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BENEFITS OF PERMANENT TRAVEL MEASUREMENT IN HIGH VOLTAGE CIRCUIT BREAKER ONLINE MONITORING

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ABSTRACT

The benefits of Condition Based Maintenance have been widely recognized for a long time. In recent years the focus shifted to its implementation. Since the resources for monitoring investments were not unlimited, the asset managers devoted their attention primarily on transformer monitoring at first, letting the condition monitoring of circuit breakers somehow fall behind (as evidenced in specific details from the CIGRE enquiry 2004-2007). Finally, circuit breakers are now getting more monitoring attention. In deciding which parameters should be kept under scrutiny to accurately assess the circuit breaker condition, travel measurement is one of the most discussed topics. Measuring the opening/closing coil current and the commutation of auxiliary contacts is essential, inexpensive and quite straightforward.

Installing SF6 gas density monitoring, in addition to an already installed threshold gas relay, finds its motivation in environmental gas leakage regulations. The measurement of travel curves requires the permanent installation of a proper transducer and additional fitting work, which has an impact on the cost of the monitoring system. Supporting the best decision whether to go for it or not, the benefits in terms of monitoring assessment are analyzed in this paper. Starting from the influence of contact travel on circuit breaker performance, typical parameters that can be derived from this measurement are analyzed and compared in relation to possible circuit breaker problems. Considerations are provided as to where to take the movement from and how to rescale the input signal. Some indications are also given on how to select a proper travel transducer and DC/DC converter power supply, what to pay attention to from an electrical as well as from a mechanical point of view to enhance reliability and measurement accuracy.

KEYWORDS

COMPONENT

CIRCUIT BREAKER

TRAVEL MEASUREMENT

MONITORING

CONDITION BASED MAINTENANCE

ENCODER

DC/DC CONVERTER

INTRODUCTION

Circuit breaker maintenance based on condition assessment was still rarely in use until ten years ago as reported in Final Report of the 2004 - 2007 International Enquiry on Reliability of High Voltage Equipment [1]. Beyond operating time and coil current, measuring the contact travel provides plenty of information. A travel measurement is usually carried out during the routine testing, after which the travel transducer is removed from the circuit breaker under test [2]. A permanent contact travel recording device can enhance the monitoring quality. To provide accurate and reliable travel monitoring it is important to correctly select the travel transducer. In the following sections, the impact of the travel curve on circuit breaker performance is reviewed and some considerations proposed to enable users to properly select a travel transducer that will monitor/survive a breaker operation.

WHY MONITORING THE TRAVEL CURVE?

The making and breaking performance of a circuit breaker are very much dependent on the correct travel curve provided by the operating mechanism [3]. A permanently installed travel transducer allows one to record the position of the contact vs. time for every circuit breaker operation. A straightforward approach is the “fingerprint” concept, according to which a travel curve is recorded as a reference and an alarm is raised if the curve exceeds given tolerances.

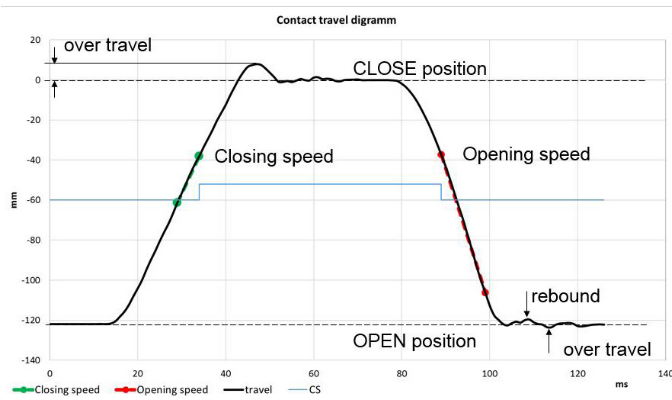


Figure 1 Typical travel curve for a CO operation.
Main calculated parameters are:
> Opening speed
> Closing speed
> Over travel and Rebound by closing operation
> Over travel and Rebound by opening operation

Additionally, the following parameters can be evaluated as shown in Figure 1:

- > Opening speed
- > Closing speed
- > Over travel and rebound by closing operation
- > Over travel and rebound by opening operation

Every deviation from normal values has an impact on circuit breaker functionality as reviewed in the following.

