

# A condition assessment algorithm based on Dynamic Time Warping for high-voltage circuit breaker

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**Abstract**—The paper presents an innovative algorithm for the analysis of the residual life of an high-voltage circuit breaker. This algorithm relies on the measurements of the accelerometer and on the Dynamic Time Warping algorithm (*DTW*). The *DTW* is used to analyze the spectrogram of the acceleration measured, permitting an analysis both in time and frequency. The indexes created are then compared to the values registered during the initial phase, firing an alarm or a simple warning depending on the deviation. The algorithm is tested on two different circuit breaker, showing its effectiveness in predicting failures.

## I. INTRODUCTION

The problem of providing the reliable operation of equipment, components and parts becomes more and more relevant every year as the equipment aging in many branches of industry significantly surpasses the rates of technical re-equipment. The process of condition assessment, in particular related to a manufacturer field, aims to identify when a particular machinery is getting *old* and consequentially aims to reduce the down time caused by a failure. The typical approach is a scheduled maintenance program, which is time consuming and resource hungry. Furthermore, this type of approach is not continuous but it is done at fixed intervals, so, in order to increase the effectiveness, the condition assessment check has to be made much frequently, increasing the costs related to this process. For the previous reasons an automatic approach that is able to continuously monitoring the condition of the plant can increase its reliability. Moreover the maintainer can be called automatically from the condition assessment system, reducing the costs.

In literature it is possible to find various types of condition or residual life assessment algorithm. Some of them are made knowing precisely the model of the system to preserve, making possible to understand if something is going wrong, for example in a transistor [1] or on a cast duplex stainless steel [2]. If the model is not well known, or too difficult to identify precisely, some different approach can be realized: in [3] and [4] the vibrations of the structure are analyzed, in time and in frequency in order to identify if something is changing. Others approach aim to evaluate how the system is working differently from the initial or typical condition, for example the current signature in motors [5].

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In this work a condition assessment algorithm based on vibration analysis will be described. In particular the *Dynamic Time Warping* [6] algorithm will be applied to the spectrogram of the vibration recorded during the operation of an high-voltage circuit breaker. It will be shown how this algorithm permits to understand if the circuit breaker is changing its behavior and, consequentially, if it requires a maintenance.

The problem faced in this paper is related to the development of a condition assessment algorithm for an high voltage circuit breaker. This problem has been already faced in literature and is possible to find various approach. The algorithms used in literature differ one to the other for the physical setup and for the method used to elaborate the data. In [7] a very expensive sensor like a thermal camera is used in order to identify some possible variations from the normal functioning. A much cheaper sensor like a current one has been used in [8] and [9]. In these two approaches the difference is made by how the data are elaborated. In the first the current flowing inside the coil which makes the circuit breaker opens and closes is analyzed using the current signature of the motor. In the second, the signal is the input of a trained neural network which is able to identify a possible fault. The most used sensor, by the way, is the accelerometer, which is able to acquire informations about the vibrations of the system. Then different analysis can be carried out:

- In [10] a vibration analysis is made simply analyzing the peaks in the spectrum;
- In [11] the analysis is made using the wavelet transform and then a classifier permits to understand the source of the fault;
- In [12] the accelerometer measurements are compared using the *Dynamic Time Warping* algorithm, which identifies the pattern inside the signals. To be noted that in this paper the *DTW* analyze only the time series registered by the accelerometer.

The proposed algorithm exploits the *Dynamic Time Warping* in order to analyze the spectrogram of the accelerometer signals, merging the time and frequency analysis. This double analysis permits to identify faults which influence the accelerometer signal both in the time and in the frequency domain.

The paper is organized as follows: in Section II the circuit breaker will be described and an analysis of the accelerometer signal will be shown. In Section III

the proposed solution is described, showing the original *DTW* algorithm and how it has been applied to the specific application. Then in the last two sessions, the results are presented and some conclusions are discussed.

