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Monitoring of the high-voltage circuit breakers condition based on number of operations and sum of breaking short-circuit currents

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SUMMARY

High-voltage circuit breaker in switching substations is one of key elements, which ensures safe and reliable operation of power system. It consists of insulation system, interrupter chamber and operating mechanism.
The condition of operating mechanism and interrupter chamber is crucial in order to ensure reliable operation of the circuit breaker. Circuit breaker maintenance manuals are providing a table, where a number of operations are shown in dependency of short-circuit current. This provides the basic time schedule for carrying out the revision procedure for the circuit breaker.
Therefore it is important to monitor the number of operations, since they affect the abrasion of different kinematic parts in operating mechanism as well as condition of isolation rod and the condition of main contact components in interrupter chamber. Besides the number of the operations, a sum of short-circuit current is also an important information for determining circuit breaker condition.
This paper presents the concept and the prototype implementation of an intelligent electronic device (IED-Q0), which enables real-time monitoring of the circuit breaker condition for CBM (Condition Based Maintenance) purposes. The basic principle of IED-Q0 is to monitor the number of operations as well as the sum of short-circuit currents for each separate phase. To acquire the number of operations, the IED-Q0 receives a signal from signal-control clutch of the circuit breaker via optical insulators. In order to properly acquire short-circuit current values, the device is using miniature current clamps, that are clamped around wires, which are connected between protection core of measurement transformer and relay protection circuit. This implementation enables a simple integration of these devices into already existing infrastructure. The communication capabilities of the IED allow for easy integration with an Asset Management System, which enables efficient realization of the condition based maintenance (CBM).

KEYWORDS

Circuit breaker, asset management, Intelligent Electronic Device, Condition Based Maintenance

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1. INTRODUCTION

High and middle voltage circuit breakers represent a key element in electrical facilities, which ensures safe and reliable operation of the electrical power system. They are designed to withstand switching off rated currents as well as higher fault currents, which can have a magnitude up to 40 kA. Servo-mechanism for driving kinematic parts is triggered by the electrical impulses, which are produced by the relay protection or control system commands. Reliable operation of the circuit breaker is dependent on various mechanical and electrical components, which have to be successfully interconnected in order to correctly and safely manipulate with the system. The circuit breaker can be functionally divided into 3 major parts: switching chamber, driving mechanism and signal-control unit.

To ensure proper operation of the circuit breaker and expand its lifetime, maintenance work is done periodically, based on maintenance timetables. In the procedure vital parts of the circuit breaker that keep the system functioning properly are inspected. This gives a general estimation as what is the general condition of the circuit breaker. However, more detailed evaluation, for example that of a switching chamber's state is done based on measurement results and data that give information of how much the contact system in the switching chamber was overloaded during operations. This data consists of number of operations and sum of breaking short-circuit currents, that happened when switching off was done successfully. This type of data and consequently necessary measurements are determined for each type of circuit breaker, and can be found in maintenance and product documentation, such as [1], [2] and [3]. This documentation is used for planning and executing maintenance work on circuit breakers.

A special IED (Intelligent Electronic Device) named IED-Q0 was developed for real-time monitoring of number of operations and sum of breaking short-circuit currents. The information about a magnitude of breaking currents, which occur at individual fault could be acquired from relay protection. However, this data would be incomplete, since currents are not measured by the relay protection, when manual switching of the circuit breaker occurs or when functional tests are taking place after the circuit breaker inspection. IED-Q0 monitors four parameters, two parameters for all operations: the number of operations, and sum of breaking currents and two parameters only for the last operation: maximum breaking current, and maximum neutral current. This data can be displayed on the local LDC display and/or can be sent through LAN connection to a remote system, such as an Asset management system. IED-Q0 consists of electronic circuit, which adjusts analog and digital signals, for microcontroller processing. Analog signals are acquired from current clamp sensors, while digital signals are acquired from relay protection 220 V DC trigger pulses. The microcontroller itself is an Arduino based platform [4]. IED-Q0 has UPS power supply, which enables the device autonomous operation.

2. TECHNICAL REQUIREMENTS FOR IED-Q0

While designing and developing the prototype of IED-Q0 the most important requirement was, that operation of the device must not have a feedback effect on the relay protection or the control circuits of the circuit breaker. For that reason, miniature current clamp sensors were used that enabled non-invasive measurement of currents. This clamps were installed on current protection circuit wires that are connected on the relay protection, which enabled that current conductors were galvanically separated from IED-Q0. Another requirement suggested, that all 220 V DC signals in electrical facilities must be isolated from common grounding point, which is also true for trigger signals from signal-control unit.

