Improving Resilience Index Quantification Using Weighted Sum Method

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***Abstract*— This paper discusses the performance of existing resilience matrix. The calculation of the resilience metrics is simulated on channel 6 of the RBTS bus using the Typhoon Vicente disturbance event in 2012. The estimation of the resilience index employed the sequential Monte Carlo method and is based on the transmission line's fragility curve. The two parameters considered in estimating resilience are the ratio of restoration speed to length of disturbance and the area of the comparison area on the system performance curve under fault conditions and normal conditions. Combining these two equations utilizes the weighted sum method, in which the weighting arrangement is carried out by simulating disturbance events in 3 scenarios. Scenario variations that are consider in this study are transmission line designed wind speed, repair speed, and the number of repair teams. Based on the simulation, it was found that the most appropriate weighting for the parameter area is 0.5, and for the speed of repair per length of time of disturbance is 0.5.**

Keywords—Resilience Index, Disturbance, Sequential Monte Carlo, Weighted Sum

I. Introduction

The increase in natural disasters in the world due to an increase in the greenhouse effect affects not only the destruction of civil infrastructure but also of electricity sectors. For instance, the fragility of the electrical system was shown during an ice storm disaster in China in 2008. That high impact with low probability (HILP) disaster damaged more than 2000 substations and destroyed 8500 poles causing loss of access to electricity in more than 170 cities. Catastrophic damage due to the HILP disaster also occurred in 2012 in America, where Hurricane Sandy destroyed 100,000 transmission lines and damaged several substations. It is estimated that around 7 million people have lost access to electricity due to this condition [1] .

Based on the events mentioned, strategic steps are needed to overcome the catastrophic impact caused by the HILP disaster on the electrical system. Thus, a calculation metric is needed to review the effectiveness of the chosen strategy. The reliability index commonly used to represent the strength of the system when an N-1 or N-2 fault occurs cannot represent a fault event [2] because in this type of HILP disturbance, the contingency could reach N-40. Thus, resilience metrics are introduced as a new parameter in quantifying system resilience when facing HILP disturbances.

Power system resilience is explained by CIGRE as the capability of a power system to plan for the absorption of, recovering from, and successfully adapting to adverse event [3]. In other sources, resilience is defined as the ability of the power system to survive HILP incidents efficiently, ensure as little power interruption as possible, and enable rapid recovery to return to normal conditions [4]. Although there is no mutually agreed-upon definition of resilience in electrical systems, resilience metrics parameter shall include withstanding capability, recovery speed, planning capacity, and adaptation capability [5]. Thus, during the equation of resilience metrics, one shall ensure these parameters can be well represented.

Several journals have proposed resilience metrics. Those proposed metrics can be classified into two types: specific and general metrics. A general resilience metric combines all system parameters into one value, which this value is considered capable of representing resilience conditions starting from the initial phase to recovery. However, the definition of resilience metrics can cause ambiguity. While specific metrics represent each phase by different parameters, including power, duration, frequency, economy, and even social. The goal is that the resulting information does not cause ambiguity and gives a complete information of the system [6]. However, general metrics are considered more potent than specific metrics regarding optimization of corrective steps and ease of calculation.

Paper [7] proposes general resilience metrics by comparing the ratio of expected supplied energy during the study period to the total energy of the system load during uninterrupted conditions. This method can help to evaluate system reconfiguration optimization and energy scheduling in disaster conditions. However, this equation cannot represent the condition during the loss of a small portion of load for an extended period. In this condition, the resilience value will be close to one, no matter how long the recovery time takes. In [5], the resilience index is defined as the ratio between the total time the component is lit per total study time. This resilience value can become a tool for assessing optimal electrical power infrastructure deployment and operation. Nevertheless, considering the time domain only will not give precise information regarding how much load is missing. Paper [8] attempt to combine the equation from [5] and [7]. Supposedly, these two factors can be described in that proposed equation. However, multiplying the two equations causes the resilience metrics to be too small and does not well represent the condition. The maximum value of the resilience index in the two initial equations is 1, where in this condition, the system runs without any loss load. Thus, multiplying these two values in the outage state will not give a proper result.

This paper defines a resilience index by combining the area under the resilience curve with the time parameter. The aim is to integrate the surviving load parameter and recovery speed parameter so that they can be used in determining the optimum strategy for increasing system resilience.

