Toward An Integrated Reliability Assessment Framework for Geomagnetic Disturbances

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***Abstract*—Geomagnetic disturbances (GMDs) threaten the grid through geomagnetically induced currents (GICs), which saturate transformers, causing operational effects such as voltage stability issues, potentially leading to load curtailment and, in extreme cases, grid blackout. GMDs pose a severe threat to system reliability, and it is imperative to model the effects of GMDs in the reliability assessment. Hence, this paper proposes an integrated reliability assessment framework wherein the GMD effects are included by adding a GMD reliability module to the generally accepted reliability assessment framework. The paper addresses the first subprocess in the integrated framework - reliability modeling of GMDs. A way to characterize the GMD storms in the context of reliability analysis is shown by introducing three parameters (TTGMD, GMDT, and GMDC) that model the storms' frequency, duration, and intensity. Over 90 years of historical geomagnetic data was processed, and historical observations for TTGMD, GMDT, and GMDC were obtained. An automatic fitter procedure then fits the historical data to probability distributions culminating in the initial steps for developing a GMD-integrated reliability assessment framework.**

***Index Terms*—Geomagnetic disturbances (GMD); Geomagnetically induced current (GICs); Coronal Mass Ejections (CMEs) ;Power System Reliability; Kp index**

2023 North American Power Symposium (NAPS) | 979-8-3503-1509-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/NAPS58826.2023.10318576

I. Introduction

RELIABILITY assessment is essential for power system planners to ensure a stable power supply, optimize system design and expansion, manage risks, and plan for the future. Power systems face various risks, such as equipment failure, cyber attacks, and natural disasters. Reliability assessment helps identify and quantify these risks, enabling planners to develop effective risk management strategies. One of these risks is a geomagnetic disturbance (GMD).Geomagnetic disturbances are caused by Coronal Mass Ejections (CMEs) from the Sun during solar eruptions that send magnetic particles hurtling toward Earth. A GMD is characterized by variations in the Earth's magnetic field resulting in electric fields at the Earth's surface, which produce low-frequency quasi-dc currents running along transmission lines and through transformer windings [1]. GMDs are a unique space weather phenomenon that differs from other extreme weather events, such as hurricanes, tornadoes, and other natural disasters affecting power systems. While extreme weather events affect the reliability parameters of the system components, e.g., the failure rates of transmission lines [2] and common mode failures, GMDs affect the grid by geomagnetically-induced currents (GICs). The flow of these GICs through the power system is related to available paths to ground, such as grounded transformers [3]. While the failure of transformers during a GMD is unlikely, GICs result in transformer half-cycle saturation during a GMD that can cause subsequent effects like voltage instability [4]. GICs can also cause overheating of transformers resulting in the wear down of insulation which might adversely affect the operating life of transformers.

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The reliability of power systems with the inclusion of weather effects has been of interest to power system planners. Evaluating the impact on failure and repair rates of system components is one way to include the adverse effects of weather on system reliability [5]. While extreme weather, such as hurricanes [6] and tornadoes [7], has been studied, there appears to be little to no literature on the effects of GMDs on the reliability of power systems. Authors in [8], discuss the relationship between geomagnetic data and transformer failure rate and provide a preliminary reliability evaluation of the system considering GMD data. A holistic approach to include GMDs within an end-to-end reliability assessment is lacking. This paper aims to propose an integrated assessment framework that includes modeling GMDs, the effects on the network, and the remedial actions to contain these effects.

The remainder of the paper is organized as follows. The next section presents the background for geomagnetic disturbances and power system reliability assessment. The third section then discusses the approach for reliability modeling of GMDs, followed by a section that proposes an integrated reliability assessment framework. The last section summarizes the paper and presents directions for future work.

II. Background

A. Geomagnetic Disturbances

The rate at which any CME travels through space is independent of other CMEs, but the values, averaged over each year, range from 200 km/s to 600 km/s. While the average speed per year is within that small range, an individual CME can reach speeds around 3000 km/s [9]. The speed of CMEs matter, as a quicker CME will result in a stronger impact when reaching Earth, resulting in disturbances in the Earth's magnetic field. Through Faraday's Law, where E and B are electric and magnetic fields, respectively, and ∇ is the curl operator, it can be shown that a change in a magnetic field will induce a change in an electric field:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1)$$

Thus, the disturbance of Earth's magnetic field leads to a change in Earth's electric field, which induces currents in conductors, like transmission lines. These currents are the previously mentioned GICs, which are low-frequency, quasi-dc waveforms that can affect electric grid components like transformers, protective relays, and transmission lines [10].