For that purpose all trigger signals, were transferred to microcontroller system through optical isolator, which are manufactured to withstand 5 kV of isolation voltage. The power supply for the device is designed to ensure autonomous operation in case of power grid failure. The device is primarily powered from 220 V inverted AC supply from the substation's UPS system. In case that UPS system would have a fault, which is highly unlikely IED-Q0 has also an internal backup power supply with 12 V DC battery, installed inside the device. This ensures that all the stored data won't be deleted, if the primary power supply is lost.
The last requirement was the ability to transfer data into an Asset Management System. An Ethernet module was implemented into IED-Q0 that takes care of this task, which gives the device an extra feature of acting as a web server, with a possibility of transferring measurement data upon client's request, making the information management simplified for the end users and maintenance purposes.
Since electrical facilities have a lot of EM disturbances, the device had to be protected from this phenomena. For that purpose shielded twisted pair wires were used for current sensors and entire device is integrated into robust metal container that decreases EM disturbances. Algorithm, which does the calculation of the measured values can be easily and quickly changed or different types of circuit breakers, which gives the device a great deal of flexibility.

3. DESIGN AND FUNCTIONING OF THE HARDWARE

IED-Q0 was designed as autonomous electronic registrator, which measures and calculates values, with microcontroller algorithm. It simultaneously monitors values of breaking short-circuit currents and number of operations for each separate pole, that is three circuit breakers, one for each phase. Mathematical part of the algorithm on microcontroller then linearizes the measurements calculates the maximum and the sum of breaking short-circuit currents.
The measuring starts, when relay protection or control system executes a command to switch off the circuit breaker. At this event a 220 V DC trigger signal is generated from signal-control unit, which indicates the beginning of this process. As mentioned before trigger signals are of high voltage and have to be separated from common ground point. Also, high voltage could damage the low voltage components inside IED-Q0, therefore snubber protection circuit was used to prevent voltage spikes and a special circuit with optical isolators was designed to galvanically separate different trigger voltage levels. Although optical isolators have a 5 kV isolation voltage, trigger signal is first divided on pairs of power resistors to further reduce voltage stress on the primary channel. A secondary channel of the isolator is then triggered, which produces 5 V DC signal, which is further adjusted with analog filters. This galvanic separation does not only protect 220 V signals from common ground point contact, but also from damaging sensitive low voltage circuit, which enables IED-Q0 to safely acquire high speed, high voltage trigger signal for measurement process triggering. The trigger signals start measurements of breaking short-circuit currents, which are captured from secondary winding on current measurement transformer, which is measuring circuit breaker current on primary winding. Each phase has its own measurement transformer, therefore it is appropriate to do four measurements, one for each of the three phase currents and additional measurement for neutral current. Secondary winding of the measurement transformer already has a certain measurement configuration, that can't be physically changed. For that purpose a non-invasive galvanically separated method of measuring current had to be applied, which suggested a use of current clamps. The measurement transformer has a turn ratio of 1:1000. Since fault currents rarely exceed 20 kA, IED-Q0 has to be able to measure currents of maximum 20 A magnitude on secondary winding of measurement transformer. For that purpose miniature current clamps Telema AC-1020 were used, that can

measure currents up to 20 A as required. Four current sensors simultaneously measure currents I_{L1}, I_{L2}, I_{L3} and neutral current $3I_0$ (I_N). Figure 1 depicts integration of IED-Q0 into already existing measuring system.

