Application Note

Using Non-linear Transfer Function for Rotary to Linear Motion Conversion

Introduction

This document explains motion measurement on circuit breakers main contacts or drive shaft using the rotary motion transducer. Selecting the proper mounting method, convenient location and proper motion conversion method are the keys to success. Most high voltage circuit breaker contacts have a linear, straight-line motion. However, there is not always a convenient location in the mechanism to install a linear transducer. In such cases the user may consider using a rotary 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, and then calculate the linear contact motion using a simple transducer scaling ratio (rotation/ distance). However, for most circuit breaker mechanisms a constant rotation to distance transducer scaling ratio does not accurately relate the measured rotation to the contact travel. Because of that, it may result in incorrect calculations of motion and velocity. This application note explains deficiencies of measuring linear travel using rotary transducers and linear conversion ratio. The document also addresses an alternative solution for measuring the linear contact (drive shaft) motion applying rotary transducers and a non-linear transfer function based on the trigonometric functions. In addition, use of this transfer function in the DV-Win software will be explained, too.

Deficiencies of Using Simple Rotation/ Distance Linear Conversion

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. If the 69 mm lever arm has a starting angle of 37° and it is rotated 106° then the resulting motion at the contact would be approximately 110 mm.

If there was no convenient way to connect a linear transducer to the linkage or mechanism shaft, then the user might consider connecting a rotary transducer to the lever's point of rotation "A" instead. Under these circumstances the "typical" approach would be relating the contact travel to the measured rotation using constant transducer scaling ratio of 110 mm/106° which can be simplified to 1.04 mm/degree. This approach brings a deficiency

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assuming the relationship between the contact travel and the rotation of the lever point "A" is linear.

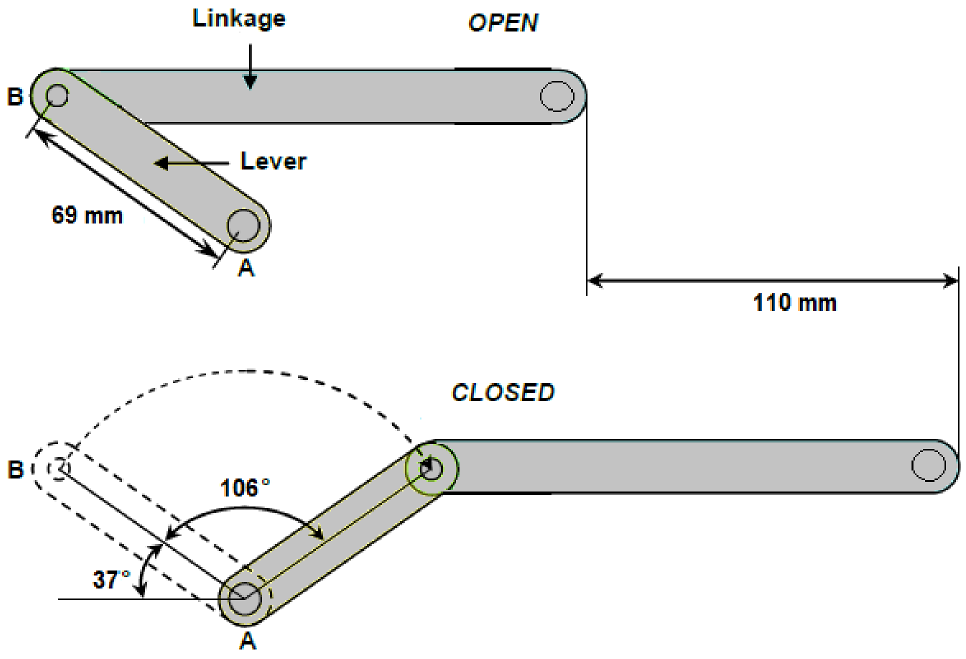

Figure 1. *Rotary to linear mechanism*

In reality this assumption is incorrect, as illustrated bellow (Figure 2). The relationship between the contact travel and the measured rotation is non-linear. It is a function of complex trigonometric relations that cannot be accurately represented by a simple, constant mm/degree transducer scaling ratio. This document describes the method supported by the DV-Win application software suite that mitigates this problem.

