Reliability-Centered Maintenance Scheduling of Photovoltaic Components According to Failure Effects

Joong-Woo Shin 1, Kwang-Hoon Yoon 1, Hui-Seok Chai 2 and Jae-Chul Kim 1,*

1 Department of Electrical Engineering, Soongsil University, 369, Sangdo-ro, Dongjak-gu, Seoul 06978, Korea; jwshin@soongsil.ac.kr (J.-W.S.); kwanghoon@soongsil.ac.kr (K.-H.Y.)
2 R&D Center, Hyosung Corporation Power & Industrial System, 74, Simin-daero, Dongan-gu, Anyang-si 14117, Korea; hschai@hyosung.com
* Correspondence: jckim@ssu.ac.kr

Abstract: In the power distribution system of South Korea, the sectionalizer minimizes and recovers the system from failures, and prohibits independent operation of distributed energy resources. Therefore, it is difficult to expect reliability improvements owing to a photovoltaic system in the power distribution system. Herein, we propose a reliability-centered maintenance-scheduling method based on an economic analysis of photovoltaic integration facilities to ensure the economic feasibility of the photovoltaic system operator and the reliability of the power distribution system. Photovoltaic integration facilities are divided into two categories based on their spread of the failure, and the maintenance scheduling is evaluated according to the maximum and minimum losses according to the time of failure. Facilities that cause power outages to photovoltaics and to loads have relatively little effect on the time of failure. This is because the effects of the power outages in the loads predominate. In contrast, facilities that only cause photovoltaic outages are affected by the generation time. In particular, insulated gate bipolar transistors that operate only during photovoltaic generation have been found to be more economical for corrective replacement than preventive replacement.

Keywords: power outage; power distribution system; photovoltaic; Weibull distribution; maintenance scheduling

1. Introduction

The application of photovoltaic (PV) systems is increasing because these systems can be configured in various capacities and have lower installation, operation, and maintenance costs than other renewable energy systems [1]. In South Korea, a PV system has the maximum power generation efficiency of 11% during the peak period [2]. Therefore, efficient PV system operation is required, and economical and reasonable maintenance scheduling of a PV system would be beneficial to increasing the PV systems’ performances [3]. Analyzing the availability of the PV systems’ components and evaluating the lifetime degradation model are necessary for their maintenance scheduling. Excessive maintenance is costly; therefore, it is necessary to determine an appropriate maintenance scheduling through an economic evaluation.

When a failure occurs in the components of a PV system, it may cause a power outage in the loads and stop the PV output. The islanding operation of a PV system improves the reliability of the power supply in the event of a power distribution system outage [4–7]. However, when the islanding operation of distributed energy resources (DERs) is prohibited, the failure of PV components contributes to power outage in the distribution system, depending on the effect of the failure.

In this regard, Mathew et al. [7] evaluated the reliability-improvement effect of the rooftop-PV islanding operation in a radial power distribution system. The rooftop PV was installed with a small generation capacity, and the islanding operation of the rooftop PV was considered probabilistic. However, owing to the unrealistic configuration of the
distribution system, when a failure occurred in the load at the starting point of the feeder, all loads in the feeder experienced a power outage. Spertino et al. [8] evaluated the reliability and maintenance effectiveness of various PV systems. The maintenance was performed according to the regulations. However, the study did not present an evaluation method for the maintenance scheduling for each component. Peters and Madlener [9] categorized PV-integration components and evaluated their costs according to maintenance schedules. However, the maintenance method was evaluated as a short-term replacement strategy and not for long-term repair operations. Xiaojing et al. [10] applied a multi-state Markov model to evaluate the deterioration lives of PV components and optimize the maintenance cycle, considering various cost factors. However, the effects on the distribution system load of various PV components were not considered. Sayed et al. [11] analyzed the appropriate lifetime model of PV components and the reliability of a PV system. However, there was no access for maintenance, and the ripple effect of failures of components was not considered. Bosman et al. [12] reviewed various approaches for PV plant maintenance. Among them, failure mode and effects analysis (FMEA) presented as a moderately economical and reliable method. Additionally, it is essential to the predictive maintenance model to consider the failure probabilities of PV system elements. Gradwohl et al. [13] presented a method that combines physical and statistical models for optimal PV plant maintenance. Its prediction of failure through diagnosis has high accuracy, but diagnosis is not a suitable practice for small-scale PV systems. Iftikhar et al. [14] presented indicators for predictive maintenance of large-scale PV plants based on measurement data. However, for relatively small PV systems, the installation of measuring equipment and data collection are not economically appropriate.

In this study, the maintenance scheduling of small and medium-scale PV systems connected to load feeder components was evaluated by considering the effects of load and PV outages on power distribution systems. Weibull distribution was used in a lifetime degradation model to reflect the maintenance effects of the PV-system components. The lifetime degradation models of circuit breakers (CBs), mold transformers, and inverters have been reported in the literature. The lifetime degradation model of the inverter interprets accelerated life test data. The lifetime degradation model under normal operating conditions was derived by considering the acceleration coefficient and operating time of the PV inverter in the accelerated degradation test data [15–17]. Next, we evaluated the reliability of the PV and power distribution systems through lifetime degradation models of PV system components. The evaluated reliability was converted into cost and used for the economic maintenance scheduling of the components.