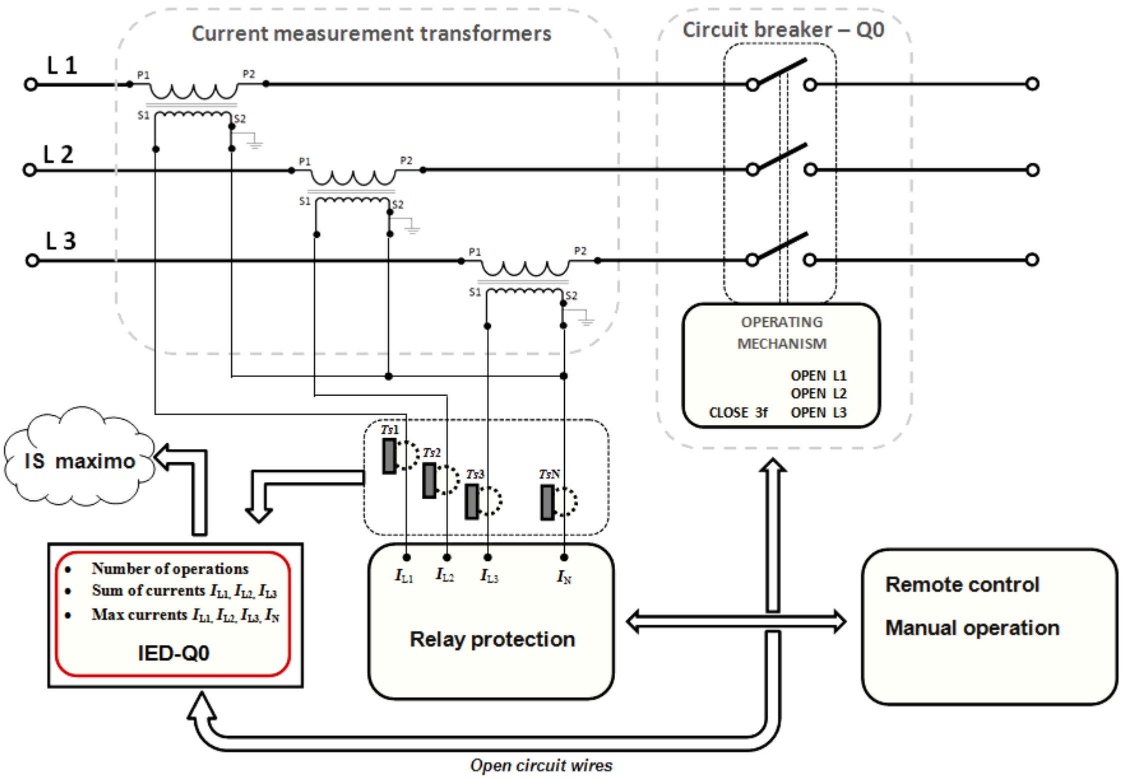

Figure 1: Integration of IED-Q0 into measuring system in substation.

Used current clamps generate currents 0 ÷ 20 mA when the output is properly configured. A minimum resistance between the sensor secondary winding pins must be used, to ensure stable operation of the transducer. In our case a 500 Ω resistor was used, which generated a corresponding 0 ÷ 10 Vpp AC signal that was further rectified with germanium diode to 0 ÷ 10 V DC. This voltage is then further adjusted and calibrated for measurement with microcontroller's A/D converter, which can measure a maximum of 5 V DC voltage. Germanium rectifier diode was chosen due to its low forward voltage drop. However, this causes a slight distortion of the signal and consequently a nonlinearity of the measurement especially at low values of the sensed currents. This is the reason for a small measurement error, that is practically unnoticeable at a single current measurement, but since the currents from each separate pole are summed together at every measurement, the error is summed also, which can lead to false measurements over time. This problem was solved with software linearization of the current measurements and proved to be a successful method especially for low current values, which was confirmed during testing phase of IED-Q0.

Exterior of the device was designed to be robust on impacts and user friendly with a simple interface. The user can monitor the calculated values locally on site with a built-in LCD display. There are three user buttons on the device. The first (squared red) button enables the user to switch on or off background lightning of the display. Second (round black) button is switching between four different monitors that are shown on the display. The first monitor shows values of the sum of breaking currents for each pole, second monitor shows the maximum values of breaking currents captured at the last measurement, third monitor shows the maximum value of neutral current ($3I_0$) that was also captured at the last measurement and the final monitor shows number of operations, that circuit breaker has preformed. The last (round red) button on the device is meant for resetting the device to its initial state, which also includes erasing all the stored measurements and values, however this is can only be done if the user has unlocked the lock above the button, which is a safety mechanism against unauthorised erasing of the data. The backside of the device has built-in connectors for the current sensors wires, trigger signal cables and two additional ports, one USB port for administrator programming of the microcontroller and one Ethernet port for communication cable that transfers data via LAN. Front panel of the IED-Q0 prototype is shown on figure 2.

