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EMBEDDED DEVICE CONCEPT FOR EARTH SURFACE POTENTIALS MEASUREMENTS OF A GROUNDING SYSTEM

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Abstract – Large substation grounding system needs to be periodically inspected in order to assure safe and reliable original purpose. Due to complicated measurements including a large amount of measuring points and a complex evaluation of measuring results, final results and conclusions are not immediately obvious. The basic idea is to build an intelligent system in order to get a rapid overview of a grounding system condition with a detailed measurement plan and on-site data analysis feasibility. For this purpose, an embedded device concept for earth surface potentials measurements of a grounding system is proposed. The described device acts as a portable measuring subsystem in conjunction with a personal computer-based integrated program environment or as a stand-alone measuring unit. The presented concept showed excellent properties regarding measurement time saving and measurement costs reduction, by simplifying the project manipulation and by automating the measuring procedures, analysis and documenting.

Keywords: Earth Surface Potentials, Embedded Measuring Device, Intelligent Instrumentation

1. INTRODUCTION

Since the early days of the electric power industry, safety of personnel in and around electric power installations has been a prime concern. A mechanism affecting personnel safety is the potential rise of grounded structures during fault conditions and the possibility of personnel getting in touch with grounded structures, which would subject them to dangerous voltages. Inspections and tests have to be carried out in order to verify the compliance of the grounding system with permissible Touch and Step voltages [1-3]. This verification is useful for predicting or establishing dysfunctions in an electrical or a mechanical sense.

A grounding system inspection includes measuring of the Ground Potential Rise, the determination of Earth Surface Potentials (ESP) map and grounding potential differences measuring (Touch and Step voltages). These measurements are performed at a test current that represents the reduced short-circuit fault current. Measured values have to be recalculated according to the rated fault current, flowing at a single-phase short circuit condition through the grounding system. Corrections by a reduction factor regarding earth wires of overhead lines and metal stealth of underground cables have to be taken into account.

The ESP measuring process starts with the Ground Potential Rise measuring (with respect to the remote earth electrode) followed by ESP map equidistant sampling in and around the electric power installation, according to the grounding system mesh schemes. At this point, equipotential lines and areas, directly derivable from obtained samples, and electric field vectors, calculable from its first derivative, might describe the grounding system conditions and point out suspicious areas requiring Touch and Step voltage measurements. The performed measurements lead to conclusion whether or not the grounding system under test complies with the related Standards.

ESP measurements of a large substation grounding system implicate a time consuming process, thus inducing uncertainties due to unstable measuring conditions (e.g. soil resistivity). Exhaustibility and high costs of such a procedure have an important impact, leading to simplified and faster solutions for simplification and acceleration of the measurement process. One of them might be the development of a highly customized personal computer (PC) based measuring system in order to achieve fast and reliable measuring procedures and moderate the disadvantages described above.

2. MEASURING SYSTEM RELATIONSHIP

A complete measuring system consists of two parts: an embedded measuring device for ESP measurement and a PC-based Integrated Program Environment (IPE) for measuring data management and analysis [4]. The measuring device position in such a system encompasses two configurations. The first one assumes that a full-featured measuring template (created on a personal computer) is “preprogrammed in” as shown in Fig. 1. Figure 2 represents the second configuration which emphasizes the measuring device as a stand-alone unit capable of its own simple project template creation.

2.1 Template based measuring projects

The measuring system conception forces the *Measuring Project* to be planned in several functional phases. Once established and archived, the same measuring project plan will be used for the measurement phases that follow and/or in the next measurement period.

The measuring project starts with a template definition (*Template EQ*) on a personal computer for the ESP map measurement. It includes the definition of measuring area boundaries and objects relationship assignment, thus making the common subtemplate, used also in following steps. After that, the measuring objects (*Measuring points and Collections*) of *Equipotential* type have to be placed according to the chosen strategy (e.g. minimum path). By using template definitions, measuring objects can be completely described by referred attributes including also the *Measuring Points Collection* relationship (measuring points interlinking information) [4]. This phase outputs the template scheme and measuring plan documentation.