A. Opening speed

The opening contact speed of the circuit breaker is a crucial parameter to guarantee its switching capability and mechanical endurance. The manufacturer specifies minimum and maximum tolerances. A value which is too low can impair the short circuit current interruption as well as the capacitive current switching.

Short circuit current clearing

Figure 2 shows that a slower speed results in a smaller pressure build up in the puffer volume which directly impacts the blowing efficiency at current zero.

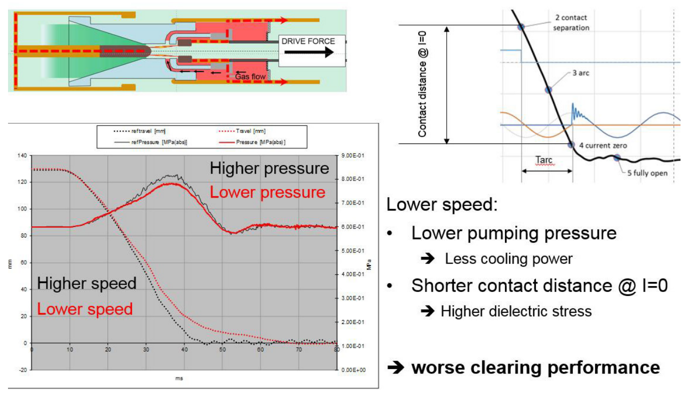


Figure 2- Impact of lower speed on short circuit switching performance. A slower speed results in a smaller mechanical pressure build up in the interrupting chamber. This reduces the blowing pressure at current zero with a consequent reduction of thermal switching capability. Additionally, the contact distance reached for the same arcing time is smaller, which increases the probability of dielectric failure around TRV peak.

The quenching medium (SF_6) decomposed in plasma form by the arc can turn back into dielectric medium only if there is enough cooling power provided by the interrupter. If the cooling power is not enough, the plasma form persists as such, therefore the gap between contacts remains conductive. The current crosses the zero-line continuing to flow. This is called "Thermal failure" and is typically visible in short line fault cases. If the cooling power is still enough to turn back the plasma into a dielectric medium, a slower speed results in a shorter contact distance for the same arcing time. The probability of dielectric breakdown around the peak of transient recovery voltage increases. If this happens, after a short pause the current starts flowing again, which results in a dielectric failure.

Capacitive and inductive current switching

While switching off a capacitive current, a 1-cos voltage rises across the contacts. To withstand this voltage, the circuit breaker has to keep the dielectric stress below the SF_6 dielectric strength by increasing the contact distance fast enough.

A slower speed makes the capacitive switching more severe.

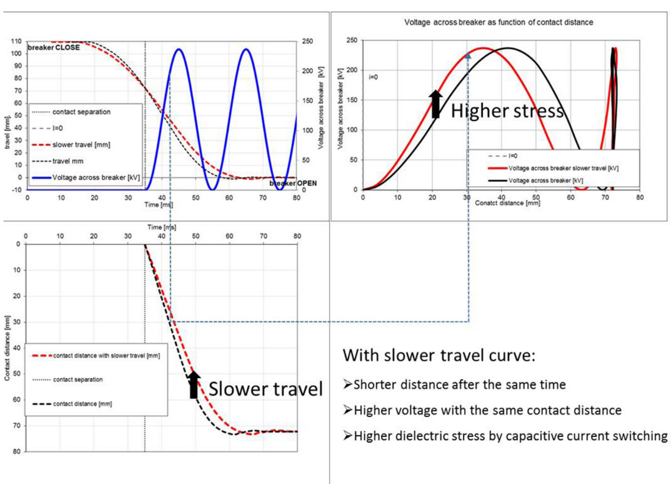


Figure 3 - Capacitive switching.
In the top left diagram a 1-cos recovery voltage in blue is shown starting at current zero is shown together with the travel curve (black) and a slower one (red). In the bottom left diagram, the contact distance is plotted vs time. In the top right diagram, the resulting voltage applied across the contact gap is plotted as function of distance for the known given travel curves. It is possible to see that with slower travel the applied voltage is higher whilst the contact distance is maintained.