Figure 2: Front panel of the IED-Q0 with user interface.

4. FUNCTIONAL DESCRIPTION OF THE SOFTWARE REQUIREMENTS

Software algorithm for microcontroller is divided into two major parts. One is the high priority measurement program, which is capturing measurements of currents, when signal triggering occurs, and second is the low priority main program, which takes care of other tasks (e.g., measurements linearization, reading of user buttons, displaying the values and Ethernet communication). Trigger signal from signal-control unit interrupts main program and starts measurement program, which reads measurements from current sensors. The frequency of measured voltage signal is 50 Hz, which is the same as the frequency of current that flows through the circuit breaker at the time of short-circuit. When the fault occurs, the relay protection needs approximately 60 ÷ 80 ms to sense and characterize the fault. During this time DC component of the fault current is already damped, so IED-Q0 is actually measuring the current only in time when arc is breaking. After this time relay protection outputs the trigger signal to operating mechanism which starts a process of switching off the circuit breaker and signals IED-Q0 to start measuring the currents. The process of switching off takes another 20 ÷ 60 ms, dependant on the circuit breaker type. During this time the current that flows through the circuit breaker is measured by the current sensors. Sampling frequency is set at 5 kHz, which is more than enough to successfully sample the maximum of 50 Hz current signal. The captured measurements are also being filtered for the maximum value, since the maximum current is the most critical for circuit breaker state. For this purpose an algorithm for maximum value filtering was implemented in the measurement program. The filtering finds maximum value of the current in real-time, while the measurements of currents are being processed. Since the filtering algorithm is fairly simple this takes less processor usage than saving measured values and sorting them later.

