MONITORING OF OIL LEAKAGES OF CIRCUIT BREAKER HYDRAULIC DRIVE

Bartosz Rusek
Darmstadt University of Technology
Darmstadt, Germany
bartosz.rusek@eev.tu-darmstadt.de

Gerd Balzer
Darmstadt University of Technology
Darmstadt, Germany
gerd.balzer@eev.tu-darmstadt.de

Abstract – Detection possibilities of the oil leakages from the circuit-breaker hydraulic drive for monitoring purposes are presented. The research was done with use of the circuit-breaker digital model that was created in MATLAB/ SIMULINK programming package. The most often leakages were chosen for simulations. The detection methods were divided into two groups respectively: directly connected with leakages and indirectly connected, which show seal defects. The presented methods will be compared and the utilisation possibilities will be given. Additionally the leakage trend and leakage rate has been defined.

Keywords: diagnostics, maintenance, monitoring, circuit breaker, hydraulic drive.

1 INTRODUCTION

The oil leakages are numbered to minor failures. However in some cases, for example when there is no more oil in oil reservoir because of the leakages then the oil pressure cannot be rebuild and therefore the required switching cannot be performed, they could lead to major failures. In order to avoid such and other critical situations the circuit breakers (CB) are usually reviewed in constant periods of time (time-oriented maintenance). Because of the liberalisation of the energy market, the time-oriented surveys are no more economically optimal. For this reason, the condition-based surveys are getting more popular. However, they require the knowledge about the actual CB condition, which is usually supplied by the different monitoring systems and this one have limited possibilities to supply data about leakages and their locations.

The leakages are common phenomenon for the hydraulic drives of CB. Normally the motor can be turned-on up to 20 times per day. The oil leakages do not cause problems immediately. Measuring some variables the failure development or failure trend can be defined. If it shows changes above predefined limits, the date of forecasted maintenance or the date of eventual failure should be given. This gives time for preparation to the maintenance procedures. Additionally the time of the maintenance itself and also the outages of the drive can be reduced because the maintenance personal knows where the failures are or can be located and what spare parts should be ordered in advance.

The results achieved from querying of database, which is in possession of the Institute of Power Systems Darmstadt University of Technology, were also motivation of this work. The database consists of 6000 failure records of 9000 CB. The majority of failures 5338 was located in SF_6 or in minimum-oil circuit breaker with hydraulic drive. Interesting is that over 40% of all failures in considered breaker group occur in drive. This conclusion has been also confirmed by CIGRE studies [1]. Considering forwardly the causes of drive failure, it can be seen that the majority of failures 72% was specified as leakages (Figure 1a). The air intrusion 8% is also connected with leakages because they are the reason of oil missing in the reservoir and as end effect of air intrusion. The rest of failures is unknown or is not connected with the considered problems.

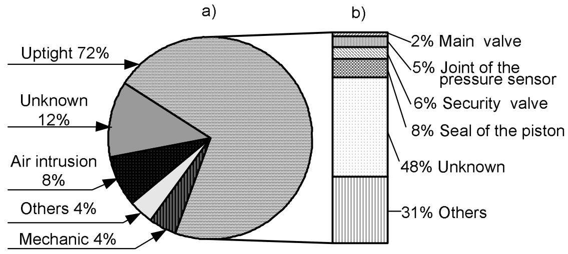

Figure 1: a) Cause of hydraulic drive failures and b) the uptight components.

The Figure 1b) shows the most often uptight components. It can be seen, that a large part of components cannot be localised (48%). This is the result of using the simple detection methods, where leakage detection is easy but exact localisation of leakage source is impossible. In such cases, all the drive seals will be changed. The database includes also the identifiable components, which are mostly connected with moving elements (except joint of pressure sensor). For this one the monitoring possibilities will be given. The rest of failures (31%) appear very seldom and the commitment of each of them to the overall number of defected components is less then 1%. They will not be considered.

In this paper, the possible leakage causes and their localisation in drive will be described. It will also be shown what methods allow detecting the leakages or defected seals and which of them are the most suitable for particular uptight component.

Presented methods lead to a better condition assessment of CB hydraulic drives. They show how to service them in case of leakages if such procedure is required.