The composition of this journal includes the definitions of resilience in Section 2, which will discuss the general nature of resilience and its parameters. Section 3 describes the weighted sum method and its usage in formulating resilience metrics equations. Section 4 explains the proposed resilience metrics, followed by explanation of simulations scenarios in Section 5. Section 6 explicitly describes the simulation results obtained for each scenario, and Section 7 contains a discussion of all the presented results. The conclusion of this paper is presented in Section 8.

II. Resileince Definition

The systems' performance during disturbance is described as a trapezoidal curve [9]. This curve describes the HILP disturbance's impact on system performance. It starts from how fast the value of the performance decreases to the rapidity of the system's restoration process, as shown in Fig. 1.

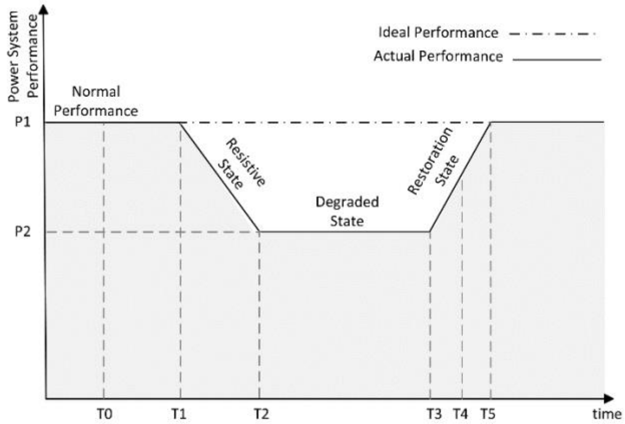

Fig. 1 Resilience Trapezoidal Curve

The stages of the disturbance itself can be divided into four periods:

- T0-T1 : In this period, the disturbance starts to approach the system (T0), but the system is still able to maintain performance as in normal conditions
- T1-T2 : The impact of system performance disturbances begins to affect at T1. As the magnitude of disaster impact grows stronger than before, the system performance will continue to decrease until it reaches its nadir point at T2 time.
- T2-T3: Disturbance no longer causes a decrease in system performance, but no recovery action has been attempted to restore system performance to normal conditions. This waiting time is generally influenced by the officers' response speed and the system's automatic response.
- T3-T5: The recovery process starts to occur, where this process starts at T3 so that the system can bounce back to its normal condition at time T5. T4 is when the system no longer feels the effects of the disaster.

III. Weighted Sum Method

In multi-objective optimization, one of the mostly used methods for combining two objective functions is the weighted sum method:

$$U = \sum_{i=1}^{k} w_i f_i(\mathbf{x}) \tag{1}$$

Where w is the weight of each objective function determined by the researcher, where the sum of all the weights is $\sum_{i=1}^{k} w_i = 1$ and each weight shall be $w > 0$ [10]. The value of w in each objective function is set so that the combination of these objective functions can meet the Pareto optimal point or, based on the researcher's preference, sort the objective functions based on their priority.

A significant difference between parameters that affect the value of resilience requires an appropriate method to unify these parameters without losing their own identity. The ease of weighted-sum method makes this method chosen as the basis for combining functions that affect the value of resilience.

IV. Proposed Resilience Metrice

The proposed resilience metrics aim to combine the comparison of system performance parameters, as in equation (2), and the equation that represents restoration speed (3).

$$R_i = E\left[\frac{\int_{T_0}^{T_5} AP(t)dt}{\int_{T_0}^{T_5} IP(t)dt}\right] \tag{2}$$

$$R_t = E\left[\frac{T_4 - T_0}{T_5 - T_0}\right] \tag{3}$$

Equation (2) is the ratio of the system's performance during disturbance (AP) starting when the disturbance begins to approach the system (T0) until the system can return to its typical performance (T5). On the other hand, equation (3) is a comparison of the disturbance duration (T4 to T0) to the difference between the end of the restoration length (T5 to T0). The weighted sum method is used to combine those two equations. Several scenarios are used to get the best value representing the system's state in evaluating the weight selection. The weighting value will be tried for several different values in each scenario based on Table 1.