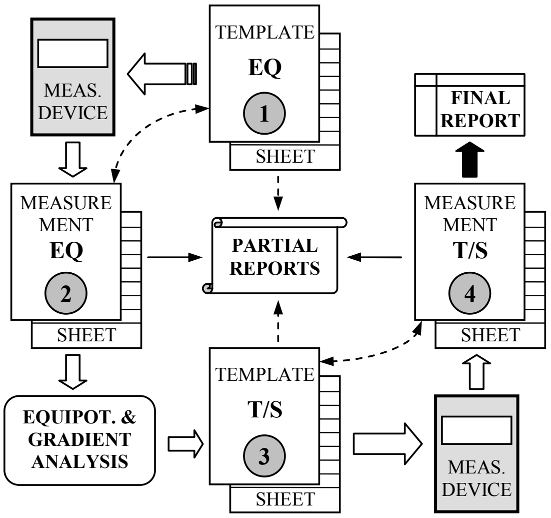

Fig. 1: Measuring device position in a full-featured measuring project configuration with predefined templates

The prepared template scheme has to be transferred to the measuring device in the form of measuring objects' descriptors in the order specified by strategy. The ESP map has to be sampled by following the generated measuring plan documentation. Measurements in this phase are conducted on a set of regularly positioned measuring sample points according to the measuring plan. The high-impedance analogue channel input is used to retrieve source voltages directly, by neglecting the soil resistance. This results in speeding up the measurement time which is important when a number of sampling points need to be examined. Inconsistencies between the created template and the actual situation encountered on-site can be easily overruled using the project management capabilities of the measuring device. After that, the measurement protocol loaded in the measuring device and the PC-template can be attuned with *Forward Annotation* and *Backward Annotation* procedures. The results obtained by measuring are transferred to functional step 2 (*Measurement EQ*) in the personal computer.

ESP map analysis yields equipotential lines and the corresponding gradient vector distribution over the entire measuring plane. Equipotential analysis gives the ESP distribution pattern which is useful for the detection of ESP migration, in comparison to performed measurements in the past periods. The equipotential lines density, analyzed in the gradient analysis module, narrows the selection of suspicious places subjected to Touch and Step voltage measuring. Assuming the portable computer is available, the on-site analysis could be performed in order to prevent the consideration of incorrect results.

Based upon previous phase analysis results, the scope of phase 3 is to create a new template (*Template T/S*) for potentials differences measuring. Using the same or updated object relationships, the new measuring point set has to be attached to the template. Unlike the template definition in phase 1, two different types of measuring points (*Touch* and *Step*) have to be differentiated and treated. A complete pertinent working documentation regarding the new measurement plan can be generated in the same way as in phase 1. This phase ends by the transfer of data to the measuring device for the purpose of Touch and Step voltage measuring.

Touch and Step voltage measurements are preformed by two measuring channels with input resistances equivalent to the Human Body Resistance Model. The measuring path strategy, predefined in the template, also includes both measuring point types. Measuring channel switching is automated by the identification of the measuring point type. After measurement completion, the results have to be forwarded to phase 4 (*Measurement T/S*) for interpretation purposes and template updating.

The obtained measuring results lead to the final conclusions regarding the grounding system quality. Grounding system areas with resulting values of Touch and Step voltages near or out of limits specified in Standards, point to dysfunctions and have to be treated. Finally, a complete report is available according to the requirements in the Standards and the agreement between contracted parties.

2.2 On-site measuring project management

If the creation of a template in phase 1 or in phase 3 cannot be performed or completed, the measuring device has a possibility of operating as a stand-alone unit. The project management capability, embedded in the device, can partly substitute the expected template, by enabling manual opening of a new project in Equipotential or in Touch/Step mode. All of the mentioned measuring point attributes can be assigned on the measuring device except the *Measuring Points Collection* relationships.

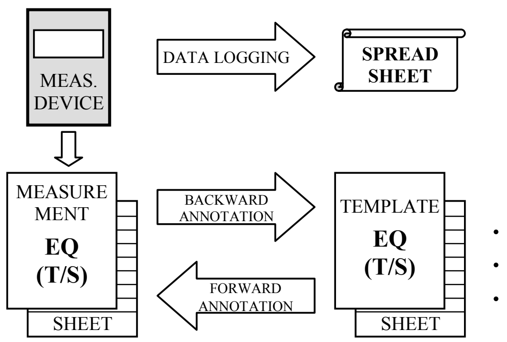

Fig. 2: Measuring device position in a project configuration without predefined templates

Measurements consisting of several measuring points (pilot measurements) may be carried out by bypassing the proposed IPE project scheme by logging the measuring results directly to a spreadsheet application.