2 CAUSES OF LEAKAGES

During the last years, the seal techniques have significantly improved. New materials as well as the new seal constructions have been introduced. However, we have to consider that the database contains breakers with build date from 1957 until 2001 so they have old and new designs. The part of this drives has been already replaced but the larger part is still in use and in those, the old seal techniques were applied. It is assumed that large part of those drives have seals made of different types of elastomer i.e. they show properties of this material.

The leakages mainly appear if the seal do not press the housing with high enough force and between those two components appears a gap. The gap can also appear in a small part of seal where for example the piston has grooves. The required press force can change because of material or construction reasons. The most important causes of the hydraulic drive seals has been chosen from references [2, 3].

2.1 Material dependent causes

The long life of the seal depends on material, which it was made of. One of the best materials to create a seal for such difficult and important application like CB hydraulic drive is elastomer. It properties depend on the named physical phenomenon:

- Thermal reconstruction by higher temperatures
- Fluid absorption, which soft the gum and can lead to "explosive decompression"
- Thermal spreading, which is higher then the housing

2.2 Application dependent causes

The most endangered on defects are seals of moving elements (Figure 1). In considered drive, these are seals of pistons and valve. Some of the most important application dependent causes are:

- Particles of wipe off, sand and dirt grains etc. in oil system can lead to appearing of grooves in cylinders and in end effect deformation of seal.
- Low-pressure side of the seal can be deformed and forced in the housing crack, because of high-pressure (about 400bar). This part can be cutout and can get-stuck in crack. This increases frictions.
- Air concentrated by the seal under influence of high-pressure leads to micro-diesel effect. This destroys extern layer of seal.
- Oil film, which is necessary to sustain good lubrication between housing and seal, can disappear because of seal deformation and relative high main piston speed (about 5m/s). This significantly increases frictions and damages the seal.

3 CIRCUIT BREAKER DIGITAL MODEL

The oil leakages are located inside the drive so it would be enough to model only drive. However, the forces originated in chamber and their transmission to the drive by mechanical connection can strongly influence for example the speed of the piston. The elastomer seals are normally applied on elements, which speed is less then 5m/sec. Piston without load forces moves much faster then that. For this reason, the leakages were modelled and simulated in a complete model of circuit breaker. The model consists of four main components (Figure 2):

- Control – fulfils control and protection tasks
- Hydraulic drive – supply and store the energy for switching operations. Model processes three types of equation: electrical (coils, motor), mechanical (all moving elements) and hydraulic (oil flows and pressure calculations).
- Mechanical, elastic connection – transmit the energy from drive to the chamber
- Chamber – is modelled as black box with one output the reaction force of moving contacts in case of load current switching

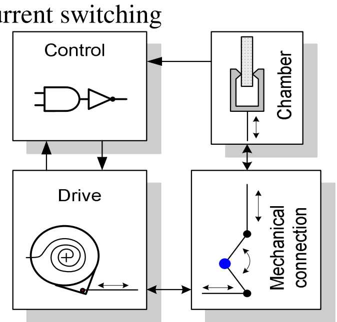

Figure 2: Circuit Breaker main components

The most advanced component and crucial for this research is the drive model (Figure 3). Because the model is quite complex only the basic work principles and main functions will be described.

3.1 Short description of drive model

Basically, the drive is modelled as 3 volumes filled with compressed oil. Two volumes over piston (block 14) and energy storage (block 7) are directly connected (block 13). The oil flows into 3 volume under piston (block 15) during switching-on and flows out during switching-off. The oil flow is controlled by 3/2 switch valve (blocks 10,11,12) which is moved by two electromagnetic coils (blocks 8,9). The energy is stored in plate spring (block 6), which through piston pushes on oil in energy storage volume. The main piston (block 16) moves according to the differential piston principle. The area over main piston is smaller then under i.e. if the pressure on both piston sides is equal (switching-on case) the force which works under piston is higher then over piston – the main piston moves up. After switching operation the oil in energy storage volume has to be refilled. It is done by pump-motor system (blocks 1,2,3,4,5).