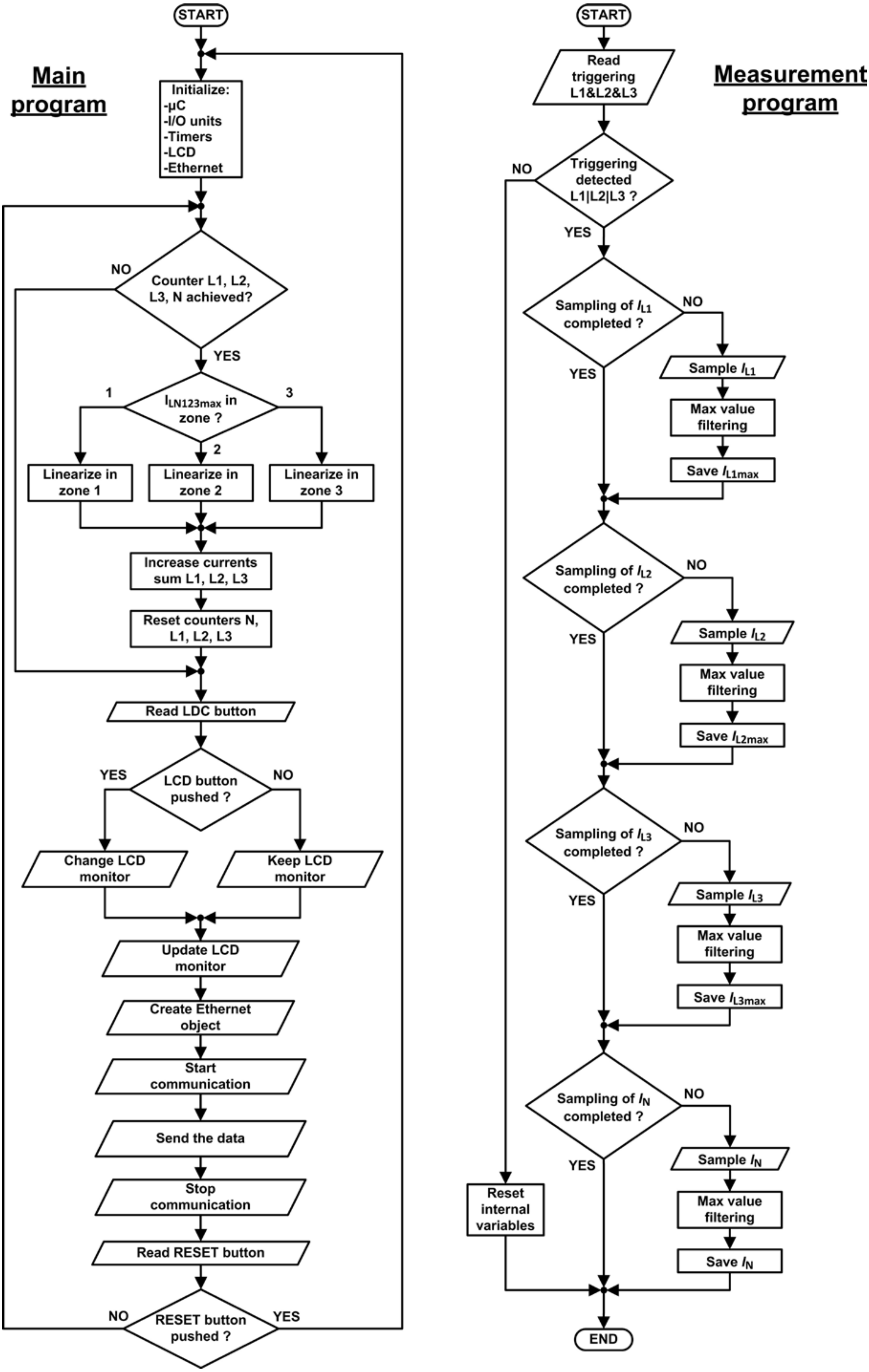

Figure 3: Conceptual flow chart of the IED-Q0 software.

Figure 3 shows a flow chart of microcontroller algorithm execution. When IED-Q0 is powered initialization of all internal units and outer modules takes place, after that the algorithm enters an infinite loop, which is suspended when the power is terminated or when the user presses reset button, which starts initialization process again and erases all the measurements. If interrupts for executing measurement program are not present the main program will read user buttons, show values of different measurements on LCD display and send the data to remote client through internet. However, in case that interrupt for measurement program occurs and measurements are successfully captured, the main program would also execute software linearization of the measured values due to previously described problem of nonlinearity. When the measurements are all captured (this takes a total of 300 ms), the maximum values are filtered and fitted accordingly to the segments in linearization curve. In experiments measurements were taken in entire measurement area up to 27 A. The sensor is functioning linear up to 20 A of secondary winding current. Over 25 A the response is getting nonlinear shape, due to core saturation in the sensor, which can be seen from a curve on figure 4 (left). For our purposes this is satisfying result, since fault currents that flow through the circuit breakers are not expected to exceed more than 23 kA (which means 23 A on the transformer secondary winding). Figure 4 (left) shows nonlinearity of the sensor, when core is saturated and figure 4 (right) shows linearization curve with three segments.

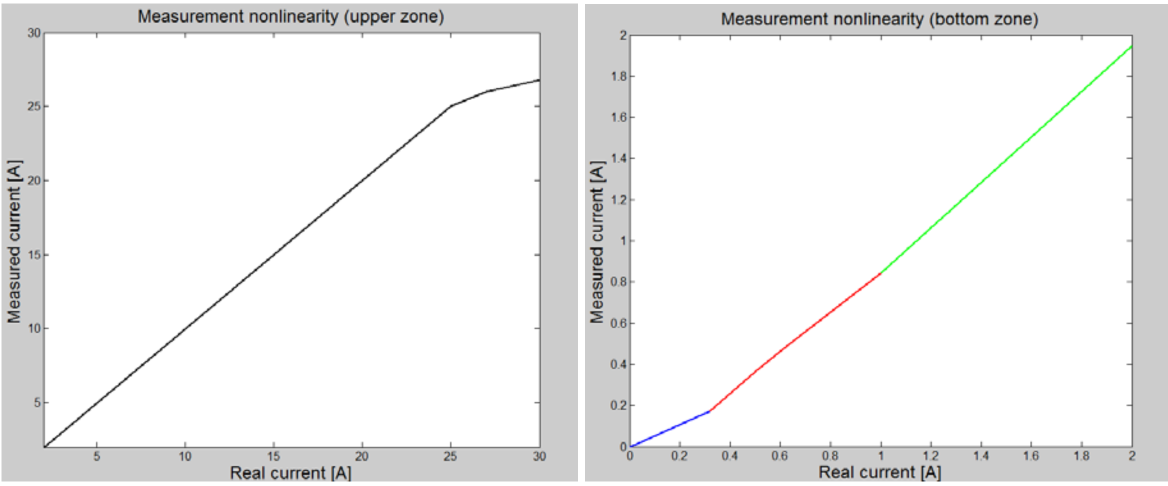

Figure 4: Nonlinearity at core saturation and linearization curve.

