Linear Motion Calculation of the High Voltage Circuit Breaker Contacts Using Rotary Motion Measurement with Nonlinear Transfer Function

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***Abstract*—Motion measurement of the contact system of high voltage circuit breakers is of crucial importance for assessing the condition and health of the test object. To monitor motion of the contact system, depending on the construction, motion transducer is usually mounted on the moving parts of the operating mechanism linkage. That introduces a measurement error into the result. This paper presents the method and the software implementation of the measurement-error mathematical-correction.**

Keywords—Circuit breaker, Motion measurement, Motion analysis, Rotary motion

I. INTRODUCTION

Life expectancy of a newly installed high voltage circuit breaker (HVCB) is approximately 40 years. Throughout its life, under normal conditions, the circuit breaker will operate less than ten minutes total. During abnormal conditions, the breaker will operate less than one minute in its lifetime. [1]

The primary goal of diagnostic breaker testing is to determine the condition of the circuit breaker. Breakers are mechanical devices that have moving parts, components that allow main and arcing contacts to open or to close. If the motion of the contact system is in accordance with manufacturer specifications, than we can reasonably conclude that all mechanical parts, from the mechanism that provides the movement to the contacts themselves, are in good condition.

The accurate motion measurement itself is very important but parameters such as speed, acceleration, arcing contact overlapping distance, overtravel, rebound, and damping time, which are calculated from the motion curve, get more exact and accurate values.

Inaccurate motion measurement can affect conclusion regarding mechanical defects of the kinematic chain, overall mechanical performance, slow operation due to jammed mechanism, deterioration of mechanical damping, contact wear, arcing contact length etc. [2]

From the motion curve or its derivatives - a velocity or acceleration curve can be calculated in order to reveal even marginal changes that may have taken place in the breaker mechanics. [3]

Furthermore, for the dynamic resistance measurement, quality of the arcing contacts is determined correlating motion and voltage drop curves. If the motion measurement is not accurate, calculation of the overlapping time and overlapping distance would be inaccurate and the overall insight into the quality of the arcing contacts would be compromised. [4]

Most HVCB contacts have linear, straight line motion. However, depending on the construction of the HVCB, placement of the motion transducer on the contacts is usually not possible and the measurement of the contacts motion has to be performed on the lever between the contacts themselves and the operating mechanism.

In such cases good option is the rotary motion transducer connected at the point of the lever rotation (which transmits a movement from the mechanism to the main contacts) or at the main shaft in the mechanism.[5] Results obtained at that point, can be converted into a linear motion of the main contacts using a simple transducer scaling ratio (rotation/ distance).

However, for most circuit breaker mechanisms a constant transducer scaling ratio of rotation to distance does not accurately relate the measured rotation to the contact motion. Because of that incorrect calculations for motion parameters and velocity may result.

Alternative solution for contact motion calculation is using a nonlinear transfer function based on the trigonometric functions, since it causes considerably smaller error compared to linear conversion.

II. MATHEMATICAL APPROACH

Consider the mechanical scheme shown in the Figure 1.

In this example a rotation at the lever's point of rotation "A" drives a lever arm connected by a linkage to the contact drive shaft which drives the moving contact inside the circuit breaker chamber.

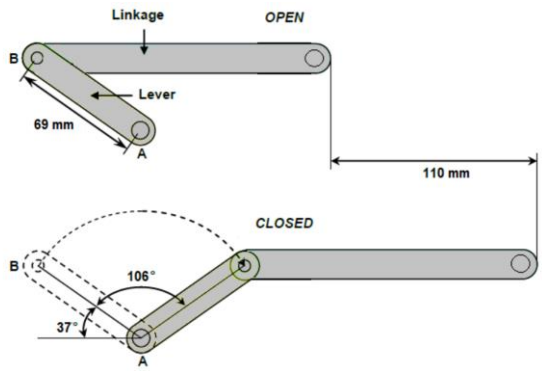


Figure 1. Rotary to linear mechanism [6]

As the lever rotates, the motion at point "B" has both horizontal and vertical components (Figure 2). Because the mechanism shaft (which drives the main contacts) is confined to horizontal travel by the shaft guide, it is only affected by the horizontal component of motion. The vertical component of motion at point "B" does not result in any motion of the contact drive shaft itself.

One approach to obtain contact motion curve would be relating the contact travel to the measured rotation using contact transducer scaling ratio of 110mm / 106° which can be simplified to 1.04 mm/°.This approach brings a deficiency assuming the relationship between the contact travel and the rotation of the lever point "A" is linear. In the reality this assumption is incorrect, as illustrated in the Figure 2.