## II. SYSTEM DESCRIPTION

The system used for the tests is an high voltage circuit breaker, which close the contacts using a rotating shaft put in movement using a spring. The spring is then reloaded using a small motor. Three phases can be identified:

- Closing: the shaft rotate, actuated by a spring, and close the contact very quickly (less than 5 *ms*). In this phase another small spring is loaded and will be used to open the contacts;
- Charging: the spring used for closing the contacts is reloaded using a DC-motor;
- Opening: the shaft come back to the original position opening the contacts.

On the chassis of the circuit breaker, an high performance accelerometer has been placed. The sensor used, as said before, is a mono axial accelerometer which is mounted pointing in the same direction of the movement of the shaft. The data are acquired during all these three phases.

The aim of the algorithm is to evaluate the condition assessment of the circuit breaker so, starting with a new one, a lot of tests has been done in order to drive the system to the failure. Each test is composed by a full cycle, meaning a closing, a charging and an opening operation.

The closing and opening operation have the higher amount of acceleration. In particular during the closing phase, which is the fastest and most impulsive, the accelerometer registers accelerations of almost 1000 *m/s<sup>2</sup>*. During the charging phase some vibration due to the charge of the motor are registered and, at the end, a peak in the acceleration happens when the spring is blocked by a hook. During the opening, some powerful vibrations are visible, but the event is less impulsive than the closing phase.

Since the aim of the project is the evaluation of the condition of the circuit breaker it is necessary to understand if the system is repeatable. Three consecutive tests has been analyzed, and the signals are shown in figure 1. The system results repeatable both in the time domain and in the frequency domain. Notice that both analysis are important, because typically a structural deterioration lead to a change in frequency that maybe is not clearly visible in the time domain [13], while a failure is much more visible in the time domain. For these reasons the analysis has been done on the spectrogram.

The spectrogram of a full cycle operation is visible in figure 2.

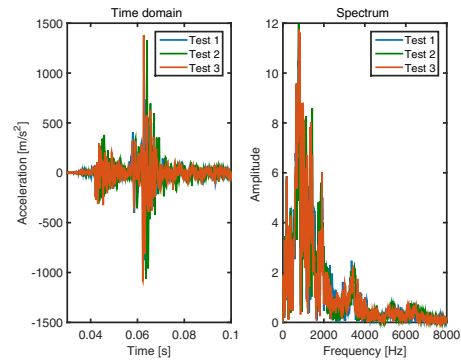


Fig. 1: Accelerations measured during the closing phase. The signal in time and in frequency is shown. Three test are overlapped in order to show the repeatability of the signals, either in time and frequency.

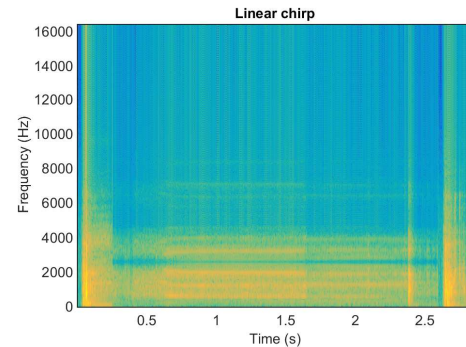


Fig. 2: Spectrogram of a full cycle composed, in order, by closing, charging and opening phase.

## III. PROPOSED SOLUTION

As discussed before the proposed solution is a variation of the *Dynamic Time Warping* algorithm. In this section, the algorithm will be described in general, and then applied to the specific case of a circuit breaker.

### A. *Dynamic Time Warping*

In time series analysis, dynamic time warping (*DTW*) is an algorithm for measuring similarity between two temporal sequences which may vary in time or speed. For instance, similarities in walking patterns could be detected using *DTW* [14], even if one person is walking faster than the other, or if there are accelerations and decelerations during the course of an observation. *DTW* has been applied to temporal sequences of video, audio, and graphics data indeed: any data which can be turned into a linear sequence can be analyzed with *DTW*. Well known application are automatic speech recognition [15], signature recognition [16] and partial shape matching application [17].