2. Reliability Assessment of Power Distribution System with PV

In this section, the lifetime model of components is assumed to be a Weibull distribution, and the reliability of the PV-integrated power distribution system is evaluated by dividing it into a load point and a PV point of view.

The islanding operation of DERs improves the reliability of a power distribution system [4–7]. However, the failure rate of the distribution system increases owing to the DER interconnecting facilities, which adversely affects the reliability of the distribution system because it prohibits the islanding operation of DERs.

The power distribution system with DERs, in which the feeder is sectionalized and interconnected with a nearby feeder, follows the recovery procedure shown in Figure 1.

2.1. Lifetime Degradation Models of PV System Components

PV systems normally comprise a PV array, a power conditioning system (PCS), protection devices, and components for interconnection with power distribution systems, such as mold transformers and vacuum circuit breakers (VCBs). The failure mode of each component may result in a fire, a partial power outage, or a PV system power outage. In particular, a failure of the inverter or components for interconnection with the power system will cause the PV system to experience a power outage [18]. In this study, the inverter, mold
transformer, and VCB, which cause power outage of a PV system in the event of a failure, were selected as the maintenance targets. The PV array causes partial outages in a PV system if a failure occurs, and it was excluded from the reliability evaluation. The inverter comprises various subcomponents. Among these subcomponents, failures of the power conversion semiconductors, such as the insulated gate bipolar transistor (IGBT), account for the largest proportion of inverter failures [19–22]. In this study, IGBT was found to be the main cause of the inverter performance degradation. IGBTs are replaced when reliability improvements are required. Figure 2 shows the PV system configuration with the maintenance targets. The maintenance targets exhibit failure effects with no energy output from the PV system.

Figure 1. Failure recovery procedure of a power distribution system with DERs.

DERs experience power outages not only in the DER integration facilities but also in the event of a power-distribution-system failure. Distribution-system failures account for the largest proportion of DER power outages [18,19].

Figure 2. PV system configuration with maintenance targets.
The components of the PV system are configured in series, except for the PV array. Therefore, the reliability function of the PV system is defined as

\[ R_{\text{PV.sys}}(t) = \prod_{i=1}^{n} R(t)_i \]  

(1)

\[ \lambda_{\text{PV.sys}}(t) = \sum_{i=1}^{n} \lambda(t)_i \]  

(2)

where \( R_{\text{PV.sys}}(t) \) is the reliability of the PV system at time \( t \), and \( \lambda_{\text{PV.sys}}(t) \) is the failure rate of the PV system at time \( t \) [23].

Reliability represents the ability to perform within a set standard for a specified time, and is expressed using various probability distributions [8,9]. The exponential and Weibull distributions are often used to describe the reliability function. When the reliability function is an exponential distribution, the failure rate of the components is constant, which does not change with the operating time [23]. Some studies have applied an exponential distribution to the PV system component lifetime degradation model [24–26]. However, the constant failure rate could not represent a decrease in the failure rate owing to the application of maintenance. Spertino et al. [8] evaluated the changing failure rate using a multi-state Markov model. However, only the reliability of PV systems was evaluated, and the effects of the power system and economic analysis were ignored. In this study, the reliability function was evaluated by applying an exponential distribution for non-maintenance targets. The Weibull distribution was applied to the reliability function of the maintenance targets. The reliability function of the Weibull distribution can express the maintenance effect as a failure rate because the failure rate changes according to the operating time. The failure rate function is defined as

\[ \lambda(t) = \frac{m}{\eta} \left( \frac{t}{\eta} \right)^{m-1} \]  

(3)

where \( \lambda(t) \) is the failure rate of the component at time \( t \), \( m \) is the shape parameter that represents the distribution of data, and \( \eta \) is a scale parameter representing the characteristic life [27].

IGBT deterioration is the main cause of inverter deterioration [20]. The life of an IGBT is evaluated by considering its operating temperature along with its operating cycle [15,16,21]. Gupta et al. [20] presented a lifetime model through the evaluation of thermal cycles according to the junction temperature of the IGBT. In this study, the lifetime degradation model of the IGBT was evaluated using accelerated degradation test data based on the thermal cycle evaluation method. Figure 3 shows the flowchart for converting the accelerated degradation test data, which is the lifetime in cycles of IGBT, into the IGBT lifetime in years.

The acceleration coefficient represents the IGBT junction temperature stress in the accelerated degradation test. The Arrhenius model is a relational expression used in the analysis of accelerated degradation tests based on temperature. The Arrhenius acceleration coefficient is defined as

\[ AF_{\text{Arr}} = e^{\left( \frac{E_a}{k} \left( \frac{1}{T_d} - \frac{1}{T_a} \right) \right)} \]  

(4)

where \( E_a \) is the activation energy [eV], \( k \) is the Boltzmann constant, \( T_d \) is the operating temperature [K], and \( T_a \) is the stress temperature [K] [28].