Measuring points containing measuring results are forwarded to the appropriate Measurement phase where they can be rearranged in the manner of the IPE project scheme.

3. MEASURING DEVICE HARDWARE CONCEPT

The measuring device represents a highly specific, battery powered, handheld, autoranging measuring unit with the main purpose of performing ESP measuring procedure steps, by following the personal computer designed protocols. The device's hardware conception is based on a distributed microcontroller subsystem with integrated peripherals and custom designed surroundings, capable to meet the design requirements above as shown in Fig. 3.

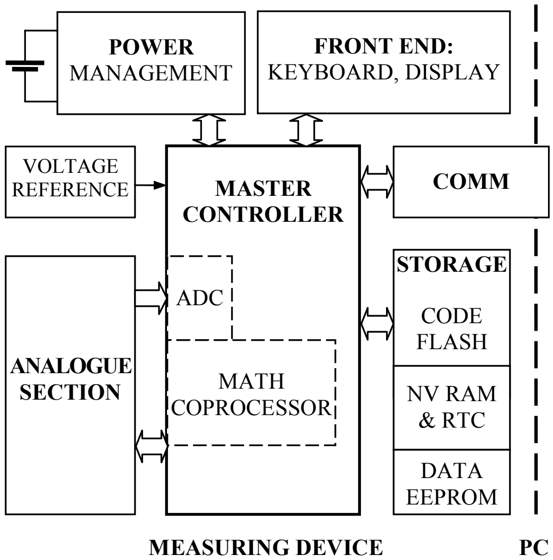

Fig. 3: Measuring device hardware structure

The surrounding hardware consists of an analogue unit for analogue conditioning of the input signal. The master controller takes care of the sampling and digital signal processing schemes as well as the analogue section controlling. The digitized signal is a subject of mathematical manipulation in order to calculate the AC root-mean-squared (RMS) value and DC value of measured signal. By using a very stable voltage reference, high measurement accuracy can be obtained.

In order to assure enough space for measuring data storage, a large non-volatile memory has to be used. Introduction of a separate EEPROM for critical system data storage increases the data integrity confidence level.

The communication module allows the measuring device to interactively exchange data with the personal computer.

The user interface (keyboard and alphanumeric display) enables user interaction with the measuring device and the visualization of measuring steps and results.

The Power Management unit assures continuous power supply and a complete battery management. The measuring device's consumption has to be minimized in order to increase the autonomy level. Therefore, the hardware must support idle and power-down modes, standby and auto-power-off features.

Figure 4 shows a detailed analogue section overview. A signal path is routed by the input selector according to measuring point types predefined in a template, thus choosing the right input connectors (*T*-Touch, *G*-ground, *S/E*-Step/equipotential). Selectable input resistances (1 MΩ and 1 kΩ) for voltage measurements are a subject of discussion below. Possible overloading occurencies (with 1 kΩ termination) can be easily investigated by autoranging using high resistance termination. The autoranging capability of the analogue section implies the usage of programmable attenuators and programmable gain amplifiers. Between them, a hardware overload protection is applied. Antialiasing filter (LPF) conditions the analogue signal for digitizing. Offset compensation is performed prior to each measurement. A complete measuring channel calibration can be performed by an external high-accuracy DC voltage source at regular mainteinance cycles.

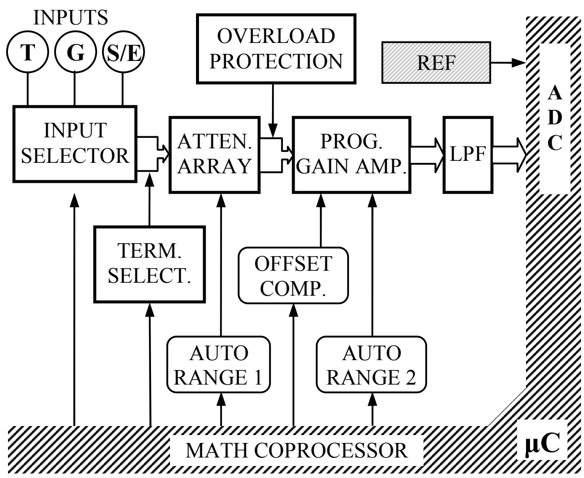

Fig. 4: A detailed analogue section overview

In the idle state, the inputs are galvanically separated from the analogue section. Furthermore, the entire analogue section is galvanically decoupled from the remaining hardware in order to suppress noise from the device's digital part.