In general, *DTW* is a method that calculates an optimal match between two given sequences (e.g. time series) with certain restrictions. The sequences are "warped"

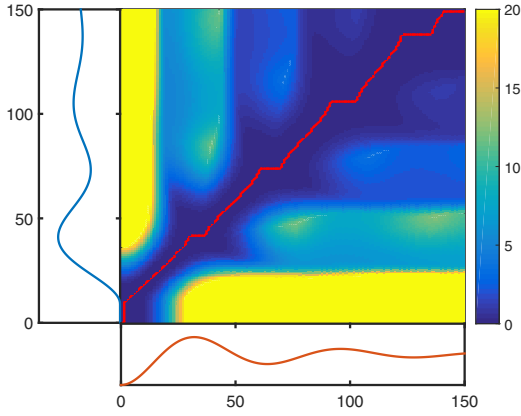


Fig. 3: The distance matrix  $D$  computed using (3); in red it is visible the optimal path.

non-linearly in the time dimension to determine a measure of their similarity independent of certain non-linear variations in the time dimension. This sequence alignment method is often used in time series classification. Although *DTW* measures a distance-like quantity between two given sequences, it doesn't guarantee the triangle inequality to hold.

The algorithm compare two time series, for instance  $S$  of length  $n$ , and  $T$  of length  $m$ , with:

$$S = s_1, s_2, \dots, s_i, \dots, s_n \quad (1)$$

$$T = t_1, t_2, \dots, t_i, \dots, t_m \quad (2)$$

To align these two sequences using *DTW*, an  $n$ -by- $m$  matrix, called  $D$ , must be constructed with the  $(i^{th}, j^{th})$  element of the matrix defined as the squared distance

$$d(s_i, t_j) = (s_i - t_j)^2 \quad (3)$$

To find the best match between these two sequences, a path through the matrix  $D$  that minimizes the total cumulative distance between the two signals must be find. This process is shown in figure 3.

In particular, the optimal path is the one that minimizes the warping cost

$$DTW(S, T) = \min \sqrt{\sum_{k=1}^k w_k} \quad (4)$$

where  $w_k$  is the  $(i, j)$ th element of the matrix  $D$ .  $w_k$  also belong to the warping path  $W$ ; in particular  $w_k$  is the  $k^{th}$  element of this path, which represent a mapping between  $S$  and  $T$  (as visible in figure ??). This path is composed by contiguous elements from the matrix  $D$ . Analyzing figure 3, you have to start from the bottom left, the zero position, and reach the end of both signals, in this case 150, following a path that minimize the warping cost described in equation 4. This path can be found using dynamic programming to evaluate the

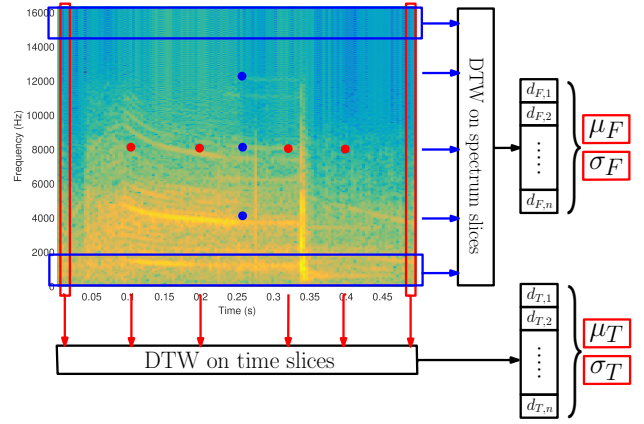


Fig. 4: Description of the *DTW* applied to the spectrogram of the closing phase. The *DTW* is applied on each band in frequency and in time, comparing these bands with the reference ones. Then the vector of distances are summarized using the mean and variance, creating 4 indexes.

following recursion:

$$\lambda(i, j) = d(s_i, t_j) + \min\{\lambda(i-1, j-1), \lambda(i-1, j), \lambda(i, j-1)\} \quad (5)$$

where  $d(s_i, t_j)$  is the distance found in the current cell, and  $\lambda(i, j)$  is the cumulative distance of  $d(s_i, t_j)$  and the minimum cumulative distances between the three adjacent cells.

The *DTW* outputs are the distance between the two signals, expressed as cumulative distance of the warping path, and the warping path itself.

Computing the *DTW* requires  $O(N^2)$  in general, since you have to travel all along the matrix  $D$ . Some techniques introduces some bounds in the research inside the matrix in order to reduce the computational burden and speed up the algorithm. This process and the possible boundaries that can be introduced, are summarized in [18].

### B. Proposed solution

The full cycle of the circuit breaker is composed by three phase: first there is the closing operation, where the contacts get closed; then a small motor recharges the spring used during the previous phase and then the contacts get opened during the opening phase, where a second spring loaded during the closing phase is used. The algorithm aim to analyze all the three phases using the *Dynamic Time Warping*.

The idea is to evaluate the condition assessment of the circuit breaker analyzing how much the behavior is moving away from the first cycles. In order to understand "how much the behavior is moving" the *DTW* will be applied to the spectrogram of the accelerometer measurements and the results compared to the behavior of the system at the beginning of its life.

Since the *Dynamic Time Warping* can be applied only to

time series or to linear sequence of data, the spectrogram will be analyzed slice by slice.

The measurements are analyzed using the *Short Time Fourier Transform (STFT)*, obtaining the spectrogram of the signal. The spectrogram process requires to chunk into small pieces the time series and then apply the *STFT* to each of these pieces. This process is made using a window which selects only a part of the signal. This window defines the time and frequency resolution of the spectrogram. As the frame (window, segment) length increases, frequency resolutions are increased, however, time resolutions are decreased. As the frame (window, segment) length decreases, time resolutions are increased, however, frequency resolutions are decreased. The window has been defined in order to obtain a time resolution of around 4 ms and a frequency resolution of around 100 Hz.

The spectrogram is then analyzed using the *DTW*; in particular each band (in time and in frequency) is compared with the reference one, created with the spectrogram of the firsts cycles. This analysis creates a vector of distances for the time slices and another one for the frequency slices. In order to have a more synthetic index, the mean and the standard deviation of these vectors is taken. The process is summarized, for the closing phase, in Figure 4.

To be noticed that the output of the *DTW*, the distance, is always a positive number, so there is no problems related to possible eliminations of effects. At the end of this analysis, for each phase 4 indexes will be generated, leading to an amount of 12 indexes for the full operative cycle. These indexes represent the actual condition of the circuit breaker referred to the first operations; evaluating the deviation of these indexes from the same indexes generated by the operation made with a new circuit breaker can express the need of a preventive maintenance.

Once the indexes are created, on these values a statistical test can be made in order to evaluate the need of a maintenance; define, for instance:

$$X = I_{k,1}, \dots, I_{k,n} \quad (6)$$

where  $I_{k,j}$  is the k-th index generated by the *DTW* computed at j-th operation, with in our case  $k = 1 \dots 12$  and  $n = 1 \dots 100$ . Taking 100 tests permits to obtain a good statistical representation of the initial state of the circuit breaker. On  $X$  the mean  $\mu$  and the standard deviation  $\sigma$  has been calculated.

The values of  $\mu$  and  $\sigma$  will be used in order to perform a statistical test to evaluate the deviation of the behavior of the circuit breaker from the first operations. In particular two threshold can be defined:

- If the distance overcome the limit of  $\mu + 3 \cdot \sigma$ , a warning can be created;
- If the distance overcome  $\mu + 5 \cdot \sigma$ , the warning become an alert, requiring a maintenance.

This process must be done on all the indexes created.

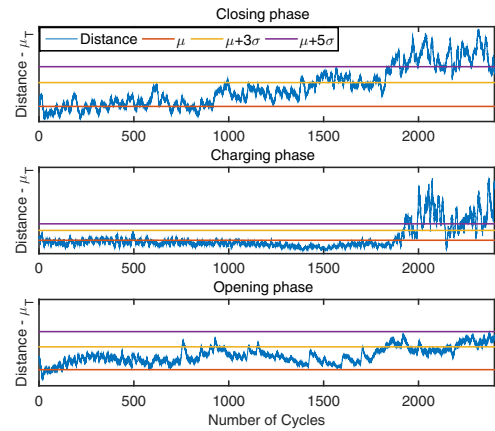


Fig. 5: Three particularly significant indexes related to circuit breaker 1. It is visible that the algorithm shows a variation in the behavior of the system. In particular this three indexes are related to a time analysis.

#### IV. RESULTS

The algorithm has been tested on two different Circuit Breakers of the same type. In this section the evolution of all the 12 indexes (4 for each phase) related to the first circuit breaker will be shown. The test consists in making the circuit breaker executes a normal cycle until it breaks. In particular for the first circuit breaker around 2400 cycles has been made, while with the second one less than 1700.

In figure 7 are summarized all the indexes registered during the analysis of the circuit breaker number 1. In particular it is possible to see the evolution of each index over all the tests. Resuming, the indexes are 12, and they can be defined as follow:

- $\mu_{Domain,Phase}$
- $\sigma_{Domain,Phase}$

Where  $\mu$  is the mean and  $\sigma$  the variance of the distance vector related to the analysis in the *Domain*, which can be *time* or *frequency*, of the spectrogram during the operational *Phase* of the circuit breaker, which are *Closing*, *Charging* and *Opening*. As an example,  $\mu_{T,CL}$  is the mean of the distance vector related to the time analysis of the spectrogram for the closing phase;

On the signals described before, the condition assessment can be made simply checking if the index overcomes the threshold for the warning or for the alert. In figure 5 it is possible to see the mean of the distance vector calculated analyzing the temporal slice of spectrogram with the *DTW* for the three working phases (closing, charging and opening).

Observing the figure is possible to underline:

- 1) around the test number 1500 the distance in the closing phase remain in a warning situation while in the other indexes the warning sometimes fire up but then the situation come back to the normality;
- 2) around the test number 1700 the index on the

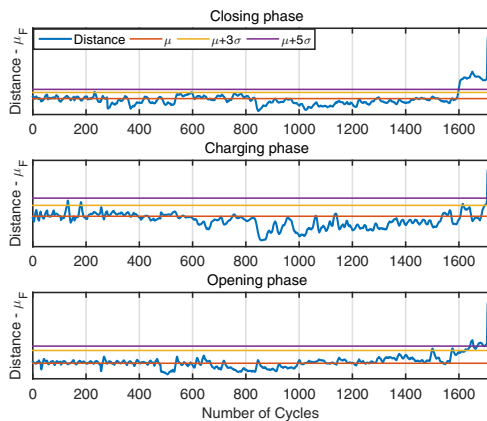


Fig. 6: Results for the circuit breaker 2. The algorithm shows a variation in the behavior around test 1600. These indexes are related to a frequency analysis of the spectrogram.

closing phase fires up an alarm; since the circuit breaker is not broken the test keep going and even the index related to the charging phase reports an alarm;

- 3) the circuit breaker undergoes a failure later, around the test number 2400. This behavior can be explained with a deterioration of the system that slowly leads to a failure.

In figure 6 the results of the second circuit breaker are shown. In this case the indexes taken into account are the mean of the distance vector calculated analyzing the frequency slices of spectrogram with the *DTW*. Even on this Circuit breaker it is pretty clear the moment when the behavior completely change. Around the test 1600, the index related to the Closing phase fired an alarm and after around 100 operation the circuit breaker has a failure.

## V. CONCLUSIONS

The proposed algorithm for condition assessment has good performance, being able to underline a change in the behavior of the circuit breaker before the failure. The analysis on the spectrogram extends the ability of the algorithm of enlightening a possible deterioration of the system, either in time or frequency domain. The technique used, the *Dynamic Time Warping*, permits to evaluate a distance value between two signal that is more advanced compared to the standard Euclidean distance.

The proposed solution is completely model-free making the algorithm applicable even to other systems. The indexes created, can be used as input in a Fault isolation algorithm in order to identify the source of the fault.

The natural continuation is obviously connected to the creation of more and more tests to validate the results obtained on the two condition assessment tested. As

discussed before, another step could be the test of the same algorithm on a system that is not a circuit breaker.