The thermal cycle of the accelerated degradation test was performed under test conditions. In the fundamental frequency cycle, the thermal cycle is the device conduction time \( t_{on} \), which is defined as

\[ t_{on} = \frac{\pi + 2\phi - 2\theta}{2\pi} \times \frac{1}{f} \]  

(5)

where \( \phi \) is the power factor angle, \( \theta \) is the firing angle, and \( f \) is the fundamental frequency [17].
2.2. Reliability Indices of the PV System

The PV system has a limit in determining the severity or importance of failure by components with basic reliability indices (failure rate, repair time, and unavailability) owing to intermittent output. Therefore, a reliability evaluation that reflects the operation and failure characteristics of each component is required. It should be noted that the inverter operates during the PV generation period. Hence, inverter failure can only occur during the PV generation period. In contrast, the mold transformer and VCB operate for 24 h, including the no-load condition.

The PV-system components are evaluated differently in the expected energy not supplied (EENS), depending on the time of failure. Therefore, in this study, the reliability of the PV system was evaluated using the following six scenarios:

- Scenario 1: Maximum EENS of inverter failure.
- Scenario 2: Minimum EENS of inverter failure.
- Scenario 3: Maximum EENS of mold transformer failure.
- Scenario 4: Minimum EENS of mold transformer failure.
- Scenario 5: Maximum EENS of VCB failure.
- Scenario 6: Minimum EENS of VCB failure.

The reliability of a PV system is expressed as the EENS and cost of failure risk (CFR) in terms of energy and cost.

\[ EENS_{PV} = P_{scenario} \times \lambda(t)_{PV} \times (r_{PV} + l_{PV}), \]  

(6)

where \( \lambda(t)_{PV} \) is sum of PV components failure rate, \( P_{scenario} \) is PV outage energy by failure scenario [MWh], \( r_{PV} \) is the repair time of PV components, and \( l_{PV} \) is the lead time of PV components.

2.3. Reliability Indices of Power Distribution System with PV

The reliability of the power distribution system was evaluated using customer-oriented, load, and energy-oriented reliability indices. The customer-oriented reliability index can accurately express the characteristics of the power distribution system. The system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) are important indices indicating the reliability of the power distribution system [29].

\[ SAIFI = \frac{\sum_{k=1}^{m} \lambda_k N_k}{\sum_{k=1}^{m} N_k}, \]  

(7)
SAIDI = \frac{\sum_{k=1}^{m} U_k N_k}{\sum_{k=1}^{m} N_k}, \quad (8)

where \( N_k \) is the number of customers in load section \( k \), \( \lambda_k \) is the failure rate of load section \( k \), and \( U_k \) is the unavailability of load section \( k \).

In this study, the impact of the maintenance target component reliability in the distribution system was evaluated. The lifetime degradation model of distribution system components uses an exponential distribution. The maintenance targets to which the Weibull distribution lifetime degradation model is applied have a greater impact on the reliability of the distribution system, owing to the operating hours. The impact of maintenance targets on power distribution system reliability is represented by the expected customer interruption cost (ECIC).

\[
\text{ECIC} = C_{ip} \times L_p \times \lambda(t), \quad (9)
\]

where \( C_{ip} \) is the outage cost of load point \( p \) (won/kWh), \( L_p \) is the load of load point \( p \) (kW), and \( \lambda(t) \) is the frequency of outage \( j \) at time \( t \) (f/year).

3. Maintenance Scheduling Method

In this section, we propose a maintenance scheduling method using the reliability index in Section 2. The components were divided into two groups for maintenance scheduling. Notably, the PV system should not degrade the power supply reliability of the load. However, without the islanding operation of the PV system, reliability issues occur because of the increase in the number of components of the power distribution system.

The maintenance scheduling of the PV system components was evaluated according to the failure effect of each component. Failure effects of the maintenance targets of the PV system can occur as follows:

- **Group A**: When a failure occurs, it causes an outage only in the PV system.
- **Group B**: When a failure occurs, it causes outages in the PV and power distribution systems.

Maintenance scheduling requires consideration of the system’s reliability and maintenance investment costs. Frequent maintenance can secure the reliability of the system; however, it cannot be considered reasonable because the maintenance investment cost can become excessive. In addition, the system’s reliability can be set differently based on the operational goals, such as the number and duration of failures. Maintenance scheduling should also be set according to the purpose of the system’s operation.

In this study, we propose a method of maintenance scheduling in light of our cost–benefit analysis that compared the investment and risk costs.

3.1. Investment Cost of Maintenance

The investment cost of maintenance is assessed as the cost of planned outage (CPM) and cost of component maintenance (CCM). The CPM was analyzed according to the scenarios described in Section 2.2. For example, the maintenance of the inverter was performed when PV power was not generated and CPM was zero. CCM includes the component construction and equipment costs, and its value was constant.