Transformers suffer from GICs, where the induced currents result in saturation, thus increasing the temperature of oil and gas, destroying insulation of the transformer. The saturation additionally induces harmonic currents into the system, affecting various equipment and protection schemes. These harmonics might lead to the malfunction of protective relays, resulting in outages or cascading failures [11]. These damages to transformers lead to increased rate of failure, if not outright failure during a GMD. Failure during a GMD itself is considered unlikely, but could transpire if the storm is powerful and temperature peaks last longer than a few days, burning through all the insulation for transformers [10]. The damage to transformers and reactive power loss from magnetic flux loss, can lead to blackouts in worst case events.

Worst case scenarios could result from powerful and quick CMEs, resulting in G5 classified storms, where G5 is the strongest storm on NOAA's scale for GMDs. NOAA scales GMDs ranging from G1 (minor storms) to G5 (extreme storms), where a stronger storm produces stronger GICs. The categorization of storms is detailed later in section III. Currently no G5 has been recorded to date; however, there have been powerful storms that have threatened the safety of the power grid. These powerful storms have gone down in history as some of the strongest GMDs to affect Earth, the Carrington Event in 1859, the Hydro-Quebec incident in 1989, and the Halloween storm of 2003. These three storms, as well as other past GMDs have wreaked havoc on power systems the world over. Some places are more susceptible to GICs than others such as Canada and places closer to the poles [12]. These GMD storms have made it clear that studies need to be done to comprehend if our systems can reliably handle GMD storms and have the resilience to stand back up, strong.

B. *Power System Reliability Assessment*

Monte Carlo simulation (MCS) methods are widely used for composite power system reliability assessment [13]. The approach is to estimate the expected value of an index of interest by sampling a system state according to its known probability distribution. In a typical MCS, power system reliability indices are computed in three main stages:

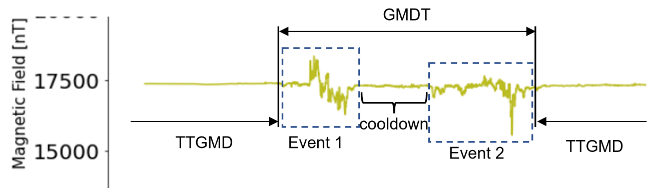

Fig. 1: Magnetic field X-direction of G4 November 2004 for Newport, Washington [16]

1) System component states are sampled based on their probability distributions.
2) The system state is characterized based on the sampled component states - usually done by power flow analysis.
3) Calculation of reliability indices is based on system states characterized in stage 2.

While the standard assessment framework is readily available in the literature, the novelty of this work is including the GMD storm effects in the framework. A GMD reliability module is included within the standard reliability framework, where the MCS transitions to the GMD module whenever a GMD is encountered.

III. Reliability Model of GMDs

Integrating GMDs into the reliability framework starts by understanding the frequency, duration, and intensity of GMDs. The following parameters are proposed to model GMDs in the context of the reliability framework:

- Duration of the GMD (GMDT)
- Time to a GMD (TTGMD)
- The intensity of the GMD (GMDC)

GMDT models the duration of GMDs, TTGMD models the time between two GMD storms, and GMDC models the max intensity of GMDs, illustrated in Fig 1. Sampling a GMD requires probability distributions of TTGMD, GMDT, and GMDC. Historical geomagnetic data from 1932-2023 is used for modeling the distributions. The data was obtained from GFZ German Research Centre for Geosciences [14], where the dataset provides the Kp-index every 3 hours. The Kp index quantifies the disturbances in the horizontal component of the Earth's magnetic field with an integer in the range 0-9, with one being calm and five or more indicating a geomagnetic storm. The specific categorization using Kp-indexes is: 5-6 is a G1, 6-7 is a G2, 7-8 is a G3, 8-9 is a G4, and a G5 is greater than nine [15].

While GMDs have a category assigned for each storm, the disturbance fluctuates throughout the duration of the storm. Fig. 1 illustrates how a GMD changes through a storm, with small fluctuations near the start before quickly ramping into larger disturbances. The disturbance does reduce for a while, the cooldown, before having a second, typically weaker, disturbance. Combing through multiple GMD storms, roughly 20 storms (ranging from G1-G4), the majority have at least two 'events' during a GMD with a cooldown between each event. The cooldown still experiences fluctuations; however, they are much weaker than the main event. It is worth noting to understand the features of GMDs that might affect the grid reliability.