As we can see on figure 4 (right), the nonlinearity effect has the most impact at the bottom 10 % of the measured current value. The greater the values of the measurements, the less nonlinearity there is. Experimental measurements have shown, that it is practical, to divide linearization curve into several segments. Figure 4 (right) shows these segments, the first segment depicts blue line, the second segment with red line and the third segment with green line. Since the circuit breaker is being monitored in maintenance and normal operational state with different software tools (ABB-CB Sentinel, SIEMENS Assetguard CBM, ABB Calpos main), the online monitoring with IED-Q0 was designed accordingly to that, which lead to the following software categorization.

If values of measured currents are smaller than 200 A, then sum of currents is not increased (the same rule applies, if the circuit breaker is tested after a maintenance check). If values of measured currents are 200 A ÷ 500 A, the algorithm is adding a value of 500 A to the sum of breaking currents. If values of measured currents are 200 A ÷ 1000 A, then the algorithm is adding a value of 1000 A to the sum of breaking currents. And lastly, if values of measured currents are more than 1000 A, the algorithm is adding a real measured value to the sum of breaking currents. In all of these cases number of operations is increased.

These rules apply not only for sum of phase currents but also for maximum values of phase currents and maximum value of neutral current, the only difference is, that phase currents are summed together with every operation of the circuit breaker, while maximum phase and neutral currents are not and the only showed values are the maximum currents that were measured during last operation. This are the rules, which take into account the worst case scenario, if values of measured currents are small.

For the purpose of remote monitoring IED-Q0 has a built in communication module, that sends the data to the remote client. Communication module is an Ethernet based standard shield, that has Wiznet W5100 integrated circuit, which takes care of converting the data from microcontroller to packets that can be send through internet. Microcontroller is sending values via SPI communication to the Wiznet W5100, and from there on the values can be streamed via UDP or TCP communication protocol to the remote client. Because IED-Q0 is a local measurement unit, it can also take a role of a simple web server allowing for a simple WEB visualisation of the data. From flow chart on figure 3, we can see that the algorithm first updates the values to the local LCD display, after that the values are send over LAN to the remote client. In the beginning of remote communication IED-Q0 opens the data stream and sends an HTTP response to the client [5]. This enables client to receive the data in a form of simple web page, which displays the values in a web browser as it can be seen on figure 5. Currently IED-Q0's operation is set to obtain a certain IP address from a local router via DHCP protocol [6]. The IP address that was set then needs to be programmed into microcontroller manually. In real implementation of the device into a substation, it is recommended that device obtains a static IP address from a local router, which is appointed by the system administrator in DHCP reservation table on the router. The data would then be send from the device to remote system also either by HTTP response or just by plain UDP or TCP data streaming. At the remote system an integration with an Asset management system can be made, usually by utilizing Web services.

