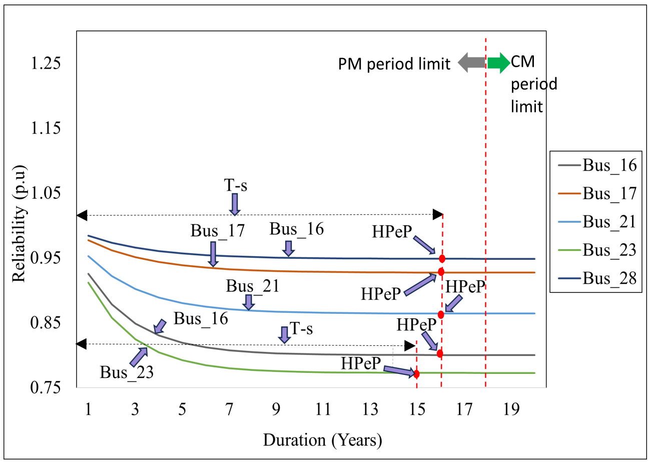


Fig. 8: Preventive to corrective maintenance transition in 18 year after used

The reliability characteristics of the five bus systems in the numerical form are presented in a polynomial with the determinant coefficient for all buses on average being (R^2)=0.99. Therefore, the steady-state reliability characteristic in the Bus 16 system is represented in Equation (28). The steady-state reliability characteristic for the Bus 17 system is expressed in Equation (26). The steady-state reliability characteristic for the Bus 21 system is presented in Equation (27). The steady-state reliability characteristic for the Bus 23 system is expressed in equation (28), and the steady-state reliability characteristic for the Bus 28 system is presented in Equation (28). From Equation (25) to Equation (29), Y_{Bus_n} n is the reliability value of the Bus system $(p.u)$, and x is the operational period (year).

$$Y_{Bus\_16} = -6(e^{-07})x^5 + 4(e^{-05})x^4 - 0.001x^3 + 0.0121x^2 - 0.0744x + 0.9874 \quad (25)$$

$$Y_{Bus\_17} = 2(e^{-06})x^4 - 0.0001x^3 + 0.0023x^2 - 0.0199x + 0.9941 \quad (26)$$

$$Y_{Bus\_21} = 5(e^{-06})x^4 - 0.0002x^3 + 0.0046x^2 - 0.0387x + 0.9846 \quad (27)$$

$$Y_{Bus\_23} = -7(e^{-07})x^5 + 5(e^{-05})x^4 - 0.0012x^3 + 0.0143x^2 - 0.0858x + 0.983 \quad (28)$$

$$Y_{Bus\_28} = 1(e_{-06})x_4 - 8(e^{-05})x^3 + 0.0016x^2 - 0.0139x + 0.9961 \quad (29)$$

The numerical form of reliability characteristics in Equation (11) is presented as a polynomial with the determinant coefficient for all mean buses (R^2)=0.99. Here are some regression equations for the bus system. The Bus system reliability characteristic trend is expressed in Equation (38) – Equation (43). Meanwhile, Equation (22) is for the Bus 9, Equation (38) is for the Bus 11, Equation (42) is for the Bus 7, and Equation (43) is for the Bus 27. Where the Y_{Bus_n} n is the reliability value of the Bus system $(p.u)$, and x is the operational period (year).

Figure 9 shows the steady-state reliability of the Bus system in the 19^{th} year. As shown, seven Bus systems experienced the end of the PM period in the 19^{th} year. Each Bus system had a different initial reliability value, between 0.9 to 0.99. However, the HPeP value of the destination Bus system varies. The Bus 12 system was the earliest HPeP, in the 13^{th} year, followed by Bus 14 and Bus 19 in the 14^{th} year, Bus 10 in the 15^{th} year, Bus 3 and Bus 4 in the 17^{th} year, and Bus 5 in the 19^{th}.