$$R = E\left[\frac{\int_{T_0}^{T_5} AP(t)dt}{\int_{T_0}^{T_5} IP(t)dt} w_1 + \frac{T_4 - T_0}{T_5 - T_0} w_2\right] \tag{4}$$

Table 1 Proposed Weighted

	w_1	w_2
Solution A	1	0
Solution B	0	1
Solution C	0.5	0.5
Solution D	0.8	0.2
Solution E	0.2	0.8

V. SIMULATION SCENARIO

In calculating the resilience index, it is necessary to simulate the disturbance conditions and the corrective steps to be taken in the system. In this case, the system used is IEEE 6 Bus [11] as depicted in Fig. 2 , which are overlaid in the South China area. Disaster simulation uses typhoon Vicente [12], which occurred in 2012. Meanwhile, to determine the strength of the system, a fragility curve is used to represent how strong the system is. In this case, under normal conditions, it is assumed that the average designed wind speed is 37 m/s with a deviation of 5 per segment. Resilience index estimation is obtained using sequential Monte Carlo Simulation.

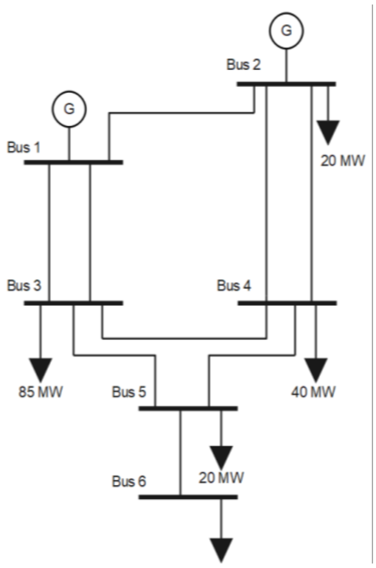

FIG. 2 IEEE RELIABILITY TEST SYSTEM 6 BUS

The simulation was carried out in several conditions:

i. Design Wind Speed Variation

   Variations of the transmission strength are 32 m/s, 37 m/s, and 42 m/s.

ii. Repair time Variation

   The speed of repair time is varied for 1 hour, 0.5 hours, and 2 hours per 500 m transmission line damaged segment.

iii. Repair team variation

   The number of repair teams will affect the total speed of repair where the number of teams varies for 1 team, two teams and four teams.

By varying the scenarios above, it will be seen how the trend of the resilience index is and whether it complies with the expected value. The analysis will be carried out to determine the most appropriate weighting value and one which can represent the condition of the system in each scenario.

VI. RESULT

A. Design Wind Speed Variation

By varying the strength of the transmission line, different expected resilience indices are obtained, as shown in Table 2 and Fig. 3. Solution A shows the estimated resilience index value, which only considers the effect of comparing system performance during disturbance and ideal conditions. The maximum value of this solution occurs when there is no decrease in system performance, as indicated by the estimated resilience index of 1. While the minimum value is 0 which showing that the performance goes to zero and the system cannot bounce back into the normal condition.

Even though Losing 20 MW for 392 hours for scenario designed wind speed of 32 m/s, the estimated resilience index in solution A still shows high results of around 0.959. In contrast, when the estimated resilience index only considers the time component of the restoration speed shown by solution B, the estimated resilience index value for the 32 m/s wind speed scenario is 0.0409. A significant increase is also shown in solution B when the designed wind speed is 37 m/s and 42 m/s. The estimated value of the index resilience is 0.131 and 0.544, respectively. This significant difference in both solutions indicates that only taking one of the parameters to define the estimated resilience index can lead to misleading results.

Different results are shown for each solution when combining the resilience index values using the weighted sum method, as shown in solutions C, D, and E. In the transmission line condition with a designed wind speed of 37m/s, the highest expected resilience value is obtained for solution D with an estimated resilience value of 0.771 and the lowest value is solution E of 0.301. A similar situation also occurs for testing the wind speed design of 42 m/s and 32 m/s, where solution E gets the lowest value of 0.635 and 0.231, consecutively.

The value of Solution E is the lowest compared to C and D solutions because it highly depends on repair time, where the average repair time required is 392 hours for a designed wind speed of 32m/s and 35 hours for 42 m/s. Compared with a load loss of only 20 MW from 165 MW for all three scenarios, the repair time effect will obviously have a more significant impact on the difference solution value.

TABLE 2 ESTIMATED RESILIENCE INDICES FOR WIND SPEED DESIGNED VARIATION

	SOL A	SOL B	SOL C	SOL D	SOL E
32 m/s	0.959	0.049	0.504	0.777	0.231
37 m/s	0.985	0.131	0.558	0.814	0.301
42 m/s	0.997	0.544	0.771	0.907	0.635

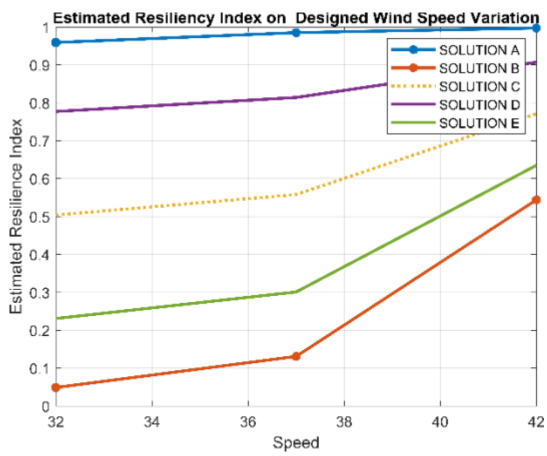

FIG. 3 TREND OF RESILIENCE INDICES FOR WIND SPEED DESIGNED VARIATION

B. Repair Team Variation

How the length of repair time variation affects the value of index resilience is shown in Table 3 and Fig. 4. While solution A and B is showing extreme high dan low value. The other three solutions are showing estimated resilience indices based on the weight proportion of equation (2) and equation (3). The highest estimated index in the scenario with the number of team one is shown by solution D with a value of 0.814. In contrast, the lowest value is found in solution E with a value of 0.301. When the number of teams increases, the repair time becomes faster, with an average of 79 hours and 26 hours for the scenario of 2 teams and 10 teams. The most significant increase was found in solution E which the estimated resilience value almost doubled when the number of teams was added from 2 teams to 10 teams.

TABLE 3 ESTIMATED RESILIENCE INDICES FOR REPAIR TEAM VARIATION

	SOL A	SOL B	SOL C	SOL D	SOL E
1 Team	0.985	0.131	0.558	0.814	0.301
2 Teams	0.992	0.246	0.619	0.843	0.395
10 Teams	0.998	0.742	0.870	0.947	0.793

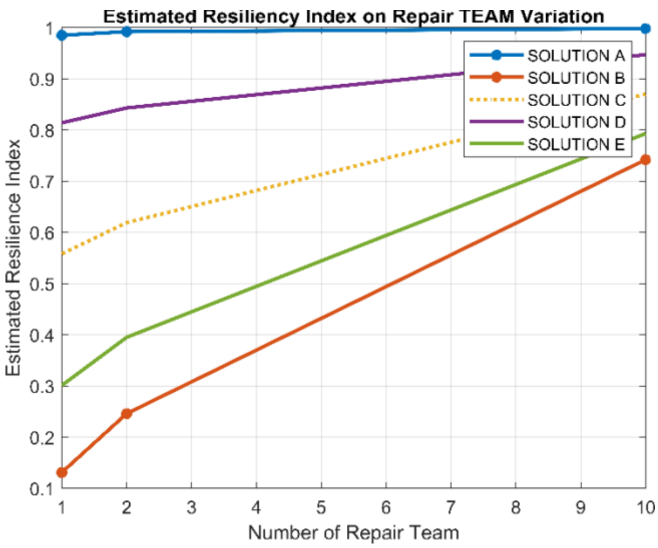

FIG. 4 TREND OF RESILIENCE INDICES FOR REPAIR TEAM VARIATION

The significant increase in solution E is caused by equation (3) changes[2] compared to equation (2). During the simulation, adding repair teams did not change the number of loss loads but will only affect the speed of system repair.