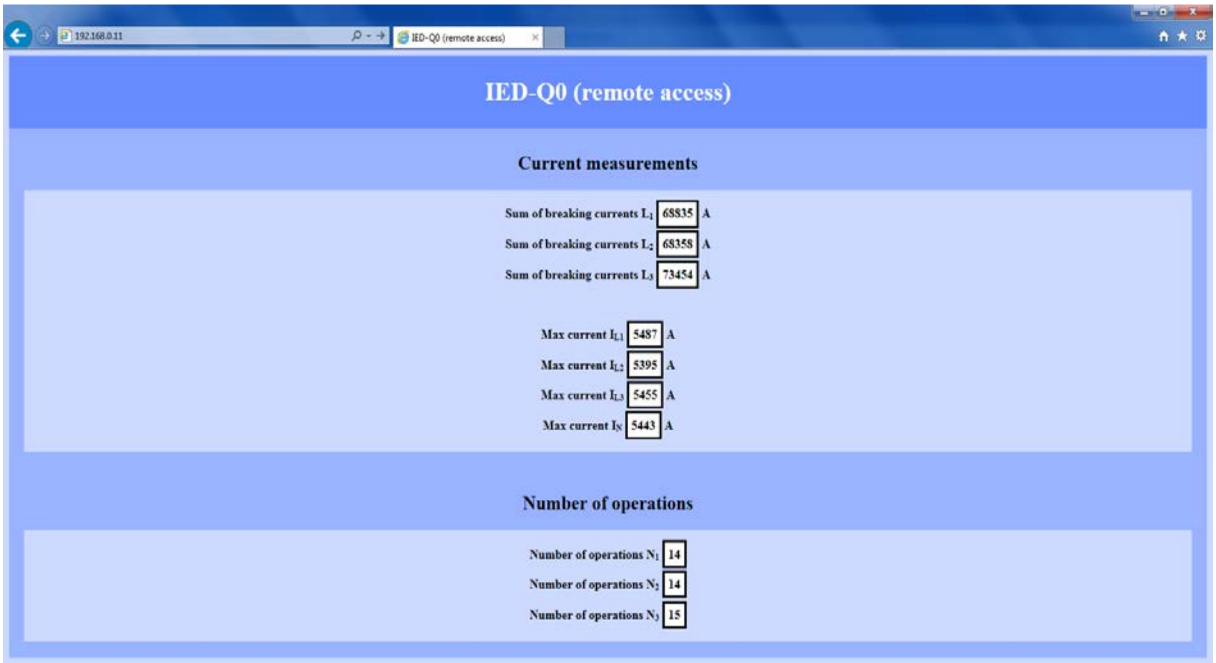

Figure 5: Measured values shown as a website on remote client.

5. TESTING OF THE PROTOTYPE

Laboratory testing of the device was done using a physical simulator of the circuit breaker. The simulator was outputting currents 0 ÷ 20 A, which were then measured by the current sensors. However, IED-Q0 will be operating inside a substation, where environment is full of EM disturbances, which can be potentially hazardous for sensitive electronic components inside a device. Therefore the design of the device was set from the start to be as robust as possible on EM disturbances and additional testing was carried out to ensure each module of the device was functioning properly in this environment. IED-Q0 was tested on real circuit breaker that switches off 110 kV powerline, all four current sensors were connected to the measurement transformers and functional testing of the device was carried out. Circuit breaker was tested for currents from 0 A to approximately 20 kA. The measurements of IED-Q0 that were shown on LDC display were compared to parallel measurements with current clamps, A-meter and oscilloscope. The results showed a good match between the device's measured values and other results. Testing was done with 220 V DC trigger signals obtained from signal-control unit, but because trip coil is connected at the output on signal-control unit, a substantial voltage spikes were expected in trigger signal, which could damage the components inside IED-Q0. Measurements with oscilloscope showed voltage spikes of 3 kV. For that reason all the digital inputs in IED-Q0 have protective snubbers, that damp voltage spikes and therefore protect the device, which was also successfully tested for each separate channel. Finally the device was exposed to EM disturbances, since it was positioned at the base of 110 kV circuit breakers. The performance was excellent and no disturbances in device's operation were detected. This experiments concluded, that IED-Q0 successfully works in real environment and is suitable for operation in a substation. In addition, we have to take into consideration, that testing was executed under extreme hazardous conditions, in reality IED-Q0 would be mounted inside a relay house, that offers some sort of shielding against EM disturbances.

6. CONCLUSIONS

For the purposes of monitoring and controlling maintenance expenses and also ensuring normal operation of the circuit breakers, real-time monitoring of certain parameters is necessary. The sum of breaking short-circuit currents and number of operations is the basic information from which a condition assessment, based on recommendations of the device's documentation can be made for circuit breakers. To prevent subjective decisions in this process, condition information have to be integrated into one of the packages for asset monitoring and thus updating CBM approach [7], [8], [9]. Prototype of IED-Q0 was successfully tested and validated. There is a possibility to further upgrade the device by monitoring all time parameters during breaking process of the circuit breaker. This would enable the possibility of real-time warnings, if the circuit breakers in each phase are not synchronized or the driving mechanism doesn't function properly. All these parameters could be monitored through inputs on IED-Q0. Manufacturers of high-voltage circuit breakers such as SIEMENS, ABB, ALSTOM, AREVA-T&D have their own monitoring devices for such purposes, but each manufacturer uses their own software and these monitoring devices usually work only for one type of circuit breaker. The advantage of IED-Q0 is the flexibility to monitor any type of circuit breaker and the ability to integrate with any kind of remote client. Last but not least, the development and manufacturing of IED-Q0 is the product of the domestic knowledge.

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