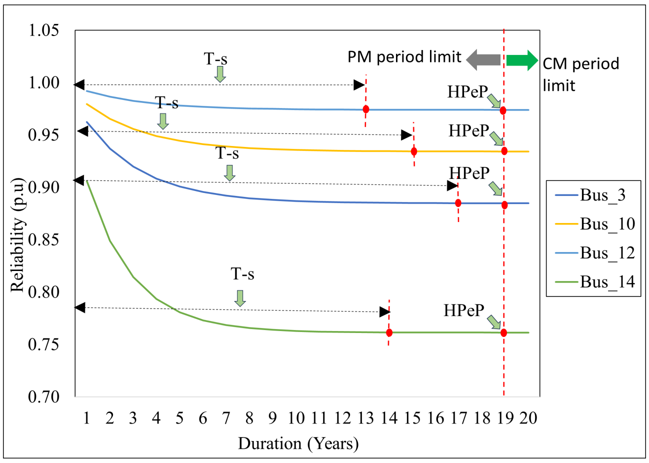
The numerical form of reliability characteristics in Figure 9 is presented as a polynomial with the determinant coefficient for all mean buses (R^2)=0.99. Here are some regression equations for the bus system. Bus 14 is presented in Equation (22). The steady-state reliability characteristic for the Bus 3 system is offered in Equation (31). The characteristic reliability for the Bus 10 system is presented in Equation (32). The steady-state reliability characteristic for the Bus 12 system is expressed in Equation (33), and the steady-state reliability characteristic for the Bus 5 system is presented in Equation (34) as show in Figure 10. The steady-state reliability characteristic for the Bus 19 system is expressed in Equation (31). Finally, Equation (36) is the steady-state reliability characteristic of the Bus 4 system as show in Figure 10. From Equation (22) to (36), Y_{Bus_n} is the reliability value of the Bus system $(p.u)$, and x is the operational period (year).

$$Y_{Bus\_14} = -8(e^{-07})x^5 + 5(e^{-05})x^4 - 13(e^{-04})x^3 + 152(e^{-04})x^2 - 0.0907x + 0.9811 \quad (30)$$

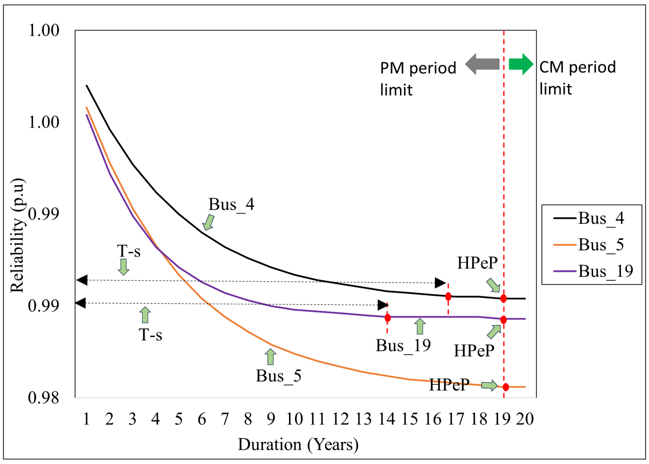
$$Y_{Bus\_3} = -3(e^{-07})x^5 + 2(e^{-05})x^4 - 4(e^{-04})x^3 + 58(e^{-04})x^2 - 0.039x + 0.9957 \quad (31)$$

$$Y_{Bus\_10} = 2(e^{-06})x^4 - 1(e^{-04})x^3 + 2(e^{-03})x^2 + 0.0179x + 0.9947 \quad (32)$$

$$Y_{Bus\_12} = 7(e^{-07})x^4 - 4(e^{-05})x^3 + 8(e^{-04})x^2 - 71(e^{-04})x + 0.9979 \quad (33)$$



(a)



(b)

Fig. 9: Preventive to corrective maintenance transition in 19 year after used

$$Y_{Bus\_5} = -4(e^{-06})x^3 + 2(e^{-04})x^2 - 32(e^{-04})x + 0.9985 \quad (34)$$

$$Y_{Bus\_19} = -5(e^{-06})x^3 + 2(e^{-04})x^2 - 3(e^{-03})x + 0.9975 \quad (35)$$

$$Y_{Bus\_4} = -5(e^{-06})x^3 + 2(e^{-04})x^2 - 3(e^{-03})x + 0.9975 \quad (36)$$