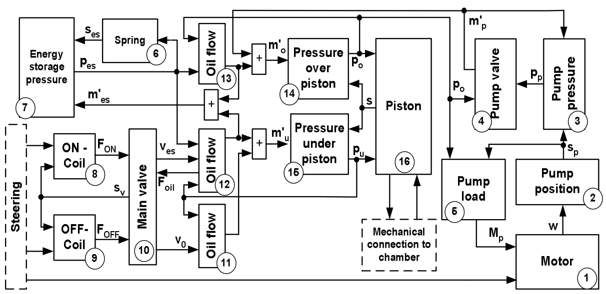

Figure 3: Model of the hydraulic drive

Named work principles are modelled by mathematical equations. (The motor- pump system will not be described because it has no influence on considered in this work cases). The pressure is required to calculate the forces which work on the pistons:

$$F = p_n \cdot A \quad (1)$$

where: F-force, p-pressure, A-piston area

The actual oil pressure (p_n) is a function of actual density (ρ_n) and oil compression ratio (κ).

$$p_n = p_0 - \frac{\frac{\rho_0}{\rho_n} - 1}{\kappa} \quad (2)$$

The compression ratio depends on oil properties i.e. the pressure with relationship $(1.54 + p*6.3*10^{-4})^{-4}$ and temperature, which for this consideration is constant 15°C.

Having the force caused by compressed oil and forces of other boundary conditions (sum of all working on piston forces F_{sum}) the new piston position (s) can be defined according to:

$$s = \iint \frac{F_{sum}}{m} dt \quad (3)$$

where: m-mass of moving elements

Change of the piston position and also valve action cause change of oil balance in volumes. For this reason, there occur some balance oil flows ($\dot{Q}$), which are calculated according to the turbulent flow equation:

$$\dot{Q} = A\alpha\sqrt{\frac{2\Delta p}{\rho_n}} \quad (4)$$

where: A – flow area, α – velocity coefficient, Δp – pressure difference, ρ_n – oil density.

Only this one type of flow is considered because it appears almost instantaneously after opening of the valve. This is caused by very big difference of pressure between opened volumes. Additionally, the drives are constructed in a way that the flows are kept as turbulent as possible, in order to use the property of turbulent flow, which is very small influence on temperature.

Integration of the oil flows ($\dot{Q}$) that flow into particular volume multiplied by the density (ρ_n) gives mass in considered volume (m_{oil})

$$m_{oil} = \int \dot{Q} \cdot \rho_n \, dt \quad (5)$$

Having mass and the volume (V) the actual oil density from equation

$$\rho_{n+1} = \frac{m_{oil}}{V} \quad (6)$$

and afterwards the new pressure from Equation (1) can be calculated. Here, the loop closes and the calculation process begins once again.

The valve movement is described by Equation 3 where the force required to move the valve is supplied by the electromagnetic coils. The coil output force is proportional to magnetic inductance in air gap quadrate. However, this inductance is not constant but depends on the position of the coil armature which is equal to position of valve. The relationship between position and inductance is quite complex. The basis of mathematical model can be taken from reference [4].

The whole digital model is much more complicated than here described. The model considers dependence of the parameter on temperature, the losses during oil flows, damping of springs, frictions and many other specific for hydraulic drive parameters.

3.2 Modeling of leakages

The leakages itself can be modeled in four different ways:

- by application of Equation 4 where the oil flow area A has very small value in range of 10^{-3} [mm^2] (leakage rate depends on pressure)
- by artificial decreasing of oil mass (for example 0.1 [g/min]) in one of the drive volume (constant leakages)
- by artificial decreasing of oil mass in over main piston volume depending on the speed of the piston (for example $m_{leck}=10^{-2}*v_{piston}$ [g]) (dynamic leakages)
- by changing of the valve opening characteristic i.e. shifting of opening point (modeling of seal deformation)

4 LEAKAGES DETECTION

The previously selected failures (paragraph 1) were simulated in a model described in paragraph 3. There has been generated several parameters like for example energy storage position which could point the leakages occurrence. The recognition process was done through comparing of the parameter characteristic with fingerprint.

The detection of the oil leakages can follow through observation of following parameters:

- motor switch counter (direct)
- energy storage position (direct)
- oil pressure (direct)
- visual (direct)
- oil level in oil reservoir (direct)
- oil flow of the leakage (direct)
- peak of the oil flow (indirect)
- derivative of the current (indirect)

The way of detection has been noticed in parental. The indirect methods do not measure the oil leakage directly. They allow defining if seal is in bad condition and this has connection with leakages in steady and dynamic state.