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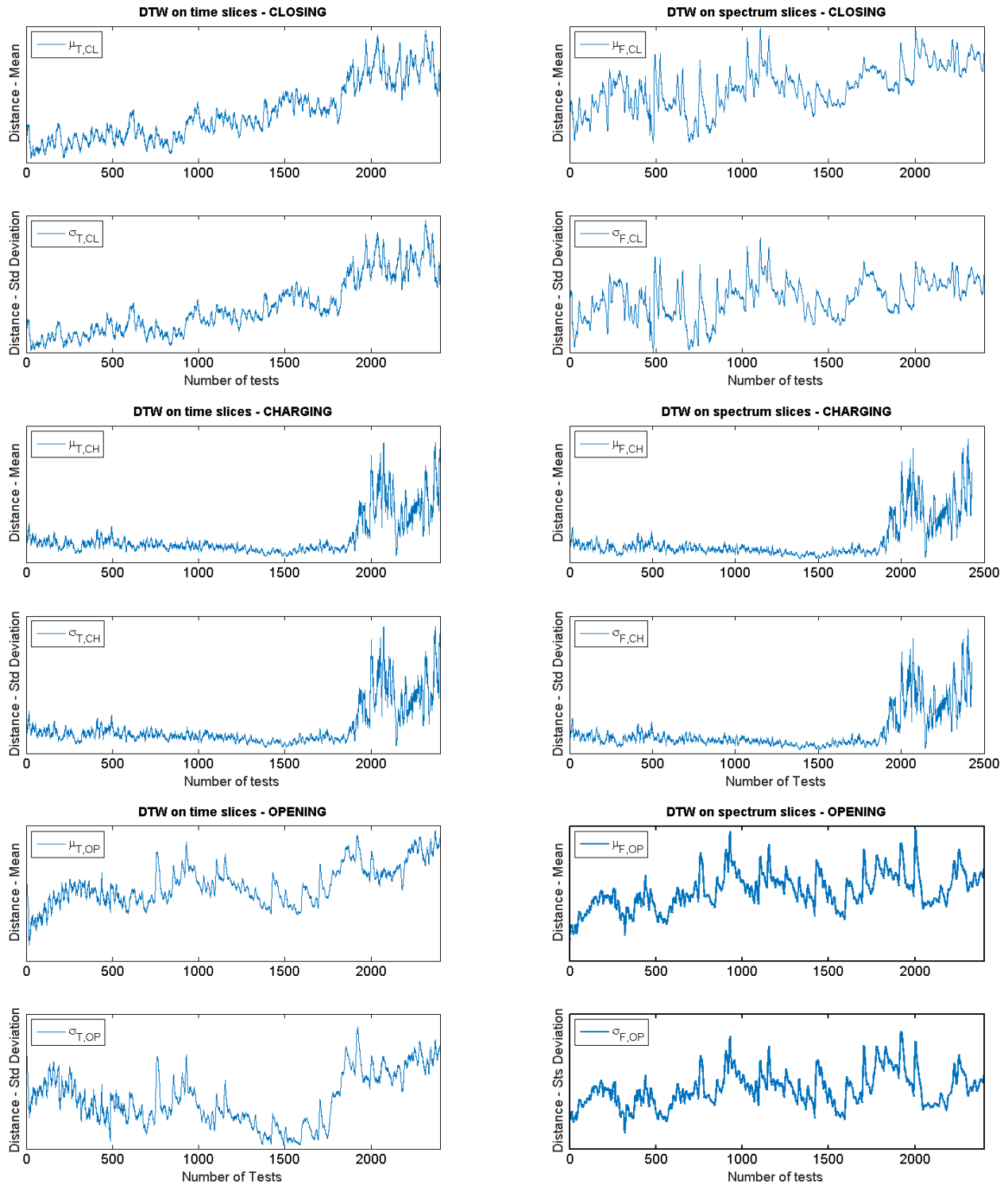


Fig. 7: Results of the first circuit breaker. The top two figures are the mean and variance in time and frequency related to the closing phase. In the middle the results related to the charging operation and at the bottom the results of the opening phase.