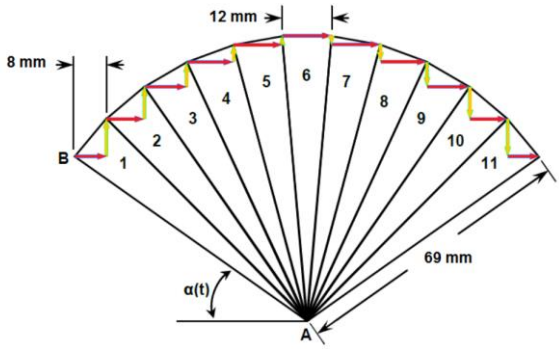


Figure 2. Motion of the mechanism's lever [6]

Relationship between the rotation of the lever and the contact motion is trigonometric function and it is described by the following equation:

$$L(\alpha) = R \cdot [\cos(\alpha_0) - \cos(\alpha_0 - \alpha)] \qquad (1)$$

where is:

R – Lever length
α_0 – Initial lever angle
α – Rotation measured by rotary transducer
$L(\alpha)$ – Linkage displacement as a function of rotation

The $L(\alpha)$ obtained in the Equation 1. is the horizontal component of the linkage motion which represents the linear contacts motion.

Therefore a constant mm/degrees ratio cannot be used to accurately calculate the motion at the contacts at each angle during the circuit breakers stroke. For example, using nonlinear conversion, ratio contact motion/ transducer rotation will be 0.83 mm/deg (8 mm/ 9.6˚) at the end positions and 1.25 mm/degree (12 mm/ 9.6˚) at the middle position of the motion, while this ratio will be always 1.04 mm/deg using linear conversion. This means, some motion parameters calculated at the end positions of motion (Overtravel, Rebound, Contact wipe, Velocity etc.) will be higher than real values when use simple linear conversion.[6] This will be shown in the following examples.

III. IMPLEMENTATION

According to the mathematical approach described in the Section II, software solution for setting the parameters, performing the calculation algorithm and result presentation has been developed. The user interface for the settings adjustment is shown in Figure 3. The software allows user to input following parameters:

- Alpha total
- Alpha zero (in relation to the X axis, Figure 4)
- Stroke
- Reference position
- Axis of the linkage motion (Figure 4)

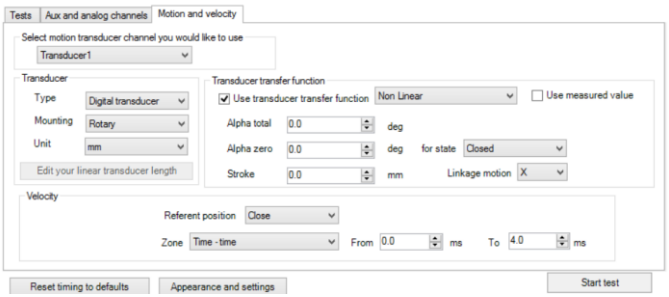


Figure 3. Software interface for the transfer function parameters input

To perform testing smoothly and faster, algorithm has been improved in the way that it takes for the Alpha total parameter value that is measured and calculated from the raw signal (Stroke parameter). This function can be switched on and off using "Use measured value" checkbox.

As mentioned above there are 5 different parameters that should be set (Figure 3.). The stroke parameter is a contact motion from fully open to fully closed position of the HVCB or vice versa. This parameter is provided by the manufacturer and can be found in the HVCB specification.

The Alpha total parameter is value of rotation measured at the place of the rotary transducer mounting and expressed in degrees during single HVCB operation. Linkage motion is the direction of movement of the linkage connected to the lever at the point of rotation where the rotary transducer is mounted.

The direction of movement along X or Y axes (Figure 4) should be set depending on the direction of linkage movement at the tested HVCB. Alpha zero parameter is initial angle of the lever in relation to X axis. In addition to this parameter, the circuit breaker state (open or closed, parameter Referent position) for which this angle is measured should be provided as an input parameter.

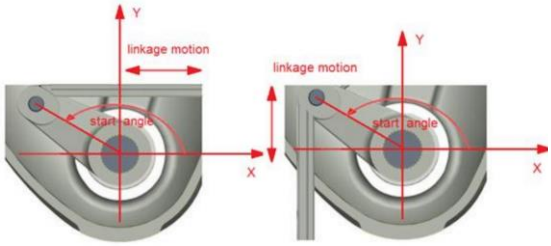


Figure 4. Mechanism linkage motion along X axis (left) and along Y axis (right)

IV. EXAMPLE I

For the purpose of mathematical approach verification (Section II) and the implementation (Section III) the experiment has been conducted on ten (10) HVCB in the field. Two chosen examples are presented in this paper.

In the first example motion measurements are performed using both, linear and rotary transducer simultaneously, and the results are compared. Also, comparison of the simple linear conversion (ratio) and the nonlinear trigonometry based conversion is performed.

The specifications of the HVCB used as a test object for the Experiment I are given in the Table 1.

The rotary transducer has been mounted on the center of the rotation of the lever between mechanism linkage and the main contacts shaft. The linear transducer has been mounted on the same lever at the point where the connected mechanism linkage is (point B, Figure 1). Transducers placement is shown in the Figure 5.

TABLE 1. The specification of the Energoinvest HG 6/8C

Manufacturer	Energoinvest
Type	HG 6/8C
Breaks per phase	1
Rated voltage	24 kV
Medium	Oil
Operating mechanism	Motor - spring

For this circuit breaker the manufacturer provided a relationship of 110 mm linear travel at the contacts corresponding to 106° measured rotation at location of the rotary transducer. In the Experiment 1, motion results from the rotary transducer are converted to linear contact motion using simple linear conversion and compared with the linear transducer measurement. Comparison between a contact motion measurement obtained with the linear transducer and converted motion measurement obtained from the rotary transducer using linear correlation is shown in Figure 6.

As can be noticed in the Figure 6, the motion curve obtained from the rotary transducer (full line) does not overlap with motion curve from the linear transducer (dashed line). These curves overlap only at the beginning, middle and the end of the contact motion. At the cursor position in the Figure 6. (where the value of motion measured with linear transducer is 85.8 mm), the measurement error with rotary transducer is more than 5 mm. As a result, the linear conversion of the rotary transducer reading will cause an error in motion parameters extracted from the motion curve such as average velocity, contact wipe, overtravel and rebound.



Figure 5. Digital rotary and analog linear transducer mounted and connected to the circuit breaker HG 6/8C

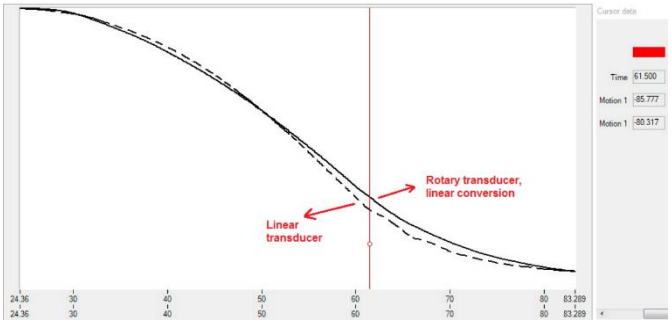


Figure 6. Comparison of motion curves obtained from linear transducer and rotary transducer with linear conversion of the measurement

Furthermore, simultaneous measurements were performed with linear transducer and rotary transducer using nonlinear conversion. Overlaid results are shown in the Figure 7. This comparison indicates that nonlinear conversion of the rotary transducer measurement causes considerably smaller error compared to linear conversion.

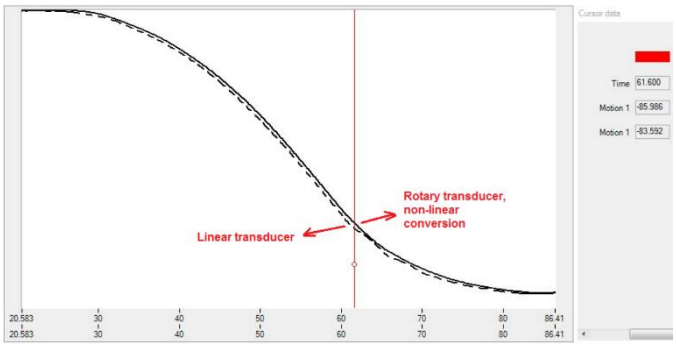


Figure 7. Comparison of motion curves obtained from linear transducer and rotary transducer with nonlinear conversion of the measurement

As can be seen in the Figure 7. motion curve obtained from the rotary transducer using nonlinear conversion almost overlaps with the referent curve obtained from linear transducer. Maximum error is only 2 mm (red cursor point) comparing the two motion curves at the same moment in time.

However, absolute error of 2 mm may be the consequence of the fact that the motion curves are obtained in two successive HVCB operations and it is not always likely that the contact motion will have the identical value at the same moment on two different operations.

Previous experiment results and deviations are shown in the Table 2.

TABLE 2. Comparison table of the measurement results for the Example 1

Experiment	Motion Ref. value [mm]	Error [mm]	Error [%]
1	85.8	5	5.29
2	85.8	2	2.33

V. EXAMPLE II

The Example II shows how Ovetravel parameter can be miscalculated using the simple linear conversion. We have shown the correction done using the non-linear trigonometric function. As a benchmark Ovetravel parameter, the data obtained with linear transducer at the previous testing of the circuit breaker is used.

Contact motion measurements are performed using digital rotary transducer which readings are automatically (by software) converted to contact motion using both linear conversion and non-linear trigonometric function. These converted results are then compared and analysis of the Ovetravel parameter is performed.

Testing was done on the SIEMENS 3AP1 FI circuit breaker equipped with the digital rotary transducer which was mounted at the lever in the bottom of circuit breaker pole (Figure 8). The HVCB specifications are given in the Table 3.

TABLE 3. The specification of the Siemens 3AP1 FI

Manufacturer	Siemens
Type	3AP1 FI
Breaks per phase	1
Rated voltage	245 kV
Medium	SF6 gas
Operating mechanism	Motor - spring



Figure 8. Digital rotary transducer mounted at the 3AP1 FI circuit breaker

According to manufacturer's specifications for this circuit breaker, a relationship of 150 mm linear travel at the contacts corresponding to 60° measured rotation at the lever where rotary transducer is mounted.

Contact motion measurement on the closing operation is analyzed. Comparison between the contact motion measurement obtained by conversion of digital rotary transducer reading using linear conversion and non-linear trigonometric function is shown in the Figure 9.

According to the linear conversion, motion of contacts is calculated using the measured rotation (degrees) multiplied by a simple, constant mm/deg transducer scaling ratio which is 2.5 mm/ deg (150 mm/ 60˚). This method of linear motion calculation from the rotary reading will result in the nonlinear error discussed in the section II.

As can be noticed in the Figure 9, the motion curve obtained with the linear conversion (dashed line) does not overlap with the motion obtained with the nonlinear trigonometric function (full line). As a result, the linear conversion of the rotary

transducer reading will cause an error in motion parameters extracted from the motion curve, especially at the end of the motion (Overtravel, Rebound etc.). For example, Overtravel parameter calculated based on the linear conversion is 21 mm, while this parameter based on the nonlinear conversion is 18 mm. Since reference value of Ovetravel parameter obtained using linear transducer is 17.5 mm, it is clear that error is smaller with application of nonlinear conversion (Table 4).

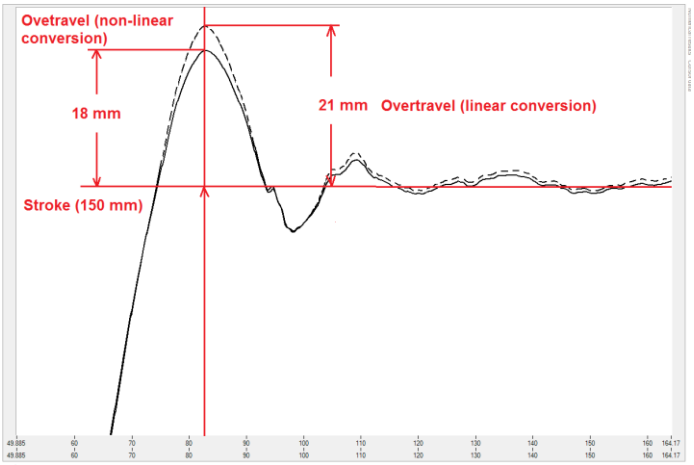


Figure 9. Comparison of motion curves obtained with rotary transducer measurement on the 3AP1 FI circuit breaker with application of linear conversion and nonlinear function

TABLE 4. Comparison table of the measurement results for the Example 2

Conversion	Overtravel Ref. value [mm]	Error [mm]	Error [%]
Linear	17.5	3.5	20
Nonlinear	17.5	0.5	2.8

These results confirm that parameters calculated in the end positions of motion curve based on linear conversion are higher than real values, i.e. higher than parameters calculated based on the nonlinear trigonometric function.

Although in this case, Overtravel parameters for the closing operation obtained with both conversions are according to manufacturer specifications (10-25 mm), problem can arise with use of linear conversion in the case of circuit breaker when real value of Overtravel parameter is near the upper limit (25 mm), but still within limits. In that case linear conversion will get Overtravel parameter higher than upper limit, which may falsely indicate a failure in the mechanism.

VI. EXAMPLE III

The Example III describes how Average velocity parameter during the opening operation can be miscalculated using the simple linear conversion and how the incorrect conclusion can be avoided using proposed non-linear trigonometric function. Testing has been performed on the SIEMENS 3AP1 FG circuit breaker equipped with the digital rotary transducer which was mounted at the lever in the bottom of circuit breaker pole (similar like for example in the Figure 8). Specifications of this CB are given in the Table 4.

TABLE 4. The specification of the Siemens 3AP1 FG

Manufacturer	Siemens
Type	3AP1 FG
Breaks per phase	1
Rated voltage	145 kV
Medium	SF6 gas
Operating mechanism	Motor - spring

According to manufacturer's specification, a relationship of 110 mm linear travel at the contacts correspond to 60° measured rotation at the lever where rotary transducer is mounted.

Further, specification limits for opening time are from 26 ms to 34 ms and for the Average velocity from 4.2 m/s to 5.3 m/s (Table 5). Measured opening time for this circuit breaker is 33.2 ms, that is close to upper limit of operating time. This should mean the circuit breaker probably operates close to lower velocity limit. Since operating times are within limits, average velocity must be within limits as well. Using the linear conversion, calculated Average velocity is 4 m/s, which is below physically possible velocity (since it is out of specified limits). According to non-linear conversion, calculated Average velocity is 4.2 m/s. This result is meaningful since it is expected that ciruit breaker operates close to lower limit velocity. The comparison of obtained and calculated results is given in the Table 5.

TABLE 5. The specifications and results for the Example 3

Parameters		Limits	Results	Comparison
Opening time [ms]		26-34	33.2	Pass
Average velocity [m/s]	Linear	4.2 -5.3	4.0	Fail
	Non-linear		4.2	Pass

Using non-linear conversion we eliminated suspicion of wrong detection of the circuit breaker condition.

Average velocity is measured in the arcing zone during the interval of 10 ms, starting from the moment of contact separation (Figure 10).

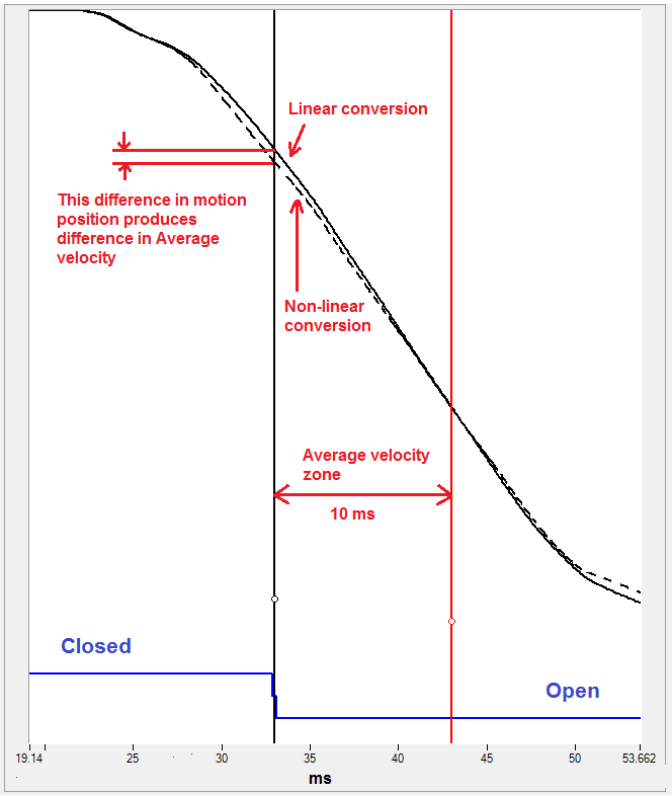


Figure 10. Calculation of Average velocity for the 3AP1 FG circuit breaker with application of linear conversion and non-linear function

VII. CONCLUSION

Since the measurement of the contacts motion often has to be performed on the linkage between the contacts themselves and the operating mechanism using rotary transducer, depending on the HVCB construction, results obtained using circuit breaker analyzer and timer devices are incorrect in the certain ranges of the motion path while applying simple linear conversion.

The conversion algorithm based on trigonometry functions and its implementation provides more accurate contacts motion measurement, which is specially emphasized in the Section IV and Section V.

Based on above considerations conclusion is that nonlinear conversion of the rotary transducer readings should be preferably used, since it causes considerably smaller error compared to linear conversion.

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