4.1 Motor switch counter

The counter belongs to the standard monitoring accessories of drive. The main its function is counting the motor operations. The motor should be switched-on if amount of stored energy is to low. The stored energy can decrease because of the CB operation or because of the leakages. The CB operation consumes lot of energy and motor has to be switched-on so the number of motor switch counter and CB operations counter should be equal. This is of course ideal case without leakages. The leakages will cause additional motor operations (normally up to 20 times per day that means 1.2 hours between to motor starts) while the CB remains in the same position.

The leakage rate can be defined by measuring the time between the consecutive motor start if CB was not operating. In considered fully charged drive, the energy storage position (ESP) amounts 53 [mm]. The motor will be switched-on if ESP decreases below 50 mm. The difference in positions (3mm) corresponds to 7.62 [g] oil mass (m_{oil}), which leak from high-pressure part. Given value is a result of simulations. The changes of the energy storage volume are not proportional to the amount of oil leakage because the oil is compressible by very high pressures and its density is higher (about 400 [bar] in drive). Considering time between motor starts (t_{break}), the leakage rate L_r amounts:

$$L_r = \frac{m_{oil}}{t_{break}} = \frac{7{,}62\,g}{1.2h} = 6.35\left[g/h\right] \tag{7}$$

The critical leakage rate (L_{max}) can be defined as the ratio of allowed oil leakage (m_{oil}) to the maximal motor operation time including time for cooling (t_{motor}). For considered motor, the maximal operation time amounts 2 min. The cooling time has been assumed equal to 10min.

$$L_{\max} = \frac{m_{oil}}{t_{motor}} = \frac{7{,}62\,g}{12\,min} = 38.1\left[g/h\right] \tag{8}$$

The critical value do not defines the safety limit. In case of external leakages, the energy cannot be refilled because of oil lack in reservoir. For this reason, the leakage rate can be also defined as the ratio of amount of oil, which is accessible in reservoir (about 1 [l] = 876 [g]) to the allowed minimal maintenance period for example 1 day to refill the reservoir. For assumed numbers, the critical leakage rate form (8) amounts 36.5 [g/h]. The number corresponds to motor switching-on every 12.5 minutes. It can be noticed that the received critical numbers do not differ a lot.

How fast the leakage develops is described by leakage trend. Trend (T_L) can be defined as ratio of the difference of the leakage rate to the time of last switching. For example, motor was turned-on after 1.2 hours break and the next turning on appeared in 0.5 hour, so the leakage trend amounts

$$T_L = \frac{L_{r2} - L_{r1}}{t_p} = \frac{7.62/0.5 - 7.62/1.2}{0.5} = \frac{15.24 - 6.35}{0.5} = 17.78\left[g/h^2\right] \tag{9}$$

Presented calculations can be only accomplished in discrete periods, which depend on leakage rate.

The value of the leakage rate and trend can change depending on the CB state. The reason is that in different CB states not the same seals are responsible for drive tightness. For such cases, the motor will be switched-on after different periods in OFF and ON-state of CB. The feature will be exacter described in next paragraph.

4.2 Energy Storage Position

A good indicator of the oil leakages is the energy storage position. This variable allows defining the leakage rate and leakage trend at any time except switching periods, with no need to wait for next motor switching-on.

During presence of leakages, the ESP decreases proportionally to leakage rate (Figure 4). The movements of the ESP can be also observed by temperature variations, so the rate defining algorithms should consider temperature influence. The intensity of this phenomenon depends on the overall oil volume and the properties of oil.

As it was already said, the leakage ratio can have different value in ON and OFF state of CB. The different wear-out of seals, which at defined state should sustain tightness, has to be considered. For example, the main piston seal can be only uptight if breaker is switched-off, because if it is switched-on the pressures on both seal sides are equal. Described feature has been simulated in the digital model. In ON-state, the piston seal is not responsible for tightness and the leakages come from other seals. The leakage rate has a nominal value (upper curve on Figure 4). After switching, the leakage rate drastically increases reaching critical value (lower curve on Figure 4). Bear in mind that there is only one additional seal, which supposed to be tight (piston seal), the leakage source can be located.