3.2. Benefit Cost of Maintenance

Cost of failure risk (CFR) can be used to calculate the expected annual cost of the outage. The CFR of A-type components (see Section 3) was used to evaluate the expected annual cost of PV outages (ECPO) due to the component failure.

\[
\text{ECPO} = \text{EENS}_{PV} \times (C_{PV} + \omega_{REC} \times C_{REC}). \quad (10)
\]

where \( C_{PV} \) is the sales price of PV generation (won/MWh), \( \omega_{REC} \) is the weight factor of renewable energy certificates (REC), and \( C_{REC} \) is the sales price of REC (won/MWh). The CFR of B-type components was used to evaluate the ECPO and ECIC. Maintenance
improves the failure rate of the components. Therefore, the effect of maintenance is evaluated as improvements in ECPO and ECIC.

\[ \Delta \text{ECPO} = \text{ECPO}_{\text{base}} - \text{ECPO}_{\text{maintenance}} \]  
\[ \Delta \text{ECIC} = \text{ECIC}_{\text{base}} - \text{ECIC}_{\text{maintenance}} \]

When maintenance is applied, the probability of component failure is reduced, and the cost of expected outages is also reduced. Therefore, the degree of change in the CFR is the economic benefit to the PV operator and grid operators. When the benefit is higher than the investment cost at the time of maintenance, the economic feasibility of maintenance can be secured. The total costs (TCs) for the maintenance time according to the component groups A and B are given as

\[ \text{TC}_A(t) = \text{CPM} + \text{CCM} - \Delta \text{ECPO}(t_A), \]  
\[ \text{TC}_B(t) = \text{CPM} + \text{CCM} - \Delta \text{ECPO}(t_B) - \Delta \text{ECIC}(t_B). \]

4. Analysis of Maintenance Scheduling of Power Distribution Systems with PV

In this section, the maintenance schedule of the PV components is evaluated based on the reliability analysis of the test model of power distribution. Figure 4 shows the test model of the power distribution system consisting of three feeders rated 22.9 kV. Each feeder had load and line length characteristics for suburban and urban areas. Feeder 1 D/L supplied power to a suburban area. The feeder length was sufficiently long and it operated under a heavy load condition. It was easy to secure a PV installation area, and 14 MW of PV was integrated. Feeder 2 D/L supplied power to rural areas. The feeder was sufficiently long and operated under a light load condition. It was easy to secure a PV installation area, and 14 MW of PV was integrated. Feeder 3 D/L supplied power to urban areas. The feeder was short and operated under a heavy load condition. It was difficult to secure a PV installation area, and only the rooftop PV was connected to the low-voltage line.

![Test power distribution system model](image-url)
Each feeder was sectionalized and interconnected. In the event of a section failure, feeder CB was operated. Subsequently, the failure section was separated, and the sound section was restored through an interconnected feeder. As the PV system cannot operate in islanding mode, the PV system in the failure section experienced outage during the repair time. The PV system in the sound section also separated from the feeder and connecting feeder during the system separation and recovery process.

4.1. Reliability Analysis of Test Power-Distribution-System Model

A minimal cut set is a set of components that cause power outages. As the power distribution system has a vast and complex configuration, the components we used to evaluate the reliability are limited. In this study, the CB, transformer, feeder, and sectionalizer were evaluated as components that cause power failure [29]. Table 1 lists the data of the feeders in the test power distribution system.

Table 1. Data of feeders in the test power distribution system.

| Feeder   | 1       | 2       | 3       |
|----------|---------|---------|---------|
| Regional | Suburban| Rural   | Urban   |
| Load section/Tie | 9/4     | 6/3     | 6/3     |
| Feeder length [km] | 25      | 23.4    | 3.25    |
| PV [MW]  | 14      | 14      | 3.99    |
| Total load (residential/commercial) [kW] | (4889/1260) | (1574/574) | (6810/1870) |

Table 2 lists the data required for the reliability evaluation of the test power distribution system model. The failure rate of a power facility indicates how often a failure causes a power outage. The data listed in Table 2 were used for evaluating the reliability of the power distribution system and the frequency of failures that cause power outages due to disconnection or insulation problems. The reliability indices of the test model of the power distribution were evaluated using the average failure rate and recovery time of each component. The maintenance targets of the PV system are classified as follows:

- Group A: Inverter and mold transformer.
- Group B: VCB.

Table 2. Reliability data of the test power distribution system.

| Parameters          | Components         | Feeder [km] | Mold Transformer | VCB   |
|---------------------|--------------------|-------------|------------------|-------|
| M (Shape parameter) | 2.21               | 2.3649      | 4                |
| H (Shape parameter) | 257.41             | 26.80       | 37.48            |
| Repair time [hours] | 1                  | 10          | 10               |
| Lead time [hours]   | -                  | 20          | 20               |
| MTTF [year]         | 227.98             |             |                   |

Table 3 lists the reliability indices of the distribution system model evaluated by the average failure rates of the components. When a mold transformer was used to supply power to load failure, the loads supplied by the mold transformer experienced outages. However, the failure of the feeder and VCB caused outages in all loads within the section. Therefore, the reliability of the power distribution system with the PV system decreased. The PVs of feeder 3 D/L were rated for less than 500 kW and were interconnected to...
the low-voltage system. Therefore, mold transformers and VCBs were not required for this interconnection. The reliability did not decrease even with PVs present in the system because the failure did not occur in the power distribution system, as protection devices were installed on the primary and secondary sides of the inverter.