A. Data Analysis

The storm category will allow for intensity separation throughout the data set for each year, separated by the 3-hour Kp indexes per day. The organized data is further separated into respected G-ratings based on the Kp index. After the data has been formatted, the TTGMD, GMDT, and GMDC are calculated in the following ways:

- GMDT: Find the beginning and end of each GMD storm via a cooldown rate of 1.5 days, meaning start the storm if Kp index$>=$ 5, and end the storm if no Kp index $>=$ 5 was found in 1.5 days.
- TTGMD: Take the end of one GMD and the beginning of the next GMD for every storm to generate the time between storms.
- GMDC: Find the maximum Kp index for each GMD and categorize the storm by the max value.

While the three parameters defined capture the duration, frequency, and maximum intensity of the storm, they fail to capture the variation in the intensity throughout the storm. The variation in intensity is vital to model the variation of GICs within the network during a GMD. A possible solution is to use Generative Adversarial Networks (GANs) to generate synthetic GMDs. The GAN can be trained on the historical GMD data with the variation in intensity, duration, and maximum intensity as the features of the data. Based on the historical training data, the GAN can generate synthetic GMDs characterized by duration, maximum intensity, and variation in intensity. While this idea is not explored in the paper, it could be a solution to model the GMDs accurately.

B. Fitting Probability Distributions

After cleaning the data and categorizing the start and end times of the GMD storms within the dataset, Univariate data of time between each storm (TTGMD) and the duration of each storm (GMDT) are obtained. The primary assumption is that these univariate data can be modeled by random variables that are independent and identically distributed according to some distribution with parameter θ.

$$X_1, X_2, ..., X_n \overset{i.i.d}{\sim} f(x|\theta) \quad (2)$$

Ten common distributions - normal, exponential, uniform, rayleigh, powerlaw, cauchy, lognormal, gamma, chi2, exponential power - are fitted to the univariate data. Sum Squared Error (SSE), Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and K-S Statistic are calculated to evaluate the fit. The best fitted distributions among the selected distributions for TTGMD and GMDT are shown in Fig. 2 and Fig. 3 respectively. The metrics calculated to evaluate the fit are shown in Table I and Table II.

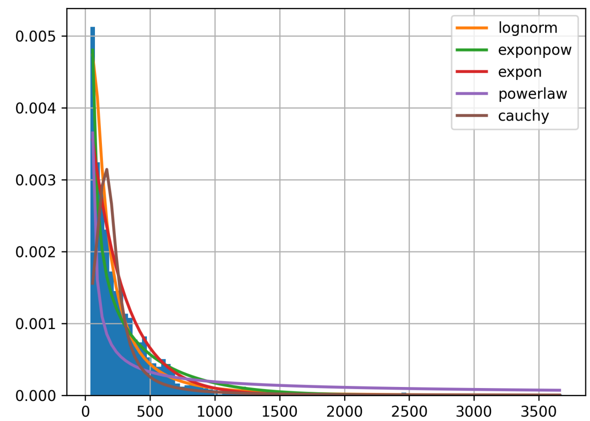

Fig. 2: TTGMD histogram

TABLE I: Distributions fitted to TTGMD

Distribution	SSE	AIC	BIC	K-S stat
lognorm	1.52E-6	2079	-49652	0.0465
exponpow	2.14E-6	2262	-48858	0.0737
expon	3.01E-6	2502	-48059	0.0742
powerlaw	1.48E-5	1773	-44307	0.2724
cauchy	1.67E-5	2162	-44033	0.2219

The categorical parameter GMDC is used to model the intensity of the storms. A probability mass function for the GMDC is developed by calculating the likelihood of each category from the historical data. Table III shows the likelihood of each category modeled based on the historical data.