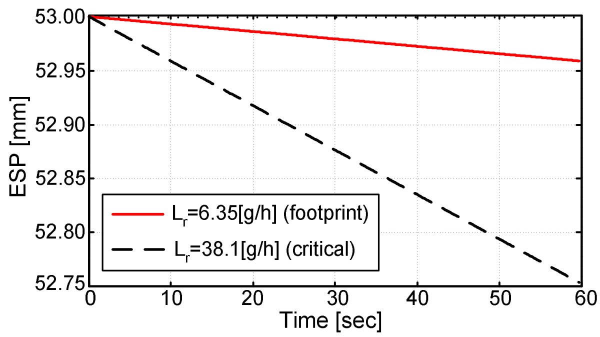

Figure 4: Energy storage position before (upper) and after (lower) switching operation for two cases with: nominal, allowed (upper) and critical (lower) leakages

There exists also possibility to monitor the energy storage velocity. However, this parameter has very low value comparing to the position deviations.

Bearing in mind, that almost all defined leakages named in database are connected with moving elements and that the seal condition is additionally strongly influenced by movements, the ESP can give very useful information about the dynamic leakages rate. In such cases, the leak of oil is seen as small difference (ΔESP) in the energy storage position after switching (Figure 5). It has to be mentioned that speed of moving elements has also influence on the dynamic leakage rate.

It can be assumed that if the piston seal has high dynamic leakage rate then the considered seal is a probable source of the leakages.

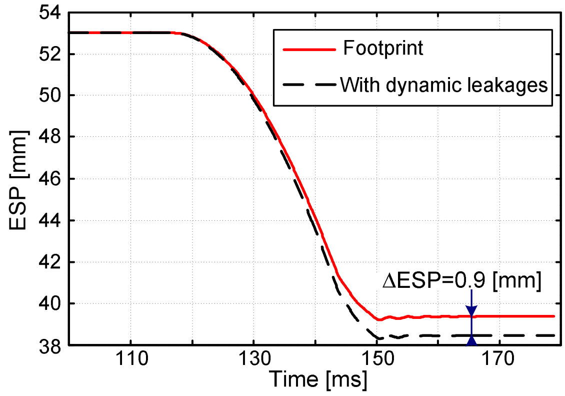

Figure 5: Energy Storage Position

Method is recommended only for commissioning checks because it is necessary to disable refilling of the oil for few seconds after switching in order to measure the ΔESP.

Because the ESP can be measured continuously, the leakage rate can be calculated with modification of the equation (7). The mass of leaked oil corresponds to the changes of the energy storage position (s) with assumption of lineal characteristic of the energy storage spring

$$L_r = 2.54\frac{ds}{dt}\left[g/h\right] \qquad (10)$$

The constant 2.54 has been experimentally designated on hand of the digital CB model. The leakage trend (T_L) can be calculated as

$$T_L = 2.54\frac{d^2s}{dt^2}\left[g/h^2\right] \qquad (11)$$

This equation would catch only very fast leakage changes which is not realistic in case of leakages, because they develop slowly. For this reason, the equation (8), which defines trend in loner period, will provide significantly more information.

4.3 Oil pressure

Not in all drives, the ESP is measured to define the amount of the stored energy. Some of them measure the oil pressure directly. The behaviour of pressure is very similar as in case of ESP i.e. it decreases if the leakages are present because of the relationship (2).

The characteristic of oil pressure is not as smooth as the ESP because the energy storage consists of piston and plate spring and has significant inertia. Excluding the pressure changes right after switching operations it can be successfully used to define the trend or rate of the leakages according to the already described principles.

4.4 Visual

This method is the simplest one because it does not require a big knowledge about drive only good eyes. The extern leakages are very well seen on the housing and can be easily spotted. Additionally the uptight seals can be directly pinpointed.

The examinations cannot be performed very often because of financial reasons. The safety during examination has to be also considered. The continuous monitoring as well as determination of the leakage rate and trend can be obviously excluded.

4.5 Oil level in oil reservoir

Monitoring of this variable can solve problems with air intrusion and allows avoiding critical situation where in reservoir is no more oil and the pressure cannot be rebuild. The intern leakages will be very well seen because the oil level will slowly increase. This can show only internal leakages. The increasing ratio will not be proportional to ESP because of the influence of spring characteristic and oil compression ratio.

4.6 Oil flow of the leakage

The last one of direct methods is detection of the oil flow of leakages, which has been described in [5]. Locating the oil flow sensors in crucial locations, the direction and magnitude of the leakage oil flow can be measured. Knowing the circuit breaker position and the described parameters, the impaired seals can be defined. However this method requires very exact oil flow sensors and there still exist the problem of small oil flows during temperature variations.