Figure 11 shows a group of Bus systems with steady-state reliability, with the most recent PM period being the 20^{th} year. There are eight Bus systems with different HPeP values. These eight systems had initial reliability values ranging from 0.97 to 0.99, but each Bus system experienced unequal steady-state changes in reliability. Figure 13 shows Bus 11 was the earliest HPeP in the 14^{th} year. Bus 7, Bus 9, and Bus 2 had the same HPeP values in year 15. Bus 15 and Bus 8 had HPeP value in the 16^{th} year, while Bus 27 had HPeP in the 17^{th} year.

$$Y_{Bus\_9} = Y_{Bus\_6} = 9(e^{-08})x^4 - 5(e^{-06})x^3 + 1(e^{-04})x^2 - 15(e^{-04})x + 0.9998 \quad (37)$$

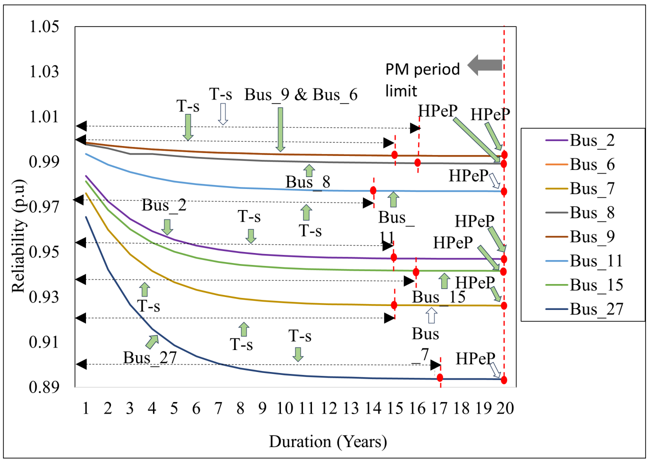


Fig. 10: Preventive to corrective maintenance transition in 20 year after used

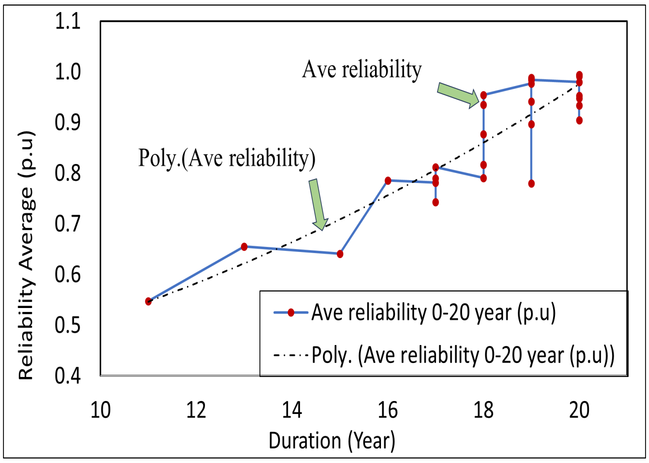


Fig. 11: Correlation of maintanance duration

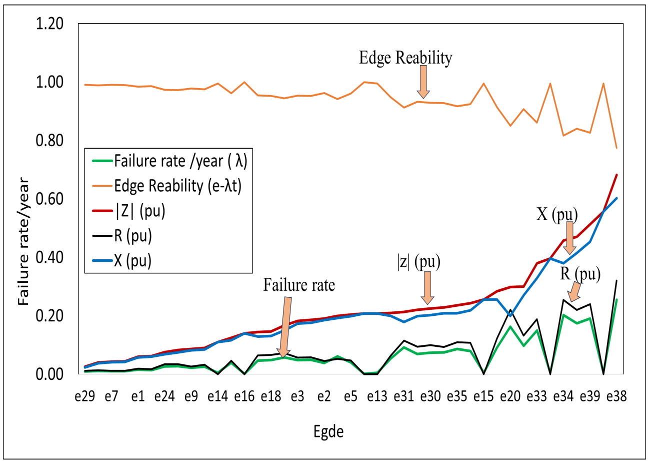


Fig. 12: Correlation of edge reliability with variable R, X, and λ to Z

$$\begin{aligned} Y_{Bus\_8} &= 2(e^{-07})x^4 - 1(e^{-05})x^3 + 2(e^{-04})x^2 \\ &\quad -24(e^{-04})x + 0.9998 \end{aligned} \tag{38}$$