The non-linear relationship between the linear contact travel and the rotation is visually illustrated in the Figure 2. Point "A" represents the center of the lever's rotating point, and point "B" represents the center of the bolt/bearing connecting lever to the linkage (e.g. same as points "A" and "B" in the Figure 1). The 106° rotation has been divided into eleven equal zones, 9.6° each, labeled 1 through 11. As the lever rotates the motion at point "B" has both horizontal (red arrows) and vertical (yellow arrows) components. 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. Even though each zone represents equal rotation it is easy to see that they do not represent equal horizontal movement (e.g. compare the horizontal motion in zone 1 and 6). Clearly the relationship between the contact travel and the rotation varies depending on the lever's angle ***α(t)***.

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As mentioned above relationship between the contact travel and the rotation is trigonometric:

$$L(\alpha) = R^* [\cos(\alpha 0) - \cos(\alpha 0 - \alpha)],$$ where is:

R – lever length,
α0 – initial lever angle,
α– rotation measured by rotary transducer,
L(α)– Linkage displacement depending on the rotation.

Non-linear transfer function is based on this equation.

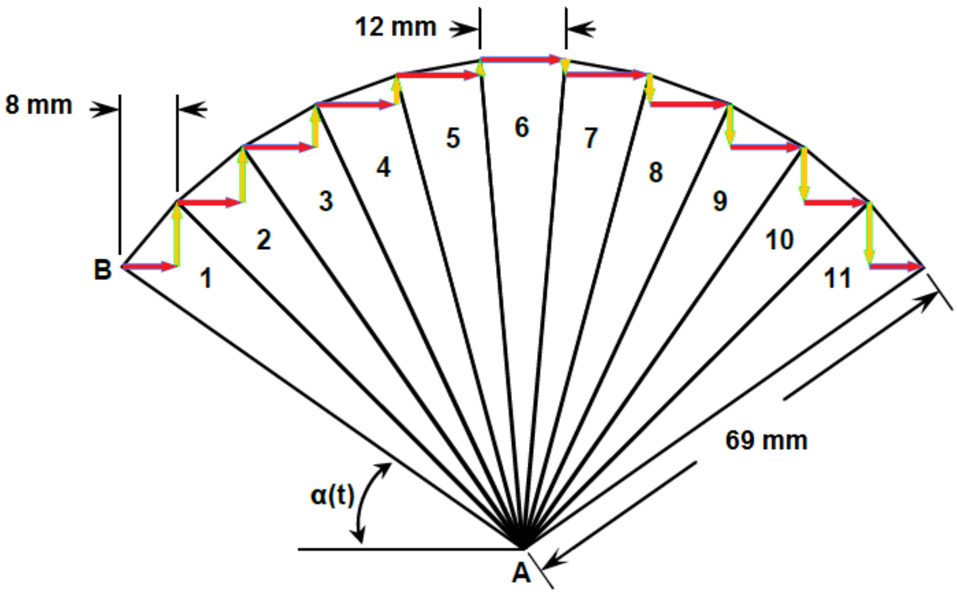

Figure 2. *Motion of the mechanism's lever*

As a consequence, a constant mm/degrees ratio cannot be used to accurately calculate the motion at the contacts (drive shaft) at each angle during the circuit breaker's stroke. For example, using a non-linear conversion, the ratio of a contact motion/ transducer rotation will be 0.83 mm/deg (8 mm/ 9.6˚) at the end position and 1.25 mm/degree (12 mm/ 9.6˚) at the middle position of the lever motion, while this ratio will be always 1.04 mm/deg using the linear conversion. This means, some motion parameters calculated at the end positions of a motion (***Overtravel, Rebound, Contact wipe, Velocity*** etc) will be higher than real values when using the simple linear conversion.