4.7 Peak of the oil flow

Presented feature of oil flow can be used to point defected valve seals. The time of first peak of oil flow depends strongly on the position of the valve (Figure 6). It occurrence is connected with very fast decompression of oil after valve opening. Few milliseconds after the pressures inside and outside of the considered volume equal (no oil flow). From this point, oil flow magnitude depends on piston velocity (slightly increasing).

If the seals operate properly then the first peak appears every time at the same valve position. However, if the seal change the shape or volume, because of already mentioned reasons, then the oil begins earlier to flow i.e. the gap between valve and housing appears faster compared to the oil flow footprint and in reference to the valve position. On Figure 6 only one characteristic of the valve position has been presented because the peak of the oil flow has very small influence on valve movement (it velocity slightly increase).

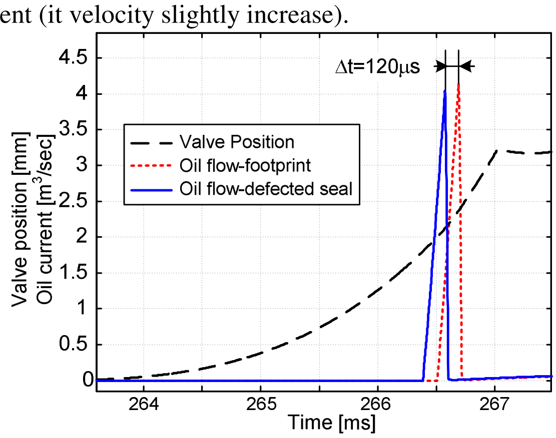

Figure 6: Valve position and oil flow magnitude for efficient and defected seal.

In case of considered valve, only one seal can be impaired so the defected seal, which is potentially the leakage source, has been located.

The disadvantage of this method is that oil flows in CB drive are difficult to measure because the technique requires additional elements in pipes, which increase the oil flow losses and in consequence decrease the dynamic of switching.

4.8 Derivative of coil current

The current, which flow through the electromagnet windings, generate electromagnetic force that moves the electromagnet armature. Armature presses on the valve and cause it move according to Equation 3. The movements of electromagnet armature cause increasing of the induction and decreasing of the coil current (Figure 7). Valve begins to move if the electromagnet force exceeds the friction forces.

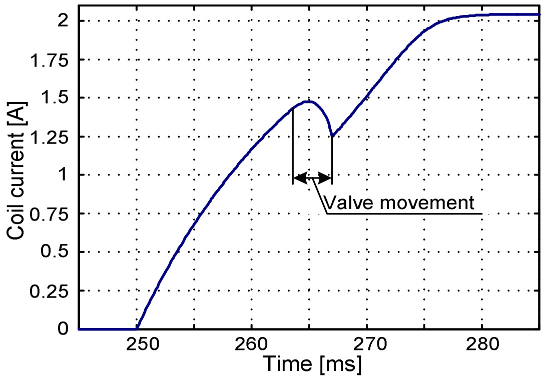

Figure 7: Coil Current

The oil flow, which presses locally the valve wall, additionally influences the valve velocity [6]. The reaction force of the oil flow is

$$F_{ax} = \rho \cdot \cos \varepsilon \cdot \dot{Q} \cdot v \qquad (12)$$

where: ρ - density, ε - oil film angle, $\dot{Q}$ - oil flow, v - oil velocity.

This force right after opening of valve additionally accelerates the valve because at this point oil flows very fast (Figure 6). Because the valve moves faster, the electromagnet armature accelerates as well and the induction of the coil changes. The coil current decreases faster. The difference between received curve and coil current footprint are very small. The differences in valve moving time are also very small. Much more information gives the characteristic of the coil current derivative (Figure 8).

The opening of the valve is seen as abrupt decreasing of current derivative. The time point at which the force (12) begins operating can be also defined. Now, if the valve seal is defected then the oil begins earlier to flow and in result the oil flow force begins earlier to push the valve. The measurements of the coil current derivative show small deviations from the footprint. The larger time discrepancy the worse condition of seal is.