Table 3. Reliability analysis result of the test power distribution system model.

| D/L | Indices | SAIFI [f/year-n] | SAIDI [hr/year-n] | ECIC [M Won] |
|-----|---------|------------------|------------------|-------------|
| 1   | Without PV | 0.27             | 1.29             | 782         |
|     | With PV    | 0.36             | 1.91             | 1156        |
| 2   | Without PV | 0.12             | 0.45             | 61          |
|     | With PV    | 0.20             | 1.61             | 140         |
| 3   | Without PV | 0.07             | 0.43             | 63          |
|     | With PV    | 0.07             | 0.43             | 63          |

The lifetime degradation model of the VCB is a Weibull distribution, where the failure rate increases with the increasing operating time. Figure 5 describes the results of Equation (9). It evaluates the ECIC of feeder 1 D/L, which increased as the VCB deteriorated. The failure of the VCB was assumed to cause a power outage in the nearby load section. To evaluate the sensitivity of VCB degradation to ECIC, the failure rates of components other than the VCB were used as the average failure rates. A VCB failure causes an outage of all loads within the same section. Therefore, the VCB in the heavy-load section had a high ECIC. The same lifetime degradation model was assumed for all the VCBs, but the variation in the ECIC was determined by the loads within the section. The failure rate of the VCB at the beginning of the operation was small. Therefore, the effect of the VCB on the reliability of the power distribution system was small. VCB 2 was installed in DL1S3, which had the highest load in the section to which feeder 1 D/L belonged, and the ECIC increased rapidly.

Figure 5. ECIC of feeder 1 D/L according to operating time of VCB.

4.2. Reliability Analysis of PV Systems in Test Power-Distribution-System Model

The reliability of the load assumes that the power is always supplied. The intermittent output of a PV system is considered via Figure 6, which shows the average PV generation with respect to time. The data accumulated for three years in an hour were processed into average data in an hour. PV generation is significantly influenced by the season and climate. In this study, we flexibly changed the short-term intermittent output characteristics of PV generation because it deals with the long-term reliability.
but the variation in the ECIC was determined by the loads within the section. The failure rate of the VCB at the beginning of the operation was small. Therefore, the effect of the VCB on the reliability of the power distribution system was small. VCB 2 was installed in DL1S3, which had the highest load in the section to which feeder 1 D/L belonged, and the ECIC increased rapidly.

Figure 5. ECIC of feeder 1 D/L according to operating time of VCB.

4.2. Reliability Analysis of PV Systems in Test Power-Distribution System Model

The reliability of the load assumes that the power is always supplied. The intermittent output of a PV system is considered via Figure 6, which shows the average PV generation with respect to time. The data accumulated for three years in an hour were processed into average data in an hour. PV generation is significantly influenced by the season and climate. In this study, we flexibly changed the short-term intermittent output characteristics of PV generation because it deals with the long-term reliability.

Figure 6. Annual average output for each time of PV generation.

The inverter can fail only during PV generation. Therefore, if a failure occurs late in the afternoon during sunset, it is rated at the minimum ECPO (S 2). In contrast, if a failure occurs in the morning when PV generation starts (S 1), it is rated at the maximum ECPO. Mold transformers and VCBs can fail at any time of the day. Therefore, if a failure occurs during the time when the PV does not generate power and is recovered before the start of PV power generation, or when there is insufficient power generation, it is evaluated as the minimum ECPO (S 4, 6). Meanwhile, if a failure occurs in the morning when PV power generation starts, a lot of loss occurs in the amount of power generated due to the time required to recover from the failure. Therefore, it is rated as the maximum ECPO (S 3, 5). Table 4 lists the scenario values of each component of the PV system. Each value was evaluated component-by-component with recovery time, as shown in Figure 6.

Table 4. Scenario values of components of the PV system.

| Scenario | Value [p.u] |
|----------|-------------|
| 1        | 3.86        |
| 2        | 0.11        |
| 3        | 6.81        |
| 4        | 3.86        |
| 5        | 6.81        |
| 6        | 3.86        |

Table 5 lists the parameters for evaluating the reduced lifetime model of the inverter. Among the inverter sub-components, the maintenance target was the IGBT. Subcomponents other than IGBT were assumed to cause accidental failure and deterioration. Therefore, IGBT assumed a Weibull distribution, and the remaining subcomponents assumed an exponential distribution [19,25]. Accelerated aging test data for the thermal cycle of the IGBT module were obtained from [32]. Table 5 lists the result of converting the accelerated degradation test to annual lifetime model using Equations (3) and (4).