Rotation of 106° presented in the Figures 1 and 2 represents a rotation at the mechanism of an old oil circuit breaker. In reality, most circuit breakers using a similar mechanical scheme would have a rotation of 75° or less.

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Advantage of Applying Non-linear Trigonometric Transfer Function - Example

To elaborate above mentioned considerations (Figure 1 and Figure 2), contact motion measurements are performed using a digital rotary transducer whose results are converted to contact motion data using the DV-Win software application. The conversion was performed using both, linear conversion and non-linear trigonometric function. The achieved results are then compared and analysis of some motion parameters has been done. Testing was performed on the SIEMENS 3AP1 FI circuit breaker equipped with the digital rotary transducer that was mounted on the lever in the lower part of the circuit breaker pole (Figure 3).

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

According to the manufacturer's specifications for this circuit breaker, 150 mm of the contacts linear motion length corresponds to 60° of the rotary transducer rotation measured at its location.

Diagram below illustrates the contact motion measurement during a closing operation. The graphs in the Figure 4 and Figure 5 depict a contact motion measurements obtained by conversion of a digital rotary transducer reading using linear conversion and non-linear trigonometric function.

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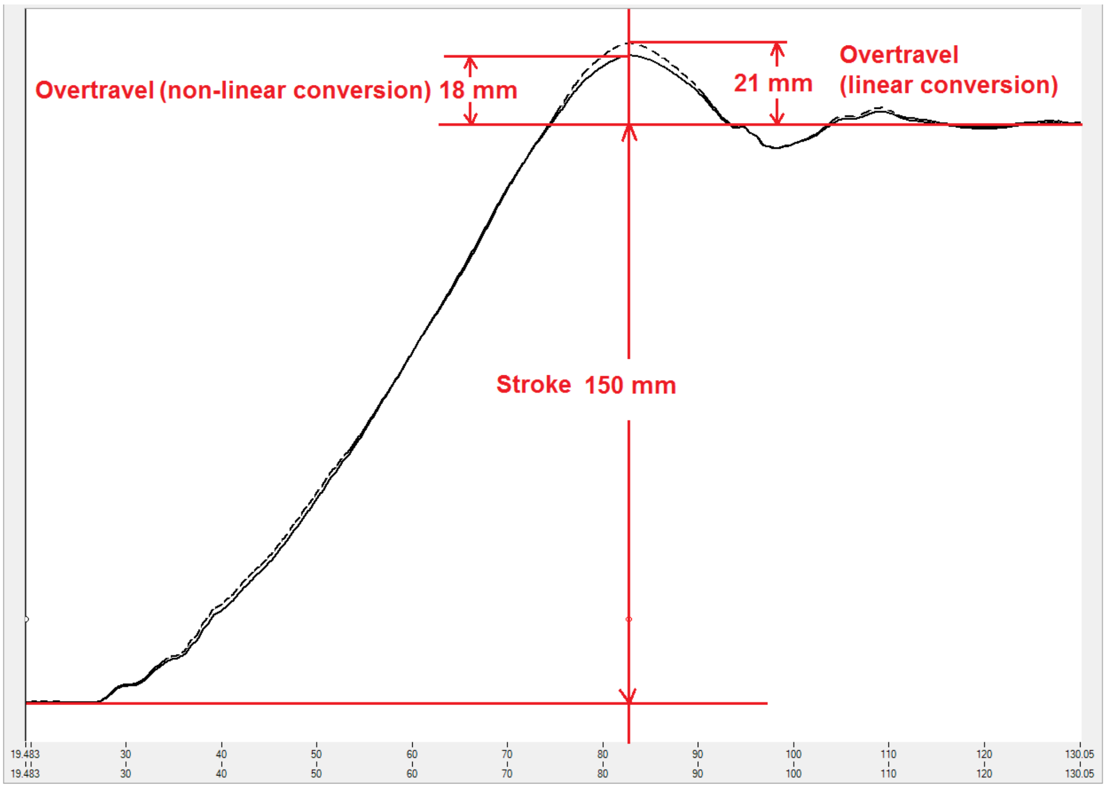

Figure 4. *Comparison of motion curves obtained with rotary transducer measurement on the 3AP1 FI circuit breaker applying linear conversion and non-linear function*

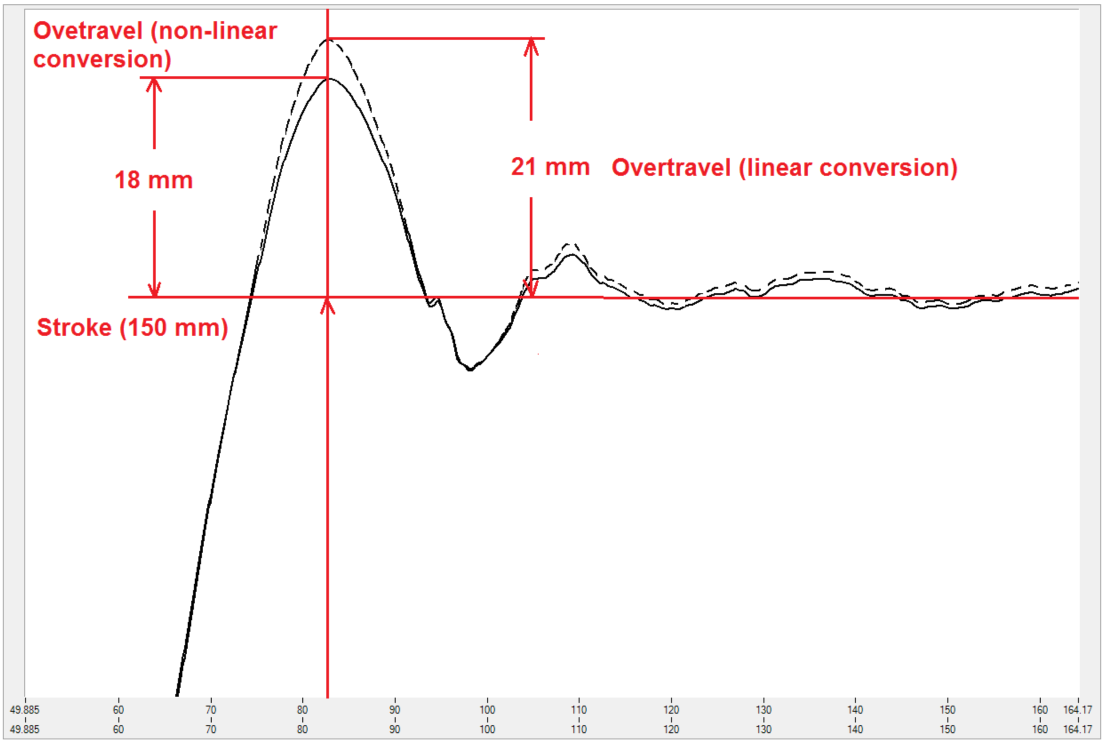

Figure 5. *Zoomed part of the motion curve in the Figure 4*

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Using the linear conversion, a motion of the contacts is calculated using the measured rotation (degrees) multiplied by a constant mm/deg transducer scaling ratio which is 2.5 mm/ deg (150 mm/ 60˚) in this case. This method of calculating the linear motion from the rotary transducer reading will result in the non-linear error described above.

As it can be noticed in the Figure 4, the motion curve obtained by the linear conversion (full line) doesn't match the motion curve obtained by using the non-linear trigonometric function (dashed line). As a result, the linear conversion of the rotary transducer reading will cause an error in detecting real motion parameters extracted from the motion curve, especially at the end positions of a motion (***Overtravel***, ***Rebound*** etc.). For example, ***Overtravel*** parameter calculated based on the linear conversion is 21 mm, while this parameter based on the non-linear conversion is 18 mm.

These results confirm that parameters calculated at the end positions of a motion curve based on the linear conversion are always higher than real values, i.e. higher than parameters calculated based on the non-linear trigonometric function. Although in this case the ***Overtravel*** parameters for the closing operation measured with both conversion methods are within the limits prescribed by the manufacturer (10-25 mm), a problem may arise when using the linear conversion in a case when a real value of the ***Overtravel*** parameter is close to the upper limit (25 mm), but still within prescribed limits. In that case the linear conversion will give ***Overtravel*** parameter higher than the upper limit, which will falsely indicate a failure in the mechanism.

Based on these considerations the conclusion is that non-linear conversion of the rotary transducer readings should be a preferred method since it causes considerably smaller error compared to the linear conversion.

Non-linear Transfer Function in DV-Win software

General recommendation to the users who consider the motion value in each point of the motion curve as important data is to use the non-linear transfer function. In this way the error in the contact motion measurement when performed using the rotary transducer will be lower.

When using the DV-Win set of software applications to perform the motion measurement, please select the ***Digital transducer*** in the ***Motion and velocity*** tab (Figure 6) first. Then enable the ***Use transducer transfer function*** option and select ***Non-linear*** transfer function in the drop box. Settings for non-linear transfer function will appear as shown in the Figure 6.

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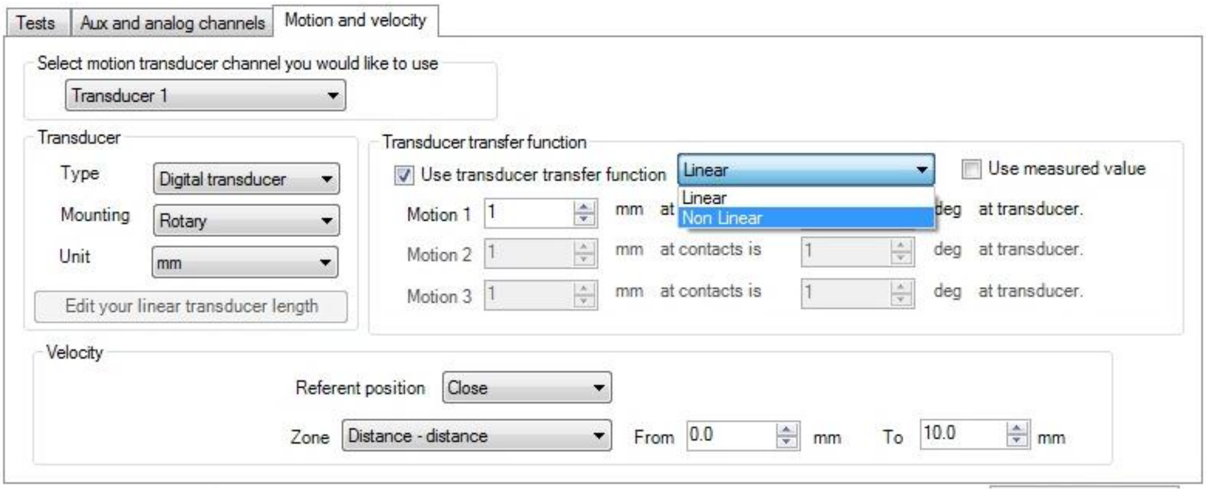

Figure 6. *Selecting option for non-linear transfer function*

As can be seen from the Figure 6, a few parameters should be set. The ***Stroke*** parameter is a contact motion from fully open to fully closed position of the circuit breaker or vice versa. This parameter is obtained from a manufacturer and it can be found in the circuit breaker specification. The ***Alpha total*** parameter (Figure 7) is also ***Stroke*** of the main contacts, but measured at the place of the rotary transducer mounting and expressed in degrees. ***Linkage motion*** is the direction of a movement of the linkage connected to the lever at which point of rotation the rotary transducer is mounted to. The direction of movement along ***X*** or ***Y*** axes (Figure 8) should be set depending on the direction of linkage movement at the tested circuit breaker. ***Start angle*** is the initial angle of the lever in relation to ***X*** axes according to positive motion direction. In addition to this parameter, the circuit breaker state (open or closed) for which this angle is measured should be also selected. This angle should be measured (using a digital protractor or some other accessories) as accurately as possible since it directly affects the accuracy of the motion measurement.