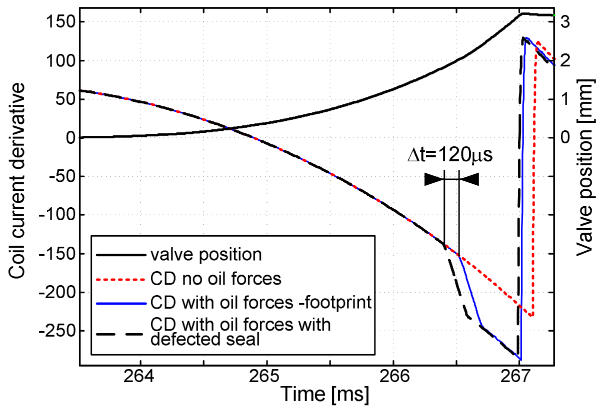

Figure 8: Coil Current Derivative

It can be also noticed that the different occurrence time of the oil flow force occur at different valve position. This property shows also the defected valve seal.

One of the possibilities to measure such short time discrepancies (~0.1ms) is to sample the coil current with very high resolution for example 1MHz. The data recording should be done only in very short period (first 30ms after engaging the coil) in order to keep recorded data file small. The detection itself can be done offline.

The circuit breaker coil current derivative has been calculated from the real measurements of coil current (Figure 8). The measurements were done by firm ABB on similar valve-coil system, so the numerical values are not the same as in considered drive. As it can be seen, the sampling rate (10kHz) is not sufficient to detect described failure type. However, abrupt decreasing of the current derivative at time 9.3 ms can be observed. This shows that such phenomenon exists and can be used for monitoring purposes.

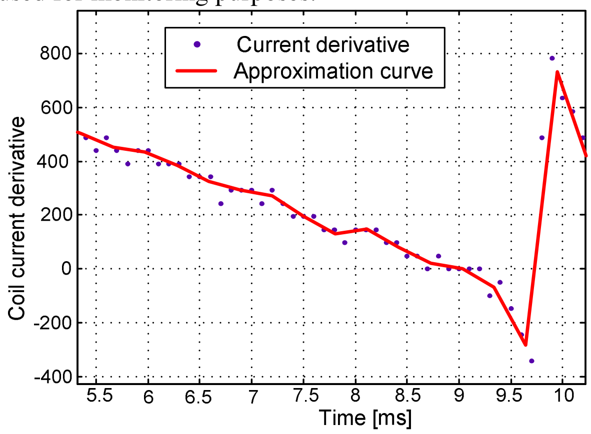

Figure 9: Coil Current derivative achieved from real measurements

There are different types of drives from different producers and not in each of them exist the possibility to measure the valve position because it is enclosed in housing. For all those solutions (including also the case from paragraph 4.5), the current derivative can be measured in order to catch the abrupt valve movements, which discrepancies in occurrence time point out the defected seal.

5 CONCLUSIONS

The possible defects of seals have been described. These in connection with the failure statistics gave an important knowledge how to simulate and model the leakages.

The leakage trend and leakage rate allow describing the failure and defining the critical limits. These parameters have been defined and typical values have been given.

The leakages in overall can be detected with use of the simple measuring methods (4.1, 4.4, 4.5). However, exact leakage location has to be done with use of more sophisticated methods (4.2, 4.3, 4.6, 4.7, 4.8). Here also the combination of the measuring method and CB state gives important information about leakage location.

6 ACKNOWLEDGMENT

This project is sponsored by DFG (Deutsche Forschungs-Gemeinschaft).

REFERENCES

[1] Janssen A.L.J at al.,"A Summary of the Final Results and Conclusions of the Second International Enquiry of High Voltage Circuit Breakers" in CIGRE 1994 session, 1994, paper no. 13-202.

[2] Müller H.K., Nau B.S.: "Fachwissen Dichtungstechnik"; www.fachwissen-dichtungstechnik.de

[3] Schmidt E.: „Handbuch der Dichtungstechnik", Grafenau/Württ. : expert-Verlag, 1981.

[4] Takashi Kajima, Yoshihisa Kawamura.: "Development of High-Speed Solenoid Valve: Investigation of Solenoids"; IEEE Transactions on Industrial Electronics Vol. 42, No 1, February 1995.

[5] Rusek B., Balzer G.: "Oil leakages of the HV circuit breaker hydraulic drive, their effects and possibilities of their detection" Distributing Power Networks - Sieci 2004, p. 365-367, Wroclaw, Poland, Oct. 2004

[6] Backe W., Tatar H.: "Untersuchung des Einflusses von Störkräften auf den Schaltvorgang bei Wegeventilen der Hydraulik"; 1975 Westdeutscher Verlag, Opladen.