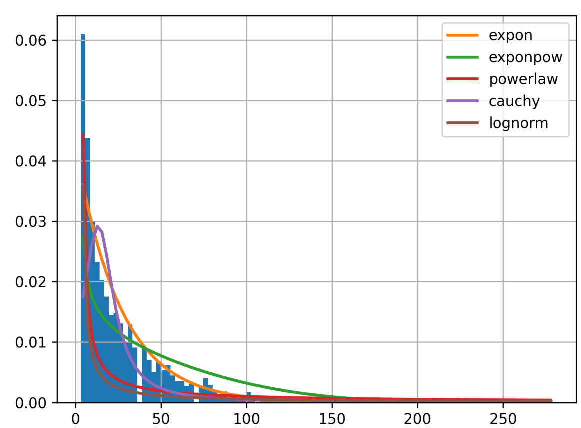

Fig. 3: GMDT histogram and fitted model

TABLE II: Distributions fitted to GMDT

Distribution	SSE	AIC	BIC	K-S stat
expon	0.00097	1706	-34571	0.1812
exponpow	0.00226	1460	-32571	0.2574
powerlaw	0.00264	1395	-32206	0.4422
cauchy	0.00274	1582	-32128	0.2582
lognorm	0.00376	1522	-31379	0.3884

TABLE III: Probability Mass Function for GMDs From Jan 1932 - May 2023

G rating	Number of Storms	Likelihood
G1	1085	0.461
G2	768	0.326
G3	329	0.14
G4	172	0.073
G5	0	0

IV. Integrated Assessment Framework

In addition to the component states, a random variable that models the TTGMD is sampled in this integrated framework. When the simulation reaches the time step where a GMD begins, it transitions to the GMD reliability module. The following steps summarize the process within the GMD reliability module.

1) Sample GMD duration from the GMDT distribution
2) Sample GMD intensity from the GMDC distribution
3) Characterize the system state with GIC flows using ACOPF
4) Perform remedial actions to address system stability issues
5) Repeat 1-4 for every time step until the end of the GMD duration
6) Sample time to next GMD from the TTGMD distribution
7) Exit the GMD module to the regular reliability module

The proposed integrated framework procedure is shown in the flowchart Fig.4. The key differences between the standard reliability framework and the GMD reliability module are the power flow model used to characterize the system and the range of possible remedial actions to address system stability. The standard reliability module uses DCOPF, where voltage magnitudes at all buses are assumed to be constant and equal to the nominal voltage, line losses are neglected, and reactive power flows are ignored. While DCOPF is not as accurate as ACOPF, it provides a computationally efficient solution to characterize the network state and evaluate the load curtailed.

GMD reliability module uses ACOPF, and it is critical to understand how GMDs affect the power grid to justify its use. Power transformers have a magnetic circuit disrupted by the quasi-DC GICs produced by the GMDs. The operating point of the transformers' magnetic circuit is offset, leading to half-cycle saturation. The shifted operating point produces harmonics in the AC waveform and localized heating, leading to higher reactive power demands, inefficient power transmission, and possible misoperation of protective measures. While a GMD might not likely cause a component such as a transformer to fail, it might cause severe voltage stability issues in the grid. Balancing the network in such situations requires significant additional reactive power capacity. Therefore, ACOPF, which considers more detailed aspects, including line losses, reactive power flows, variable voltage magnitudes, and phase angles, is the right choice to model power flows in the GMD reliability module.

The GMD reliability module includes remedial actions, which will need to be added to ACOPF simulations for a more realistic approach. Currently there are proposed methods to reduce GICs on a short term, but a more long term solution is GIC blocking devices. GIC blocking devices are placed on the neutral wire of transformers to lessen the amount of GICs entering a transformer, thus reducing the chance of saturation, leading to voltage instability. One testing scenario, is to optimize the location of GIC blocking devices and add them to simulations standards, and [17] describes a method to optimize the location of GIC blocking devices. Remedial actions are a critical aspect of the integrated framework, which will improve reliability of the grid during GMD storms.

Another critical aspect of the integrated framework is the choice of the MCS method. Two types of MCS methods, non-sequential and sequential MCS, are used in composite system reliability evaluation, and the choice of the simulation method depends on the system's behavior. Non-sequential MCS is computationally efficient and the preferred choice of reliability evaluation where time-related behavior is absent in the system. Sequential MCS is beneficial to simulate time-related behaviors of the power system. Since GMDs are time-dependent, where the GMD intensity is variable within the storm's duration, sequential MCS is the preferred choice for the GMD-integrated reliability framework.

V. Summary

This paper has introduced the framework for a reliability assessment of the power grid under GMDs, and the methods to model said GMDs in the context of reliability assessment. This paper proposes two temporal features (GMDT & TTGMD) and one intensity feature (GMDC), and generates distributions from historical data for assessment. The framework will allow for more accurate risk assessment of high impact GMDs on the power grid.