$$\begin{aligned} Y_{Bus\_11} &= 6(e^{-07})x^4 - 3(e^{-05})x^3 + 6(e^{-04})x^2 \\ &\quad -0.006x + 0.9986 \end{aligned} \tag{39}$$

$$\begin{aligned} Y_{Bus\_2} &= 1(e^{-06})x^4 - 8(e^{-05})x^3 + 16(e^{-04})x^2 \\ &\quad -144(e^{-04})x + 0.9959 \end{aligned} \tag{40}$$

$$\begin{aligned} Y_{Bus\_15} &= -1(e^{-07})x^5 + 8(e^{-06})x^4 - 2(e^{-04})x^3 \\ &\quad +29(e^{-04})x^2 - 0.0194x + 0.998 \end{aligned} \tag{41}$$

$$\begin{aligned} Y_{Bus\_7} &= -2(e^{-07})x^5 + 1(e^{-05})x^4 - 3(e^{-04})x^3 \\ &\quad +37(e^{-04})x^2 - 0.0249x + 0.9973 \end{aligned} \tag{42}$$

$$\begin{aligned} Y_{Bus\_27} &= -2(e^{-07})x^5 + 2(e^{-05})x^4 - 4(e^{-04})x^3 \\ &\quad +53(e^{-04})x^2 - 0.0358x + 0.9961 \end{aligned} \tag{43}$$

$$Y_{Y reliability} = 0.0014x^2 + 0.0034x + 0.3364 \tag{44}$$

Based on Table 2, the reliability system has significantly changed from year 0 to 6^{th}. The operational duration and then converted into the average value of reliability and then compared with the year at the end of the PM period of each Bus system. The relationship between the system reliability and the operational period is expressed in Equation (44), where the determinant coefficient $(R^2) = 0.8$, $x = 18.07$, $y = 0.87$, then the correlation coefficient (R_{yx}) is 0.893. Therefore, the higher the reliability, the longer the Bus system can operate as shown in Figure 12.

E. Edge Reliability Analysis

The comparison of system failure rate per year and edge reliability need to be observed to find the correlation. Figure 13 shows the effect of various variables on the transmission system based on the impedance values, sorted from small impedance to large impedance. Generally, the impedance (Z) value positively affects the load of resistive (R), Admittance (X), and failure rate/year (λ). However, the Z value negatively affects the edge reliability. This means that the greater the impedance value (Z), the longer conductor between the Bus system in the transmission network, and vice versa. In addition, the higher the Z value, the lower the edge reliability value. This means that the greater the impedance value (Z), the longer conductor between the Bus system in the transmission network, and vice versa. In addition, the higher the Z value, the lower the edge reliability value.

The arrangement based on network impedance shows that Edge (e_{29}) has the shortest distance between buses, and Edge (e_{38}) is the edge with the farthest distance between buses. The R-value affects the failure rate value linearly, meaning that the higher the R-value of a conductor, the higher the failure rate that occurs. This result is in accordance with the prevailing theory of the transmission system.

F. Implementation

We successfully tested the Markov method on a 30-Bus power system model from IEEE. Currently, we are implementing the Markov method for steady-state analysis on a power system installed in Java-Bali Island, Indonesia, consisting of 20 Buses. This implementation test aims to demonstrate the effectiveness of the Markov method for analyzing the reliability duration of the Java-Bali transmission power system. Figure 14 presents the reliability characteris-

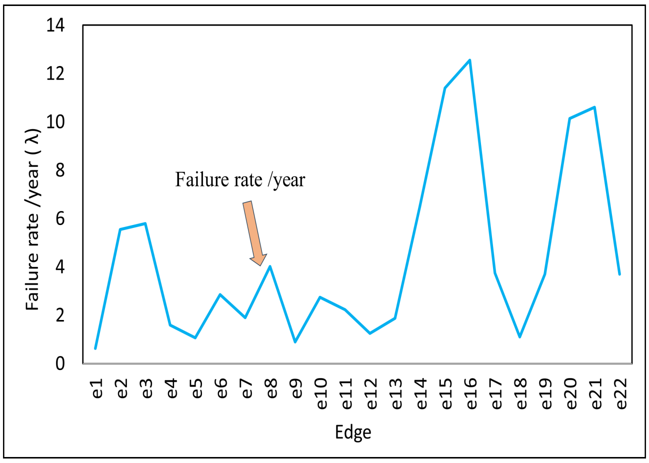


Fig. 13: The characteristics of failure rate per year

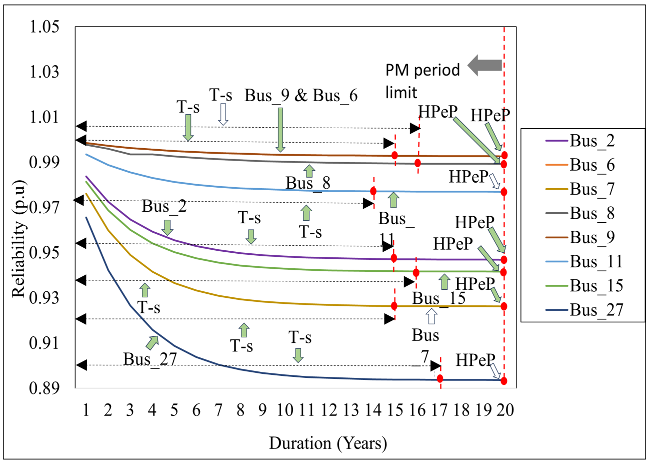


Fig. 14: Preventive to corrective maintenance transition in 20 year

tics of the transmission lines in the Java-Bali power system. These lines range in length from 12.48 km to 202.783 km.

Figure 14 shows the reliability identification analysis of each Bus system based on the operational year. The Bus 6 system exhibited the lowest reliability at 32.65%, which occurred in the 6^{th} year. On the other hand, the Bus 2, Bus 5, and Bus 7 systems showcased the highest reliability, exceeding 92%, as they continued to operate until the 18^{th} year.

V. CONCLUSION

Several important findings were obtained regarding the detailed comprehensive identification of the performance of a high voltage system operating with a 30-Bus system. The lowest point of power system operational degradation, based on 20 years of operation, was identified. In addition, the urgency level of performance degradation was identified using the Markov method as a function of time.

In general, the bus units in the power system are affected by the initial reliability of each bus. Therefore, the electrical load on the bus system is sought following the capabilities of the bus system. Overloading will shorten the system's lifetime, impacting the reliability of a failed system. The Markov method was successfully implemented in the system's reliability characteristics analysis in a long- term period. This study shows that the Markov Method can obtain the value of the steady-state reliability or the minimum reliability value of the bus terminal, indicating the time for maintenance.

The reliability values of Bus 23, Bus 26, and Bus 29 in the first year were 0.9117, 0.7335, and 0.8224, respectively. This means that in the first year, the probabilities of Bus 23, Bus 26, and Bus 29 networks performing their functions were 91.17%, 73.35%, and 82.24%, respectively. There was a decrease in reliability in the transmission system. Bus 23 had reliability decline in year 18, Bus 26 occurred in the year 11, and Bus 29 occurred in the year 15. The reliability values did not decrease in the following years and remained at 0.7726 for Bus 23, 0.5296 for Bus 26, and 0.6193 for Bus 29. This state is called the steady-state reliability value. This reliability value indicates the long-term probabilities of Bus 23, Bus 26, and Bus 29 functions were 77.26%, 52.96%, and 61.93%, respectively. Furthermore, the steady-state transients for Bus 23, Bus 26, and Bus 29 occurred in year 15, year 11, and year 13, respectively. The time range between transient-state and steady-state is the adequate time for maintenance. The average effective maintenance time for each bus in this system network is 3.9 years per bus. In this case, the determinant coefficient (R^2) is 0.89, which means that the effect of the time variable on reliability is 0.8, while the remaining 0.2 is influenced by inherent variability. In other words, the greater the reliability value of a system, the longer the preventive maintenance duration.

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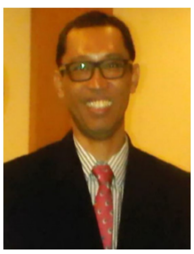

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