Table 5 lists the parameters for evaluating the reduced lifetime model of the inverter. Among the inverter sub-components, the maintenance target was the IGBT. Subcomponents other than IGBT were assumed to cause accidental failure and deterioration. Therefore, IGBT assumed a Weibull distribution, and the remaining subcomponents assumed an exponential distribution [19,25]. Accelerated aging test data for the thermal cycle of the IGBT module were obtained from [32]. Table 5 lists the result of converting the accelerated degradation test to annual lifetime model using Equations (3) and (4).
Table 5. Reliability data of the inverter.

| Parameters            | Components | IGBT | CB | FAN | EMI Filter |
|-----------------------|------------|------|----|-----|------------|
| M (Shape parameter)   | 7.6927     | .   | .  | .   | .          |
| H (Shape parameter)   | 28.957     | .   | .  | .   | .          |
| Failure rate [f/year] | .          | 0.0017 | 0.0339 | 1.0 × 10⁻⁸ |
| Repair time [hours]   | 2          |     |    |     |            |
| Lead time [hours]     | 12         |     |    |     |            |

- Constant failure rate.  
- Time-varying failure rate.  
- Values from [19,24].

Figure 7 illustrates the ECPO according to the deterioration of the components of the PV system. Mold transformers had a small failure rate at the beginning of the operation. However, the rate of deterioration was fast, and the recovery time was long; therefore, the ECPO increased rapidly as the operating time elapsed. VCBs had a small failure rate at the beginning of the operation and a slow rate of degradation. Therefore, although the recovery time was long, the variation in ECPO was small. Inverters had a large failure rate at the beginning of the operation. However, because the degradation rate was the slowest and the recovery time was short, the ECPO variations were small.

Figure 8 shows the total cost curve for the maintenance of the components of DL1PV1. For CCM calculations for these components, the values [33–35] were applied. Maintenance is performed when the benefits exceed the investment cost. Maintenance (Scenario 1) refers to the expected TC when the maintenance of Scenario 1 is performed. Maintenance should not be performed until the next scheduled maintenance in the scenario, as the benefit is less than the investment cost.
5. Conclusion

In this study, a maintenance scheduling method using a long-term perspective for the efficient operation of PV system components was proposed. The first limitation of existing studies was that the deterioration characteristics of PV components were not reflected. This was addressed by assuming the lifetime model to be a Weibull distribution. For the lifetime model of the components, reference values were used, and for the IGBT, accelerated degradation test data were converted into an annual lifetime model. The second limitation of other studies was that the impact of the power distribution system in the case of PV component failure was not considered. By referring to the FMEA of PV components, maintenance scheduling was established depending on whether a load outage occurred. The third limitation was that the times of corrective
Table 6 lists the maintenance scheduling results of PV components of the test power distribution system model. The inverter was found to have a maintenance period of more than 20 years in Scenarios 1 and 2. Considering the average expected lifetime of the PV system, it is economical to apply corrective replacement rather than preventive maintenance. For mold transformers, the ECPO increases almost proportionally with the number of days of operation. Therefore, we determined a constant maintenance schedule for all mold transformers. The maintenance of the VCB improves the reliability of both the power distribution and PV systems. However, frequent maintenance is not required because of low failure rate. The VCB installed on 2 D/L with a heavy-load condition has a shorter maintenance period compared to 1 D/L.

Table 6. Maintenance schedule for PV components in the test power distribution system model.

|                | Inverter | Mold Transformer | VCB |
|----------------|----------|------------------|-----|
|                | S 1      | S 2              | S 3 | S 4 | S 5 | S 6 |
| DL1PV1         | 20       | 24               | 6   | 22  | 11  | 14  |
| DL1PV2         | 20       | 37               | 6   | 22  | 9   | 11  |
| DL1PV3         | 20       | 24               | 6   | 22  | 11  | 13  |
| DL1PV4         | 20       | 24               | 6   | 22  | 9   | 12  |
| DL1PV5         | 20       | 23               | 6   | 22  | 9   | 12  |
| DL1PV6         | 23       | 25               | 6   | 22  | 11  | 13  |
| DL2PV1         | 22       | 27               | 6   | 22  | 8   | 10  |
| DL2PV2         | 21       | 38               | 6   | 22  | 8   | 10  |
| DL2PV3         | 21       | 40↑              | 6   | 22  | 8   | 10  |
| DL3PV          | 29       | 40↑              | -   | -   | -   | -   |

5. Conclusions

In this study, a maintenance scheduling method using a long-term perspective for the efficient operation of PV system components was proposed.

The first limitation of existing studies was that the deterioration characteristics of PV components were not reflected. This was addressed by assuming the lifetime model to be a Weibull distribution. For the lifetime model of the components, reference values were used, and for the IGBT, accelerated degradation test data were converted into an annual lifetime model. The second limitation of other studies was that the impact of the power distribution system in the case of PV component failure was not considered. By referring to the FMEA of PV components, maintenance scheduling was established depending on whether a load outage occurred. The third limitation was that the times of corrective replacement and preventive maintenance were not separated. As preventive maintenance is carried out in a planned outage, it can save component purchases and transportation time. Similarly, it is possible to minimize the decrease in PV output by proceeding during the period when there is no PV output. In the present case study, it was assumed that the recovery time of the PV components can be divided into load and repair times, and that maintenance was performed during the periods of no PV output.