A too high opening speed, besides mechanical overstress, increases the mechanical pressure build up and the consequent gas blowing between contacts. In case of small inductive current switching this can cause current chopping with consequent higher over-voltages.

B. Closing speed

Deviations from the rated closing speed can impair the 'making' capability of the circuit breaker. In Error! Reference source not found, a closing operation is shown with current making as it would happen if the circuit breaker closes against a fault.

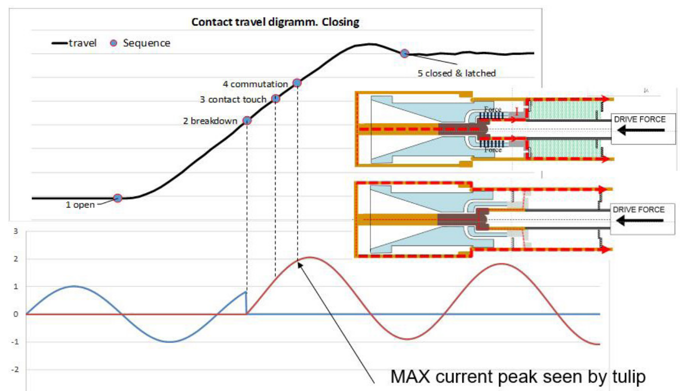


Figure 4 - Current making by closing operation.
Travel (black), applied voltage (blue) and current (brown) as function of time. A lower closing speed will increase the time between breakdown and contact touch as well as from contact touch to commutation. This increases the thermal and mechanical stress for the tulip and plug.

The current starts flowing before the contact touch. The time between current start and contact touch is called pre-arcing time.

A lower speed by closing operation increases the duration of pre-arc resulting in a heavier thermal stress of the arcing contacts. The time interval between contact touch and current commutation to main contacts increases as well, exposing the tulip to higher current values and consequent electrodynamic forces. The resulting higher friction between the tulip and plug could prevent the breaker from completing the intended closing operation with possible failure of latching, or in the worst-case scenario, damage the arcing contact system causing an internal catastrophic fault. When the closing speed exceeds the maximum value, depending upon the specific design, the consequences can go from higher mechanical stress to irreparable damage of the nozzle, plug and tulip with fatal consequences on the next opening operation.

C. Over-travel by closing

In many circuit breakers equipped with a spring operating mechanism, a minimum over-travel is required to ensure latching by closing. The manufacturer provides tolerances on these parameters not to be exceeded; An over travel which was too low would prevent latching. An intended closing operation would thereafter result in a Close to Open operation.

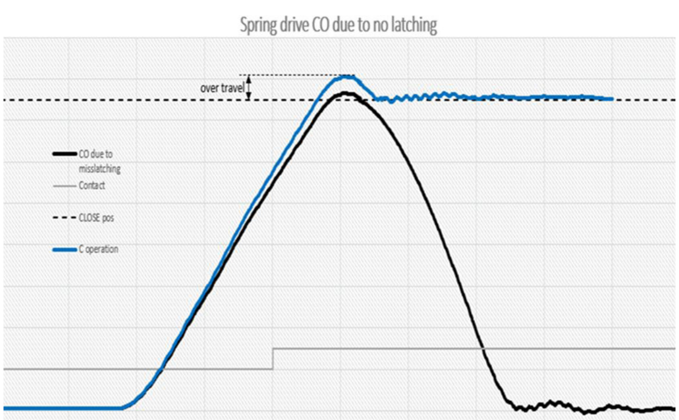


Figure 5 - Travel curve of a circuit breaker with spring operating mechanism.
- If the over travel is below the minimum, the latching is not successful and the contacts open again. A Close operation results in a Close-Open sequence.