The principle of deep analogue hardware control allows adaptation of the device to the specific requirements of customized measuring procedures.

4. MEASURING DEVICE FIRMWARE CONCEPT

On the firmware level, the measuring device is organized as shown in Fig. 5. Three basic layers describe the firmware structure: *System Layer*, *Measuring Data Layer* and *Data Link Layer*.

The *System Layer* comprises the Basic Input-Output System for peripherals managing and the Power Management section. The Power Management section supervises the power supply system, reacts on accidental power loss in non-maskable routines and supplies the battery, using algorithms for proper battery care. It also provides the accurate capacity monitoring by using benefits of a slave battery controller unit.

The *Measuring Data Layer* incorporates the units for Measurement, Data Management, Communication and Backup Management.

The Data Management unit takes care of the project management both in configuration with and without the predefined template (measuring points overview, appending, deleting and moving) as well as of measured data manipulation and integrity. On-site measurements without a computer predefined template can be done using the simple project template, created on the measuring device.

The Measurement unit performs the measurement procedure by controlling the analogue section (input selection, termination selection, autoranging and offset compensation) and calculating true RMS values from digitized samples using customized measuring algorithms. The measuring cycle duration (100 ms) for determining the AC value of applied input voltage covers both power frequencies of 50 Hz and 60 Hz. The computation of pertinent high order harmonics is limited by the antialiasing filter cutoff frequency and/or by computational unit capabilities.

The flexibility of full analogue unit control enables the introduction of both continuous and single measuring modes.

Huge measuring projects (several thousands measuring points) should be split up to the linked subprojects prepared for distributed measuring using multiple devices in order to speed up measurements. Once the measurements are completed, project must be restored by an inverse (merging) process.

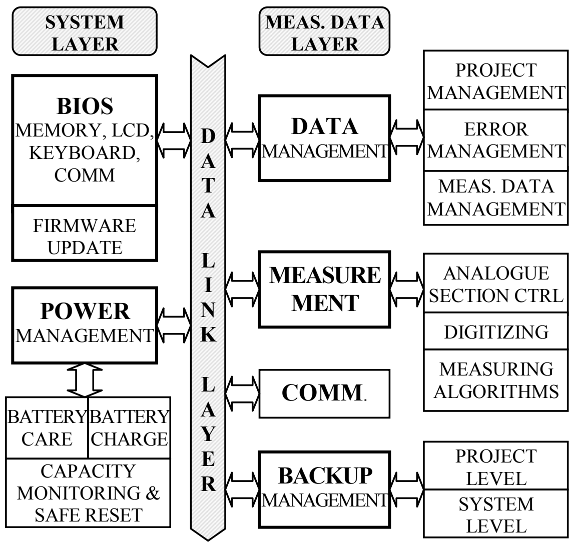

Fig. 5: Measuring device firmware structure – layered event driven conception

Interactions between the measuring device and the personal computer should be done over a standard serial communication port upgraded with a higher communication protocol.

The measuring project integrity and the measured data safety are extremely important and have to be considered as a special part of the *Measuring Data Layer*. Therefore, a Backup Management has to be developed to make safe copies of a project image or a complete device memory image on the personal computer. Data integrity should be verified through multiple CRC-32 (Cyclic Redundancy Check) checksums, which are saved several times to a data EEPROM with a coded entry. The boot-up sequence performs simple statistics over the check summed data to verify data integrity for corruption reporting purposes.

Special attention is paid to the user interface ergonomics planning. Due to the single-user-single-hand operating conception, a customized keyboard with general-purpose and dedicated application specific keys has to be designed. Large alphanumerical Liquid Crystal Display (LCD) allows implementation of a menu driven user interface and data visualization routines.

5. DISCUSSION

IEC 479-1 and IEEE Std 80 Standards differ in their description of the Electric Shock Model regarding Body Resistance, Thevenin Equivalent Resistance, Thevenin Equivalent Voltage and Permissible Body Current [5]. The Permissible Body Current parameter is a subject of safety criteria (permissible Touch and Step Voltages) whilst the others pertain to the measurements equivalent circuit. According to IEC 479-1, the Body Resistance Model depends on applied voltage and current path, while IEEE Std 80 prefers fixed 1 kΩ value. Thevenin equivalent parameters are not guided in IEC 479-1, while IEEE Std 80 uses simplified equations and computer models for this purpose.

By the dual measurement approach, using both high-resistance (1 MