# PREDICTING RECLOSER FAILURE RATES FROM FIELD CONDITION ASSESSMENT

A Thesis by

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FIELD CONDITION ASSESSMENT

I have examined the final copy of this Thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science in Electrical Engineering.

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Dr. Ward Jewell, Committee Chair

We have read this Thesis
and recommend its acceptance:

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Dr. Asrat Teshome, Committee Member

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Dr. Scott Miller, Committee Member

DEDICATION

To my parents

Bob and Louise Warner

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# ABSTRACT

This research develops a technique to predict the failure rate of a power distribution system recloser. The prediction is based on suggested criterion given and defined within this paper. Because inspection practices differ among utilities, the technique will apply to whatever data is available, and make the best prediction from that data. Examples of using the technique are provided. Predicted failure rates can then be used in system simulations to predict system reliability indices, and the effect routine maintenance has on them.

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| | |
|---|---|
| NEMA | National Electrical Manufacturers Association |
| SAIFI | System Average Interruption Frequency Index |
| $\lambda(x)$ | Failure Rate Function defined with lambda |
| $x_0$ | The Best Condition Score Recorded |
| $x_1$ | The Worst Condition Score Recorded |
| $x_{cs}$ | Recloser Sheet Condition Score |
| $x_{fs}$ | Failure Rate Function Score |

# CHAPTER I

## INTRODUCTION

There are approximately 1 million reclosers active on the U.S. power grid. As with all devices, mechanical and electrical, reclosers need routine maintenance to maintain performance relatively close to original specifications. Maintenance budgets are limited, requiring utilities to make decisions on which units to maintain each year. The repercussions of uneducated decisions either show up in the budget or the system reliability indices. These decisions must be made more frequently, due to an aging power utility system. A method is being developed to determine an optimal annual preventive maintenance routine based on available budget and personnel resources. Presently, failure rates of individual components are used in a system reliability model to estimate system reliability indices. However, a method to estimate the failure rate of a specific recloser has not been instituted. Therefore, this paper discusses a suggested methodology for estimating the failure rate of a recloser that is in service on the system. This research is part of a larger project where maintenance tasks are selected and scheduled based on the improvements to reliability indices due to the effect routine maintenance has on the parameters of interest.

CHAPTER 2

# METHODS AND PROCEDURES

In Figure 1, we see a simplified life-cycle of a recloser. Quantifying condition assessment and the improvement maintenance has on the condition are the two steps that are addressed in this paper. We are interested in the maintenance routine loop.

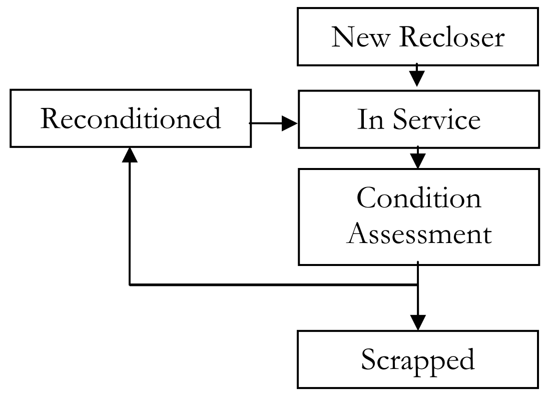


**Figure 1 - Recloser Life Cycle**

## Condition Assessment

The methodology begins by assessing the condition of the recloser. A scoring sheet that itemizes relevant failure causes is shown in Table 1.

The criteria on the score sheet have been chosen carefully. They are all items that contribute to the reliability of a recloser, and most of them can be improved by routine maintenance. Those that cannot be improved are still quite relevant in determining the recloser's condition. These include the age of the recloser, the duty cycle rate and environmental factor, which are a function of placement on a distribution system rather than maintenance.

| **Criterion** | **Weight** | **Score (0 - 1)** |
|---|---|---|
| | | **Pre-Maintenance** |
| Age of Oil | | |
| Duty Cycle Rate | | |
| Environmental Factor | | |
| Oil Dielectric Strength | | |
| Condition of Contacts | | |
| Age of Recloser | | |
| Experience with this Recloser Type | | |
| Condition of Tank | | |
| **Sum** | | |
| **Weighted Average** | | |

**Table 1 - Recloser Score Sheet**

### Scoring

Scoring a recloser begins with first deciding on which criteria from Table 2 to score for that recloser. Different types and models of reclosers, for example, will use different criteria. The score for each recloser assessed will then be normalized by dividing its score by its maximum possible score for the scored criteria. For example, to check the contacts and the oil dielectric strength, the recloser must be taken out of service; however, the cost to do this outweighs the benefit, unless removing the device is going to be done regardless. Therefore, these will not be included in the assessment or maximum possible score.

The score for each item is a percentage of the state of the recloser criterion. For example, if the contacts are 60% of their original size, their score would be 0.60. A recloser that has completed 75% of its recommended duty cycle would have a duty cycle score of 0.25, indicating the remaining 25% of its duty cycle. The resulting condition score, between 0 and 1, is denoted as $x_{cs}$.

### Weighting

The weight column in Figure 2 represents the influence a particular condition actually has on the failure rate of a recloser. As this directly influences the actual score, much consideration should be made to determine the specific weights applied to the scoring sheet.

The weights of most inspection items are determined by the combined opinion of manufacturers and experienced field personnel. However, certain items are utility dependent, such as the environment factor inspection item.

## Criterion Definitions

The following are explanations of why the criteria were selected, their importance to the condition of a recloser, and a suggested method of scoring. When scoring a recloser, not all of these criterions have to be scored to return an estimated failure rate.

### Age of Oil

The oil in a recloser is the most important dielectric in the unit, especially if the contacts are not in a vacuum. The oil helps extinguish arcs as contacts open and close, keeps arcs from occurring between other electrical conductors within the recloser, lubricates most of the moving parts, and is used to raise the trip piston after the set operations. Expected oil life is generally 3 years. Oil age thus provides an estimate of the oil's dielectric strength without having to remove the recloser from service.

### Duty Cycle Rate

Duty cycle is a measure of the level of use a recloser has experienced since its last maintenance, and is one of the most important issues for determining when maintenance should be done again. Duty cycle is a combination of the number of interruptions the recloser has performed and either the percent of rated interrupting current or the circuit X/R value. The National Electrical Manufacturers Association (NEMA) has defined a standard duty cycle for distribution class reclosers, shown in Figure 2 [2]. Constant monitoring of every recloser's duty cycle is impractical, so an alternate criterion, duty cycle rate, is defined.

**The NEMA standard duty cycle for distribution class reclosers is as follows:**

| Percent of Rated Interrupting Current | No. of Operations | Circuit X/R Value |
|---|---|---|
| 15- 20 | 40 | 2 |
| 45- 55 | 40 | 4 |
| 90-100 | 20 | 8 |
| | 100 | |

**Figure 2 - NEMA Standard Duty Cycle**

To calculate the duty cycle rate, the number of faults a recloser will see per year in a certain location is determined from the historical data used to calculate the utility's System Average Interruption Frequency Index (SAIFI), which is easily obtainable with automated outage systems described in [4]. The value of system X/R at the recloser location is determined from system data. Then the NEMA standard duty cycle definitions of Figure 2 give the number of operations per duty cycle for that location. Dividing the operations/cycle by expected operations/year gives the duty cycle in years/cycle for a recloser at that location.

This is compared to expected oil life:

Duty cycle rate = expected duty cycle/expected oil life

This score is high for high expected remaining duty cycle. If the score is greater than one, then the expected duty cycle is longer than the expected oil life, and the score is entered as one. This score is a function of recloser location on the system, and not of actual recloser condition.

**Environment Factor**

This criterion is for reclosers in locations that require special consideration for more frequent maintenance. This is a combination of recloser placement and environmental effects on the physical condition of the recloser. For example, a recloser bank protecting a feeder along the coastline will experience air with a much higher salt content than those located farther inland. The salt may cause the dielectric strength of the recloser oil to fall below standards much sooner than normal. This criterion addresses such conditions.

**Oil Dielectric Strength**

This score is important if the maintenance routine includes filtering the oil instead of replacing it. The score should be given as the difference between the new oil dielectric strength and the post-maintenance oil dielectric strength divided by the difference between the new and minimum oil dielectric strengths. i.e.

$$\frac{d_{new} - d_{now}}{d_{new} - d_{min}} = \text{score}$$

**Condition of Contacts**

This score is given as a percentage of remaining useful contact life.

**Age of Recloser**

The age of a recloser is important because, as with all machines, reclosers become less reliable with age, and will fail at some point. However, reclosers have proven to last for many years, and age is not a reliable predictor of failure. Recloser age should still be monitored, though, to help determine where new reclosers should be placed to increase reliability.

**Experience with this Recloser Type**

This criterion is used to differentiate among failure rates for different recloser manufacturers or models, types, and sizes of reclosers.

**Condition of Tank**

If a tank has excessive damage, either from nature or handling, it could need maintenance before it is justified by the other factors.

The score sheet is suggested, and does not have to permanently be the above. However, it is a guide that includes what is most important to a recloser's sure operation for an extended period of time. That being said, all criterions need not be scored to obtain a condition score either.

Next, the score – failure rate relationship is defined followed by examples.

# CHAPTER 3

## FAILURE RATE CALCULATION

The relationship between a recloser's condition score to its actual numerical failure rate is presented in [1]. Historical failure rate data from a number of systems were compiled for various power system components, including reclosers. From this data the best, worst, and average failure rates for each component were calculated. The resulting values for reclosers are:

$\lambda(0) = 0.0025$ (Best) $\lambda(1/2) = 0.015$ (Average) $\lambda(1) = 0.060$ (Worst)

If no historical data exists for the system to be modeled, then these values can be used. If, however, historical data is available for the system, then that data can be used to determine recloser failure rate statistics for that system. Equation 1, given in [3], demonstrates how a system-wide average recloser failure rate can be calculated:

$$\lambda(1/2) = \frac{Total\ \ no.recloser\ \ failures}{(No.reclosers)\, x\, (No.years)} \qquad (1)$$

The historical failure rate is determined by dividing the total number of documented recloser failures by the product of the number of reclosers on the system at the time of the failures and the period of time the data is recorded. Obviously, the longer the period of time information over which is collected, the more accurate the failure rate calculation. Even though the calculation is simple, realizing it proves difficult for a few simple but noteworthy reasons.

The first is that detailed records of the relevant information must be kept. For example, the number of reclosers on a system should be known constantly to ensure calculation accuracy. For this to take place, a utility must develop and implement a strategy to effectively collect and store the pertinent data.

Even when such a strategy is in place, reclosers inherently rarely fail, which is the second obstacle. A lengthy period of diligent record keeping thus precedes accurate rate calculate for a specific system. Although most utilities do keep records, they may not include the correct data needed to calculate recloser failure rates. Thus the main complication in calculating accurate failure rates is the tedious, never-ending process of accumulating specific data. However, once implemented, this process becomes routine and proves beneficial in many ways.

A growing number of utilities have implemented automated systems to accurately keep track of their reliability indices, as stated in [4]. These systems are an example of how accumulating component data and calculating their effective failure rates can be done; however, time is still needed to attain an acceptable level of accuracy.

Once the best, worst, and average failure rates for reclosers on a system are determined, either from historical or published [1] data, A, B, and C parameters are calculated using equation 2 [1]:

$$A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)} \qquad (2)$$

$$B = 2\ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right)$$

$$C = \lambda(0) - A$$

The parameters should be recalculated periodically as more historical failure rate data is collected.

These parameters are then used in equation 3 to estimate the failure rate for a recloser [1]:

$$\lambda(x) = Ae^{B*x} + C \qquad (3)$$

In equation 3, $\lambda(x)$ is the failure rate calculated from x, the relative condition score for the recloser. A high value of $x_{cs}$ represents a low failure rate, and a low value represents a high failure rate. Scores and failure rates must be directly related, so a new score is calculated:

$$x = 1 - x_{cs} \qquad (4)$$

However, using the condition score calculated in equation 4 to determine a failure rate using equation 3 will skew the resulting failure rates. A recloser would need a score of $x_{cs} = 1$ to be assigned the worst failure rate on the system. But to get such a score of $x_{cs} = 1$, a recloser would have to completely fail every condition with a score of zero, which is not practical.

To correct this, the best and worst scores on the system should relate to the best and worst historical failure rates. This is done in equation 5, which modifies equation 4:

$$x_{fs} = 1 - \frac{x_{cs} - x_1}{x_0 - x_1} = \frac{x_0 - x_{cs}}{x_0 - x_1} \qquad (5)$$

In this equation, $x_1$ is the worst recloser condition score recorded on the system, and $x_0$ is the best. With failure scores set this way, the lowest condition score recorded on the system will result in that recloser being assigned the lowest recorded failure rate.

If any of the failure scores from equation 5 are negative, or greater than one, then the condition score $x_{cs}$ would replace the appropriate best or worst historical score, respectively. The high and low condition scores should be updated as appropriate:

if $x_{fs} < 0$, $x_{cs}$ is the updated $x_0$ (6)

if $x_{fs} > 1$, $x_{cs}$ is the updated $x_1$ (7)

## CHAPTER 4

## EXAMPLE

Six years of outage data was obtained from a utility, and is used to illustrate the method developed in this paper. From the data, recloser failure rates are calculated. There were 23 recloser failures out of a total of 341 reclosers on the system over a span of 6.44 years. Equation 1 produces an average failure rate, λ(1/2) of:

$$\lambda(1/2) = \frac{23}{341 * 6.44} = 0.010473$$

The best and worst failure rates, λ(0) and λ(1), are then calculated. Each recloser on the system failed either zero or one time during the six year period. This gives failure rates of:

λ(0) = 0 failure / 6.44 years = 0.00000

λ(1) = 1 failure / 6.44 years = 0.15528

These are too low and too high, respectively, to be practical, so published failure rates [1] are used for the best and worst values:

λ(0) = 0.0025

λ(1/2) = 0.010478021

λ(1) = 0.060

Next, the A, B, and C parameters are calculated using equation 2 to be:

A = 0.0015321 B = 3.6514524 C = 0.0009679

The resulting equation is:

$$\lambda(x) := 0.0015321 \cdot e^{3.6514524 \cdot x} + 0.0009679$$

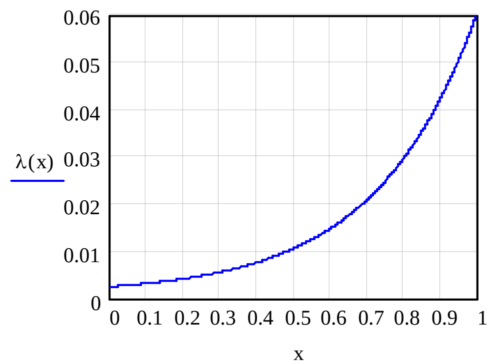


**Figure 3 - Score/Failure Rate Relationship**

and the relationship of assessment score to failure rate is shown in Figure 3. It is next assumed that the worst ($x_1$) and best ($x_0$) historical scores for reclosers are 0.31 and 0.95, respectively.

The scores for a recloser that has been left in service until it fails are shown in Table 2. The recloser was considerable past its expected duty cycle. It was removed from service and scored. The resulting condition score $x_{cs}$ is 0.392. Equation 5 corrects this to

$$x_{fs} := \frac{0.95 - 0.392}{0.95 - 0.31}$$

$$x_{fs} = 0.872$$

which results in a failure rate, equation 3, of

$$\lambda(0.872) = 0.038$$

The low condition score, 0.392, as expected, produced a higher than average failure rate.

| Criterion | Weight | Score (0 - 1) Pre-Maintenance |
|---|---|---|
| Age of Oil | 20 | 0 |
| Duty Cycle Rate | 20 | 0.5 |
| Environmental Factor | 20 | N/A |
| Oil Dielectric Strength | 15 | N/A |
| Condition of Contacts | 15 | N/A |
| Age of Recloser | 10 | 0.65 |
| Experience with this Recloser Type | 10 | 0.7 |
| Condition of Tank | 5 | 0.4 |
| **Sum** | 65 | 25.5 |
| **Weighted Average** | | 0.392307692 |

**Table 2 - Low Scoring Recloser**

Next, a recloser is scored, Table 3, with approximately the average failure rate.

This score produces the estimated failure rate:

$$\lambda\left(\frac{0.95-0.667}{0.95-0.31}\right)=0.00867$$

This is close to the system average of 0.01048. Once again, notice that a score had been determined even though three of the criterions have not been scored. The score sheet demonstrates that we do not have any environmental issues on our system, and we did not remove the recloser from service to check the oil dielectric strength or the contacts.

| Criterion | Weight | Score (0 - 1) Pre-Maintenance |
|---|---|---|
| Age of Oil | 20 | 0.33 |
| Duty Cycle Rate | 20 | 0.9 |
| Environmental Factor | 20 | N/A |
| Oil Dielectric Strength | 15 | N/A |
| Condition of Contacts | 15 | N/A |
| Age of Recloser | 10 | 0.65 |
| Experience with this Recloser Type | 10 | 0.9 |
| Condition of Tank | 5 | 0.65 |
| **Sum** | 65 | 43.35 |
| **Weighted Average** | | 0.666923077 |

**Table 3 - Average Scoring Recloser**

Finally, Table 4 scores a relatively new recloser, one that underwent scheduled maintenance about a year before it was scored. This is indicated by the age of the oil in the recloser. The recloser is not expected to complete a duty cycle before the oil is due to be changed again. The estimated failure rate for this recloser is:

$$\lambda\left(\frac{0.95-.861}{0.95-0.31}\right)=0.00351$$

This failure rate is close to 0.0025, the best failure rate previously found on the system.

| Criterion | Weight | Score (0 - 1) Pre-Maintenance |
|---|---|---|
| Age of Oil | 20 | 0.66 |
| Duty Cycle Rate | 20 | 1 |
| Environmental Factor | 20 | N/A |
| Oil Dielectric Strength | 15 | N/A |
| Condition of Contacts | 15 | N/A |
| Age of Recloser | 10 | 0.95 |
| Experience with this Recloser Type | 10 | 0.9 |
| Condition of Tank | 5 | 0.85 |
| **Sum** | 65 | 55.95 |
| **Weighted Average** | | 0.860769231 |

**Table 4 - High Scoring Recloser**

# CHAPTER 5

# CONCLUSION

This methodology allows quantifiable assessment of the condition of a recloser. The assessment can be done either in the field, without removing the recloser from service, or in the shop, after removal from service. The methodology then converts the assessment score to a predicted failure rate, which is based on historical data.

The assessment criteria are directly related to maintenance tasks that may be performed on the recloser. Each maintenance task will increase the score for the associated criteria, resulting in a lower calculated failure rate. A similar method can be applied to other power distribution system electro-mechanical devices. The method will be used to schedule preventive maintenance to optimize system reliability indices.

## Optimization

This thesis is part of a larger project that focuses on optimizing the distribution system routine maintenance to minimize the system indices.  The maintenance tasks associated with each criterion will increase the affected criteria score; this may be 1, or something less than 1. The cost of each maintenance task will be defined, along with all labor and overhead costs involved with taking a recloser from service.  Once all this information is gathered, optimization software will determine which reclosers and other equipment will be removed from service for maintenance, and in what order, to optimize system reliability indices.

## Future Research

There are a few areas of this paper that need to be tested and researched more.  First, actual system data needs to be used to determine the difficulty of gathering the data, and integrating all the ideas to perform the analysis. Second, calculating failure rates generally provides indices for a system model that do not calculate indices that are similar to historical data [1]. To remedy this issue, calibration has been used to correct the difference between the two. The least squares approach using the method of gradient descent is suggested in [1]. This method adjusts the failure rates until the predicted reliability indices match historical values. Other non-invasive measures that are being used utilize sensors of various types to monitor abnormalities in sound, temperature, etc. to determine whether a failure is imminent.

LIST OF REFERENCES

## LIST OF REFERENCES

1. Brown, Richard E., "Failure Rate Modeling Using Equipment Inspection Data", IEEE Transactions on Power Systems, vol. 2, pp 782-787, May 2000.

2. Cooper Power Systems, "Type H Single Phase Maintenance Instructions", Service Information number S280-10-1, January 1970, pg. 3

3. Horton, W.F.; Goldberg, S.; Volkman, C.A., "The failure rates of overhead distribution system components", Transmission and Distribution Conference, 1991., Proceedings of the 1991 IEEE Power Engineering Society, 22-27 Sept. 1991 pp 713 – 717

4. Musser, Phil, "The Many Routes of Reliability", Transmission and Distribution World, vol. 56. No. 6, June 2004 pg. 32.