D. Overtravel and rebound by opening

Sometimes these two parameters are also specified by the manufacturer. A rebound by opening means the contacts come together after having reached their fully open position representing a risk of re-strike by clearing. An excessive over travel while opening could come from an opening speed which is too high or a possible problem with the damper of the operating mechanism. The consequences of this range from a general higher mechanical stress up to damage of the interrupter due to internal collisions. If the opening speed is correct and the over travel and rebound by opening has the tendency to increase, it is a good indication that the damper in the operating mechanism is less and less efficient.

WHERE TO MEASURE THE TRAVEL CURVE

The final target is getting the travel curve of the moving contact. All the travel curve parameters are referenced to the actual position of the contacts, which is not accessible for measurement. The travel transducer takes the movement from the most convenient accessible point along the linkage between operating mechanism and interrupter. What is measured is not the actual contact displacement and the relationship between the two values is not always linear. Figure 6 shows a typical case of the use of a rotary travel transducer applied to the shaft of the interrupter bell crank.

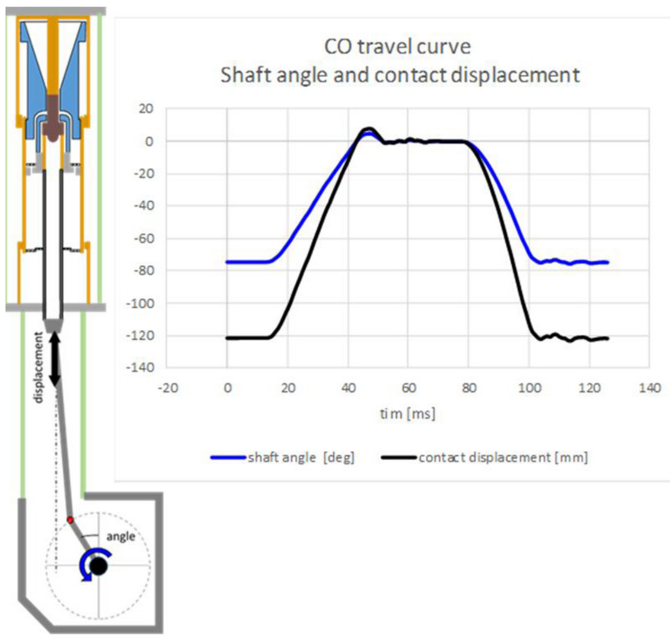


Figure 6 - Example of travel measurement at the bell crank shaft.
The relationship between the angle and the displacement is not linear.

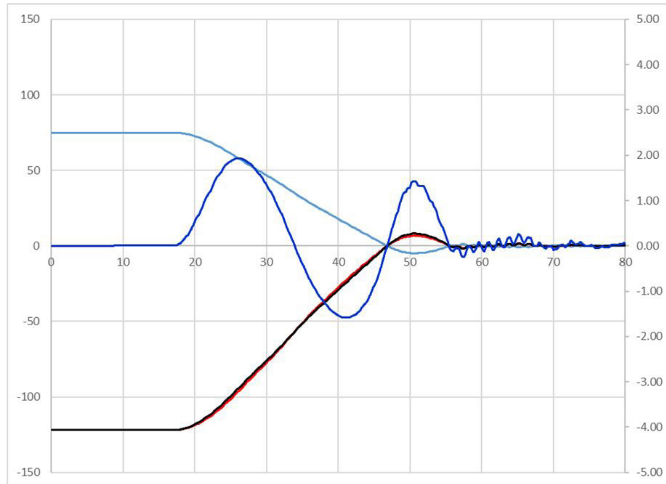


Figure 7 – Travel curve by closing.
From the measured angle, linear rescaled measurement and actual contact position are compared. A difference of 1.5 mm could cause 20% to 30% error in the evaluation of the over-travel evaluation.