C. Repair Time Variation

Variations in repair time were carried out for three conditions: 1 hour, 0.5 hours and 2 hours for repairing one transmission line segment. Estimation of the resilience values are shown in Table 4 and Fig. 5. Between solution C, D, and E in the 1-hour scenario, the highest value is obtained by solution D of 0.814, and the lowest is obtained by solution E of 0.301. Speeding up the repair time to 0.5 hours per segment will increase the estimated resilience index values for the three solutions to 0.619, 0.843 and 0.396. Meanwhile, when repairs were carried out for 2 hours per segment, the most significant decrease in the resilience index was found in solution E to 0.251.

TABLE 4 ESTIMATED RESILIENCE INDICES FOR REPAIR TIME VARIATION

	SOL A	SOL B	SOL C	SOL D	SOL E
1 hour	0.985	0.131	0.558	0.814	0.301
0.5 hour	0.992	0.246	0.619	0.843	0.396
2 hours	0.971	0.071	0.521	0.791	0.251

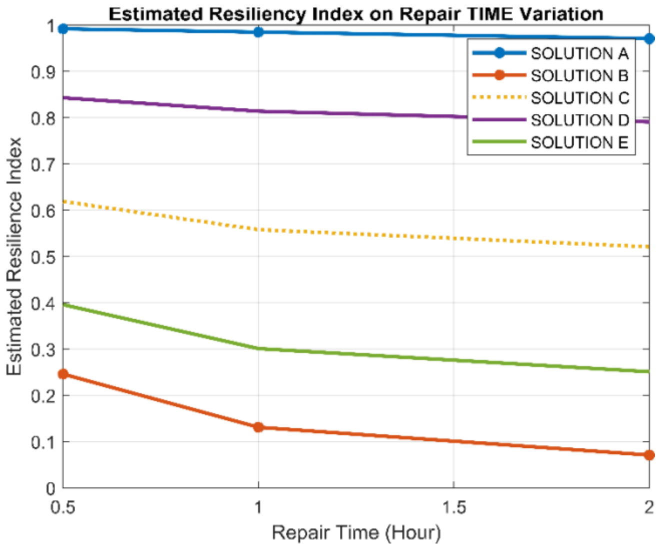

FIG. 5 TREND OF RESILIENCE INDICES FOR REPAIR TIME VARIATION

Solution E shows the most significant difference between each scenario because the parameter affected is the restoration speed, as shown by equation (2). Meanwhile, the amount of disturbed load remains the same so that changes in equation (1) are not too significant.

VII. DISCUSIION

Based on the simulation for the three scenarios, it was found that changes in the values of equation (2) and equation (3) are affected by different parameters. Changes in restoration time, both due to an increase in the number of teams and changes in repair time, give a significant contribution to equation (3) so that the value of solution B and E which has a weighting of equation (3) 1 and 0.8 will change significantly. In contrast, wind speed design scenarios should provide an overview regarding changes in load to resilience indices. When the wind design was varied, it impacted the number of affected segments. However, the loss load did not change because the affected segments are in the same transmission line. This simulation result causes the depth of the curve declining, as in Fig. 1, does not change but only the length of the restoration time. In this condition, the parameter in equation (2) is affected.

Proportional weight assigning is needed so that the parameters observed in equations (2) and (3) can be appropriately described. Based on the simulation, the weighting that can show this is $w_1 = 0.5$ and $w_2 = 0.5$. This is because when this weighting value is used, the resilience indices can be reflecting the loss of load and repair period properly.

VIII. Conclusion

This paper discusses the definition and parameters that shall be included in the resilience matrices. The simulation used 6 bus IEEE RBTS using typhoon Vicente disturbance in 2012. The estimated resilience value is obtained using the Monte Carlo Sequential method based on the component's fragility curve. The equation for calculating resilience must consider the parameters of withstand capability, recovery speed, planning capacity, and adaptation capability but maintain the easiness to use, especially for optimizing the system's action to enhance resilience value.

The weighted sum method combines the restoration speed parameters and the amount of lost weight. Choosing the proper weighting is crucial because it determines the estimated value of the resilience obtained for each condition. Based on the simulations carried out for three-scenario variations: variation in the number of teams, variation of wind speed design, and variation of repair time, it was found that $w_1 = 0.5$ and $w_2 = 0.5$ were considered capable of well representing the system condition during a disturbance.

In future research, this equation can be utilized to optimize the determination of system improvement steps, whether in network strengthening, network reconfiguration, or mobilizing a repair team.

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