The maintenance schedule of PV components converted the reliability evaluation results into economic indices and was prepared using a cost-benefit analysis. The evaluated maintenance schedule allowed more economical operation than the corrective replacement of PV components. The components of the PV system varied and had various failure effects, such as instability, fires, and partial outages. The proposed maintenance scheduling method for PV components is suitable for PV systems connected to the load feeders of the power distribution system. In general, PV systems connected to load feeders are small and medium-scaled, and it is difficult to secure economic feasibility when applying equipment for measuring climatic conditions and diagnosing components. Therefore, maintenance scheduling is applied through statistical reliability evaluation to ensure moderate reliability and economic feasibility.

The reliability evaluation of the PV system applied in this paper did not consider partial power outage and efficiency degradation. A partial power outage can be caused
by various components. In addition, the efficiency of PV system components decreases depending on the number of operating days. For efficient PV system operation from a long-term perspective, systematic collection of failure and maintenance history data and maintenance scheduling in consideration of efficiency are required. Predictive maintenance should consider various factors for accuracy of prediction. The accuracy of failure prediction can be improved through the use of diagnostic data and climate data of PV components. However, equipment for diagnosis and measurement of all PV systems is not possible. Therefore, statistical methods for the reliability approach should be applied to diagnosis, so that failure prediction will be possible in a more economical and reliable way.

**Author Contributions:** Writing—review and editing, J.-W.S.; data curation, K.-H.Y.; methodology, H.-S.C.; supervision, J.-C.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Energy Efficiency and Resources of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), grant funded by the Korea Government Ministry of Trade, Industry, and Energy (20193710100061).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest. The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