The transducer measures an angle that is in relation with the actual contact displacement with a function defined by the linkage geometry. A linear re-scaling of the input signal to the actual contact stroke introduces a linearity error that is higher towards the extremities of the linkage positions and for a wider angular movement. An example of comparison between the actual contact position and the linearly rescaled angular measurement is given in Figure 7.

To enhance the measurement accuracy of the actual contact position, a translation function from rotary measurement to linear contact displacement can be used as shown in Figure 8.

Figure 8 – Principal data processing for getting the actual contact displacement

For comparison with routine test reference values, the speed between two defined points will be calculated for C and O operations. The point definition datum points will be independent for closing and opening operations and configurable according to the following criteria:

> Time difference from auxiliary contact commutation (52 a/b)

> Percentage of the stroke

> Distance between datum points based on travel curve

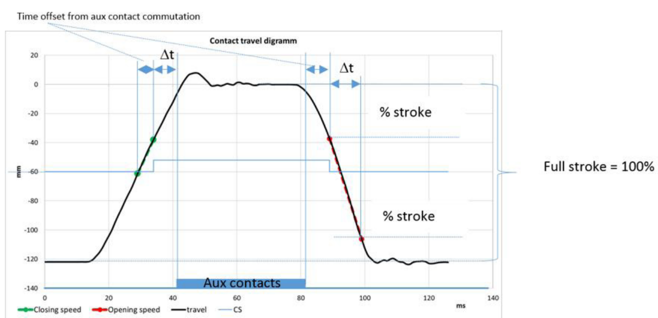


Figure 9 – Travel curve speed evaluation
For both opening and closing operation the speed is the average between two points defined independently
- 2 for closing
- 2 for opening
The points can be defined as a % of the total stroke or time.

An example of typical defined intervals for speed measurement is:

Opening operation

> 1st point: at Contact Separation

> 2nd point: ~7.5-10ms after contact separation

Closing operation

> 2nd point: at contact touch

> 1st point: ~ 5ms before contact touch

TRANSDUCER CHARACTERISTICS

From a movement typology view point there are linear and rotary transducers. The type to select naturally depends on the type of movement to measure. If there is the possibility to choose, rotary transducers are in general more reliable due to their compactness. The installation is generally less critical and the mechanical resultant actions are more secure.

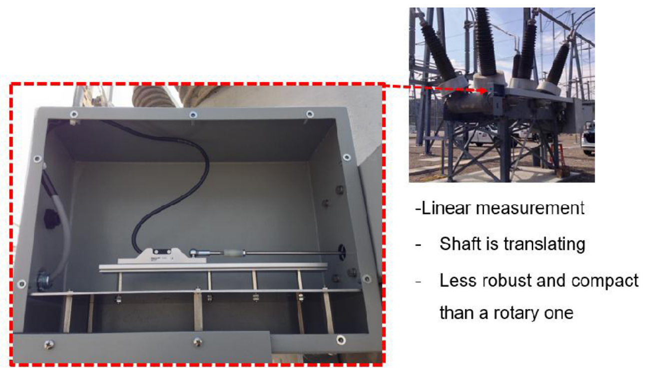


Figure 10 - Linear transducer with linkage

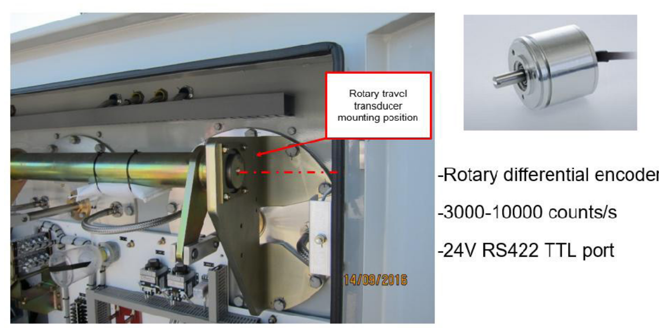
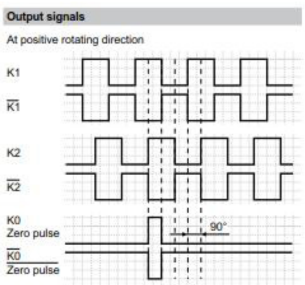


Figure 11 - Rotary transducer

A. Resistive or Encoder type

For temporary routine breaker offline test travel measurements, resistive transducers are very often used since they provide an accurate analogue voltage signal which can easily be recorded with a standard data logger or oscilloscope.