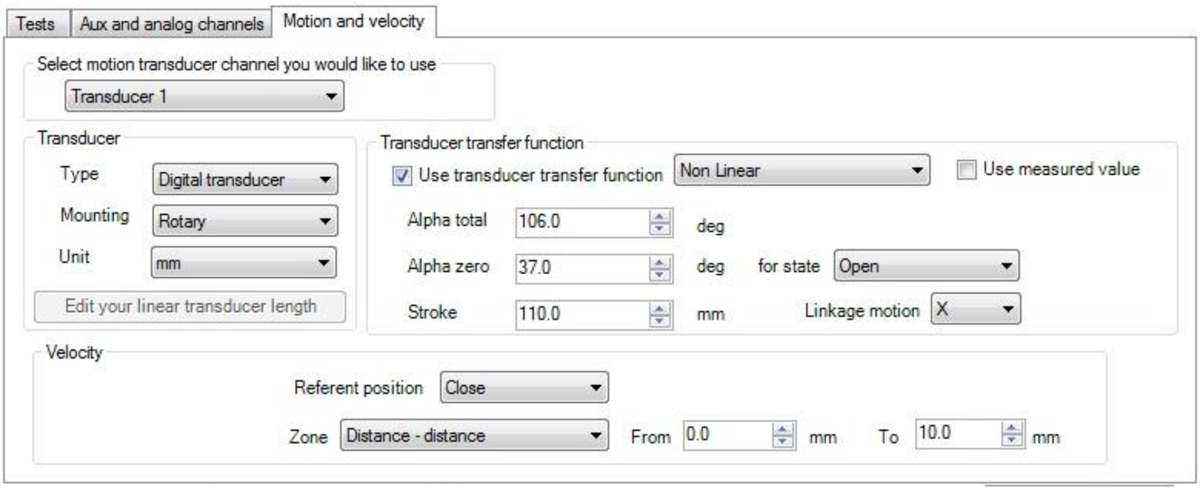

Figure 7. *Settings for non-linear transfer function*

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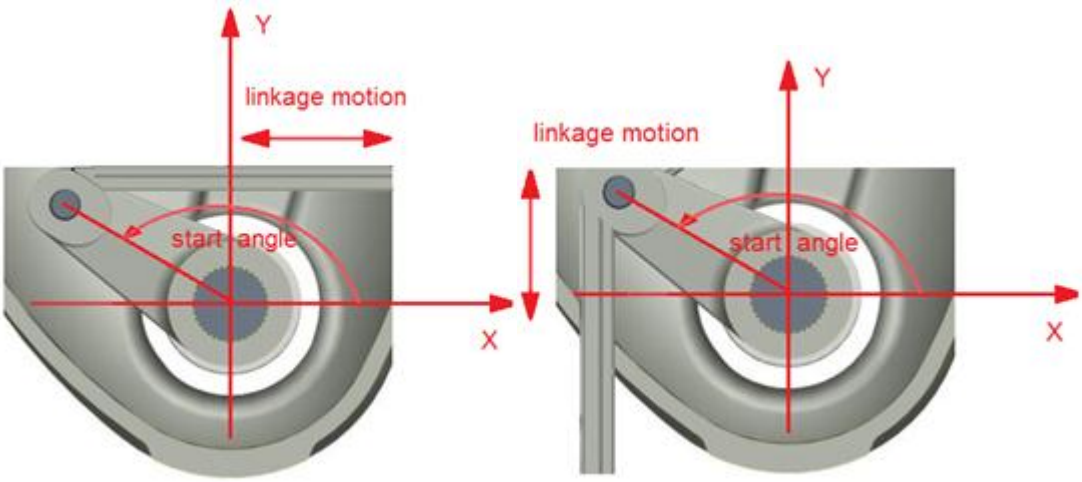

Figure 8. *Mechanism linkage motion along X axes (left) and along Y axes (right)*

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