**References**

1. Vega-Garita, V.; Harsarapama, A.P.; Ramirez-Elizondo, L.; Bauer, P. Physical integration of PV-battery system: Advantages, challenges, and thermal model. In Proceedings of the 2016 IEEE International Energy Conference (ENERGYCON), Leuven, Belgium, 4–8 April 2016.
2. MOTIE. The Contribution of PV Generation to Summer Power Supply and Demand; MOTIE: Moscow, Russia, 2021. Available online: https://www.motie.go.kr/motie/ne/presse/press2/bbsView.do?bbs_seq_n=164428&bbs_cd_n=81&currentPage=1&search_key_n=&cate_n=&dept_v=&search_val_v= (accessed on 20 December 2021).
3. Osmani, K.; Haddad, A.; Lemenand, T.; Castanier, B.; Ramadan, M. A review on maintenance strategies for PV systems. *Sci. Total Environ.* 2020, 746, 141753. [CrossRef] [PubMed]
4. Adefarati, T.; Bansal, R.C. Reliability assessment of distribution system with the integration of renewable distributed generation. *Appl. Energy* 2017, 185, 158–171. [CrossRef]
5. Güner, S.; Erenoğlu, A.K.; Şengör, İ.; Erdinç, O.; Cataláio, J.P.S. Effects of on-site PV generation and residential demand response on distribution system reliability. *Appl. Sci.* 2020, 10, 7062. [CrossRef]
6. Su, S.; Hu, Y.; He, L.; Yamashita, K.; Wang, S. An assessment procedure of distribution network reliability considering photovoltaic power integration. *IEEE Access* 2019, 7, 60171–60185. [CrossRef]
7. Mathew, R.K.; Ashok, S.; Kumaravel, S. Impact of rooftop solar PV based DG on reliability of distribution systems. In Proceedings of the International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE), Shillong, India, 12–13 June 2015.
8. Spertino, F.; Chiodo, E.; Ciocia, A.; Malgaroli, G.; Ratclif, A. Maintenance activity, reliability, availability, and related energy losses in ten operating photovoltaic systems up to 1.8 MW. *IEEE Trans. Ind. Appl.* 2020, 57, 83–93. [CrossRef]
9. Peters, L.; Madlener, R. Economic evaluation of maintenance strategies for ground-mounted solar photovoltaic plants. *Appl. Energy* 2017, 199, 264–280. [CrossRef]
10. Xiaojing, Q.; Zheng, J.; He, W.; Yin, D.; Yin, H. Multi-objective maintenance strategy optimization of distributed photovoltaic plants. In Proceedings of the 1st China International Youth Conference on Electrical Engineering (CIYCEE), Wuhan, China, 1–4 November 2020.
11. Sayed, A.; El-Shimy, M.; El-Metwally, M.; Elshahed, M. Reliability, availability and maintainability analysis for grid-connected solar photovoltaic systems. *Energies* 2019, 12, 1213. [CrossRef]
12. Bosman, L.B.; Leon-Salas, W.D.; Hutzel, W.; Soto, E.A. PV system predictive maintenance: Challenges, current approaches, and opportunities. *Energies* 2020, 13, 1398. [CrossRef]
13. Gradwohl, C.; Dimitrievska, V.; Pittino, F.; Muehleisen, W.; Montvay, A.; Langmayr, F.; Kienberger, T.A. Combined Approach for Model-Based PV Power Plant Failure Detection and Diagnosis. *Energies* 2021, 14, 1261. [CrossRef]
14. Iftikhar, H.; Sarquis, E.; Branco, P.J. Why Can Simple Operation and Maintenance (O&M) Practices in Large-Scale Grid-Connected PV Power Plants Play a Key Role in Improving Its Energy Output? *Energies* 2021, *14*, 3798. [CrossRef]
15. Bouguerra, S.; Yaiche, M.R.; Gassab, O.; Sangwongwanich, A.; Blaabjerg, F. The Impact of PV panel positioning and degradation on the PV inverter lifetime and reliability. *IEEE J. Emerg. Sel. Top. Power Electron.* 2021, *9*, 3114–3126. [CrossRef]
16. Denk, M.; Bakran, M. Online junction temperature cycle recording of an IGBT power module in a hybrid car. *Adv. Power Electron.* 2015, *2015*, 652389. [CrossRef]
17. Bouguerra, S.; Yaiche, M.R.; Gassab, O.; Sangwongwanich, A.; Blaabjerg, F. The Impact of PV panel positioning and degradation on the PV inverter lifetime and reliability. *IEEE J. Emerg. Sel. Top. Power Electron.* 2021, *9*, 3114–3126. [CrossRef]
18. Denk, M.; Bakran, M. Online junction temperature cycle recording of an IGBT power module in a hybrid car. *Adv. Power Electron.* 2015, *2015*, 652389. [CrossRef]
19. Colli, A. Failure mode and effect analysis for photovoltaic systems. *Renew. Sustain. Energy Rev.* 2015, *50*, 804–809. [CrossRef]
20. Gupta, N.; Garg, R.; Kumar, P. Sensitivity and reliability models of a PV system connected to grid. *Renew. Sustain. Energy Rev.* 2017, *69*, 188–196. [CrossRef]
21. Yang, Y.; Sangwongwanich, A.; Blaabjerg, F. Design for reliability of power electronics for grid-connected photovoltaic systems. *CPSS Trans. Power Electron. Appl.* 2016, *1*, 92–103. [CrossRef]
22. Formica, T.J.; Khan, H.A.; Pecht, M.G. The effect of inverter failures on the return on investment of solar photovoltaic systems. *IEEE Access* 2017, *5*, 21336–21343. [CrossRef]
23. Moon, J.-F.; Shon, J.-G. Reliability evaluation of power distribution system considering maintenance effects. *Trans. Korean Inst. Electr. Eng. P* 2010, *59*, 154–157.
24. Oprea, S.-V.; Bara, A.; Preotescu, D.; Elefterescu, L. Photovoltaic power plants (PV-PP) reliability indicators for improving operation and maintenance activities. A case study of PV-PP Agigea located in Romania. *IEEE Access* 2019, *7*, 39142–39157. [CrossRef]
25. Li, H.; Ding, J.; Huang, J.; Dong, Y.; Li, X. Reliability evaluation of PV power systems with consideration of time-varying factors. *J. Eng.* 2017, *2017*, 1783–1787. [CrossRef]
26. Altamimi, A.; Jayaweera, D. Reliability of power systems with climate change impacts on hierarchical levels of PV systems. *Electr. Power Syst. Res.* 2021, *190*, 106830. [CrossRef]
27. Weibull, W. A statistical distribution function of wide applicability. *Mechanics* 1951, *18*, 293–297. [CrossRef]
28. Materials & Components Technology Network. Accelerated Life Test. Available online: https://www.mctnet.org/mct/MessageBoard/ArticleRead.do?forum=104861&id=48c896 (accessed on 25 March 2022).
29. Allan, R.N.; Billinton, R.; Sjarief, I.; Goel, L.; So, K.S. A reliability test system for educational purposes-basic distribution system data and results. *IEEE Trans. Power Syst.* 1991, *6*, 813–820. [CrossRef]
30. Youn, K.-H.; Lee, H.-J.; Kim, J.-C. Life evaluation of mold transformer in distribution station using Weibull distribution. In Proceedings of the KIEE Conference, Seoul, Korea, 19 March 2011; The Korean Institute of Electrical Engineers: Seoul, Korea, 2011; pp. 457–458. [CrossRef]
31. Schneider, D.; Feller, L.; Trussel, D.; Hartmann, S.; Klaka, S. Designing an IGBT module packaging for high quality and reliable operation. In Proceedings of the International Exhibition and Conference for Power Electronics, Intelligent Motion and Power Quality (PCIM Europe 2008), Nuremberg, Germany, 27–29 May 2008.
32. Schneider, D.; Feller, L.; Trussel, D.; Hartmann, S.; Klaka, S. Designing an IGBT module packaging for high quality and reliable operation. In Proceedings of the International Exhibition and Conference for Power Electronics, Intelligent Motion and Power Quality (PCIM Europe 2008), Nuremberg, Germany, 27–29 May 2008.
33. Lee, C.-Y.; Lee, M.-K. Commercial (100 kW) photovoltaic system cost structure: The cases of Korea, Germany, and China. *Ksnre* 2019, *15*, 31–41. [CrossRef]
34. Korean On-Line E-Procurement System. Mold Transformer. Available online: http://www.g2b.go.kr/index.jsp (accessed on 20 December 2021).
35. Korean On-Line E-Procurement System. Inverter. Available online: http://www.g2b.go.kr/index.jsp (accessed on 20 December 2021).