On the contrary, for online permanent monitoring, resistive transducers showed reliability problems. The high number of operations combined with quite variable weather conditions were very often damaging the internal sliding contact. Contactless encoder-based transducers should be preferred given that they do not suffer from mechanical wear and also because their differential quadrature RS-422 digital outputs make the measured signal conversions less sensitive to noise. An example of an incremental encoder is shown in Figure 12.



OG 60

Pulse number

10	300	625	1800	4096
20	360	720	2000	5000
60	400	900	2048	6000
100	500	1000	2500	8192
200	512	1250	3000	10000
256	600	1500	3600	

Figure 12. Typical output signal of an incremental encoder.
There are two sets of impulses with each set 90 deg shifted from each other that allows determination of the rotational direction.
A reference pulse for every revolution (K0) is also given, but not used.
The number of pulses per revolution is selectable per the above chart.

Incremental encoders do not require "remembering" the starting position. By counting the pulses and knowing the deg/pulse it is possible to measure the incremented position from the beginning to end of the measurement. Absolute encoders are also available, but they are in general more expensive, more delicate and not applicable for this application.

It is possible to select the number of pulses per revolution with the purchase. In the specific case given in Figure 12, a value from 10 up to 10,000 pulses per revolution can be selected.

B. Which Pulse number

The number of pulses is a function of the stroke to measure. Typical values for circuit breaker strokes and operating times are given in Table 1.

Parameter		From	To	Comment
Typical angular stroke	deg	60	150	Bell crank design dependent
Stroke	mm	100	200	Higher values for higher rated voltage (145kV -550 kV)
Closing speed	m/s	4	10	Higher values for higher rated voltage (145kV --> 550 kV)
Opening speed	m/s	4	13	Higher values for higher rated voltage (145kV --> 550 kV)
Acceleration	m/s2	500	2000	Acceleration peak during latching or bouncing could be even higher

Table 1 - Typical parameters of a circuit breaker travel curve

Resolution

The encoder is a digital output transducer sending an impulse for every part of its total stroke. The resolution at which a measurement is taken is the percentage of the measured stroke per single pulse. In the majority of the cases a 0.2% resolution can ensure a quite high position accuracy. For a stroke of 200mm contact stroke this would lead to 0.4 mm/pulse.

Pulse number

Having set the desired resolution, R% the number of pulses to measure for the contact stroke is given by:

$$N_{mp} = \frac{100}{R\%} \qquad \bullet\bullet\;\bullet\bullet$$

In case of 0.2% resolution, the contact stroke can be measured with 500 pulses. The number of pulses per revolution depends by the actual measured angle α.

$$N_{ppR} = N_{mp}\,\frac{360}{\alpha} \qquad \bullet\bullet\;\bullet\bullet$$

As shown in Table 2, reducing the measured angle α to 30 deg or smaller values, the needed number of pulses per revolution to ensure the wanted Resolution increases up to 10,000.

Resolution *R%*	measured pulses to cover breaker stroke *N_mp*	measured angle *α*	Pulses per revolution *N_ppr*
	pulses	deg	pulses/rev
0.20%	500	150	1200
0.20%	500	120	1500
0.20%	500	90	2000
0.20%	500	60	3000
0.20%	500	30	6000
0.20%	500	18	10000

Table 2- Pulses per revolution as function of Resolution and Measured angle

Pulse frequency

If selecting the highest available number of pulses available would allow covering every possible measured angle, it is not necessarily the best choice.

For fast circuit breakers this could require a very high pulse frequency that the monitoring device must accommodate.

The pulse frequency is a function of maximum speed of the breaker V, its Stroke, number of Pulses per Revolution, and measured Angle α.

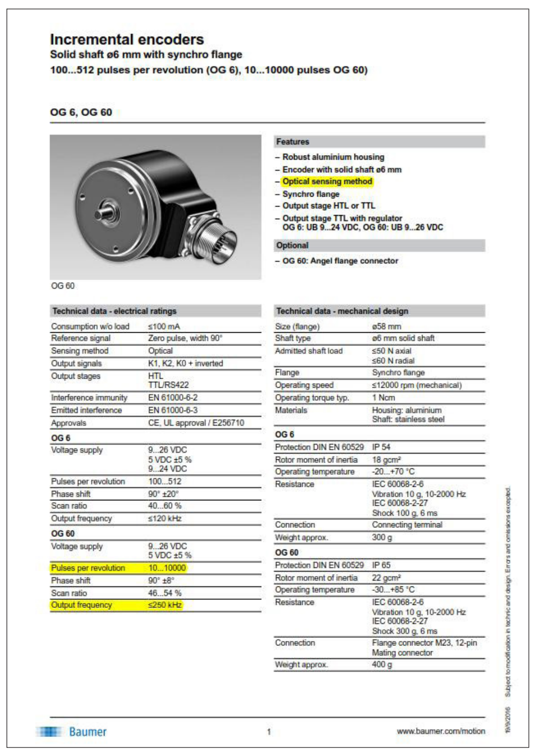
$$f_p = \frac{\alpha \cdot N_{ppR} \cdot V}{360 \cdot S} \quad \bullet\bullet\bullet\bullet$$

For detecting deviation from the rated travel curve, speeds up to twice the normal value should be measurable. This means selecting an encoder and a monitoring device able to work up to 2 × f_p.

mea-sured angle	pulses per revolu-tion	measured pulses to cover breaker stroke	resol-ution	assumed speed	breaker stroke	pulse frequency	frequency requirement
a	N_{ppR}	N_{mp}	R%	V	S	f_p	2 x f_p
deg	pulses/rev	pulses		m/s	m/m	kHz	kHz
150	10000	4167	0.02%	10	200	208	417
120	10000	3333	0.03%	10	200	167	333
90	10000	2500	0.04%	10	200	125	250
60	10000	1667	0.06%	10	200	83	167
30	10000	833	012%	10	200	42	83
18	10000	500	0.20%	10w	200	25	50

Table 3 – Pulse frequency as function of measured angle α assuming a breaker Stroke of 200mm and Pulses for revolution equal to 10,000.

In Table 3 the Frequency requirement is evaluated for different values of the measured angle α, using an encoder having 10,000 pulses per Revolution. The resulting pulse frequency can be quite high exceeding the maximum guaranteed value by the encoder manufacturer. As an example, a typical encoder can manage up to 250 kHz output frequency (Figure 13).



Incremental encoders
Solid shaft ø6 mm with synchro flange
100...512 pulses per revolution (OG 6), 10...10000 pulses OG 60)

OG 6, OG 60

OG 60

Features
- Robust aluminium housing
- Encoder with solid shaft ø6 mm
- Optical sensing method
- Synchro flange
- Output stage HTL or TTL
- Output stage TTL with regulator OG 6: UB 9...24 VDC, OG 60: UB 9...26 VDC

Optional
- OG 60: Angel flange connector

Technical data - electrical ratings	
Consumption w/o load	≤100 mA
Reference signal	Zero pulse, width 90°
Sensing method	Optical
Output signals	K1, K2, K0 + inverted
Output stages	HTL TTL/RS422
Interference immunity	EN 61000-6-2
Emitted interference	EN 61000-6-3
Approvals	CE, UL approval / E256710
OG 6	
Voltage supply	9...26 VDC 5 VDC ±5 % 9...24 VDC
Pulses per revolution	100...512
Phase shift	90° ±20°
Scan ratio	40...60 %
Output frequency	≤120 kHz
OG 60	
Voltage supply	9...26 VDC 5 VDC ±5 %
Pulses per revolution	10...10000
Phase shift	90° ±8°
Scan ratio	46...54 %
Output frequency	≤250 kHz

Technical data - mechanical design	
Size (flange)	ø58 mm
Shaft type	ø6 mm solid shaft
Admitted shaft load	≤50 N axial ≤60 N radial
Flange	Synchro flange
Operating speed	≤12000 rpm (mechanical)
Operating torque typ.	1 Ncm
Materials	Housing: aluminium Shaft: stainless steel
OG 6	
Protection DIN EN 60529	IP 54
Rotor moment of inertia	18 gcm²
Operating temperature	-20...+70 °C
Resistance	IEC 60068-2-6 Vibration 10 g, 10-2000 Hz IEC 60068-2-27 Shock 100 g, 6 ms
Connection	Connecting terminal
Weight approx.	300 g
OG 60	
Protection DIN EN 60529	IP 65
Rotor moment of inertia	22 gcm²
Operating temperature	-30...+85 °C
Resistance	IEC 60068-2-6 Vibration 10 g, 10-2000 Hz IEC 60068-2-27 Shock 300 g, 6 ms
Connection	Flange connector M23, 12-pin Mating connector
Weight approx.	400 g

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Figure 13- Datasheet of incremental encoder [4]

C. Mechanical stress

The transducer is connected to moving linkage of the breaker and as such it has to withstand the mechanical stress coming from the movement.

Acceleration of the movement

In Table 1 values between 500 and 2000 m/s2 are given as typical. In case of rotary transducer, the corresponding angular acceleration can be estimated considering the actual rotary measured stroke:

- angular stroke: 75deg =1.31rad
- linear stroke = 120mm = 0.12m
- linear acceleration = 2000 m/s2
- corresponding angular acceleration:

$$2000 \cdot \frac{1.31}{0.12} = 21{,}833 \frac{rad}{s^2}$$

A typical maximum applicable value is 100,000 rad/s2

D. Ambient temperature and Ingress Protection

When selecting a travel transducer, the operating temperature range where the circuit breaker is installed must be known. The selected travel transducer must be able to operate over the entire environmental temperature range and be sealed for at least an IP 54 rating to provide ingress protection for the prevailing humidity and dust conditions where the travel transducer is installed.

E. Travel Transducer Power Supply Selection Criteria

Choosing a proper DC/DC converter power supply for travel transducers requires consideration for ambient temperature, ingress protection, mechanical vibration survival within an operating circuit breaker and a voltage output that fits well within the input voltage range required by the travel transducer. The DC/DC converter power supply must be able to meet or exceed the aforementioned specifications required for the selected incremental travel transducer encoder.

Travel Transducer Input Voltage Range Requirements
Travel transducers such as the device depicted in the Figure 13 datasheet that could be used for online breaker travel analysis have input voltage requirements of 5vdc with a tight operating tolerance of ±.25vdc or can be purchased with a much wider input power requirement range of 9-24vdc or 9-26vdc.

Recommended Travel Transducer Input Voltage Ranges
Whenever possible it is advisable to select an incremental travel transducer that has the wider input voltage range. With 9-26vdc or a 9-30vdc input power requirement such as that required by other incremental travel transducers, DC/DC converters with a 12vdc, 15vdc or 24vdc output would perform very well as there would be no concern for voltage drops or noise on the power cable should the DC/DC converter be located some distance from the travel transducer. A 5vdc travel transducer having a tight tolerance for operation could malfunction due to severe voltage drops or excessive noise injected onto the power cable unless both devices are installed very close to each other.

CONCLUSION

Monitoring the travel curve can enhance the level of condition monitoring of a circuit breaker. Although apparently very simple, a reliable permanent travel measurement for online circuit breaker monitoring applications is not trivial to get.

Attention must be paid while selecting the travel transducer from a mechanical stress point of view. Selecting the proper pulse number allows the user to get an accurate travel curve without hitting the upper frequency limit of the transducer and monitoring device's input card.

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