The future work of this paper is to implement the framework, and reduce the temporal scale of over 90 years, to individual solar cycles or individual years. Generating the data for the assessment will be created through machine learning programs, such as GANS, with GMDT, TTGMD, and GMDC as inputs. Multiple GMD storms will be given as training, to produce similar, but individualistic storms that mimic the varying intensity shown through GMDs. The generated magnetic field outputs will be converted into electric field, then further

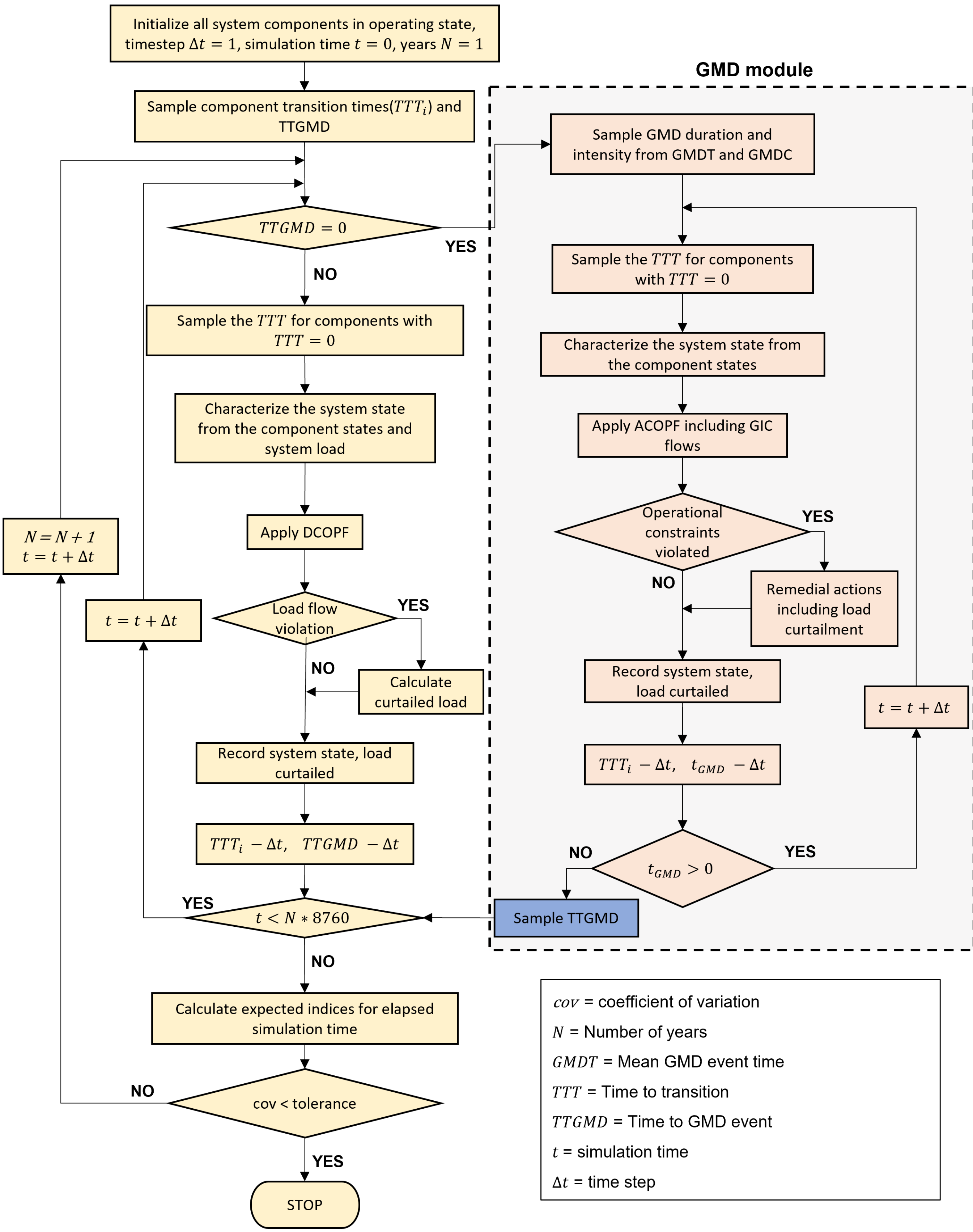

Fig. 4: Integrated Reliability Assessment Framework

converted into respected GIC values. Developing remedial actions, combined with the methods illustrated above form a comprehensive approach for an encompassing reliability assessment including GMDs.

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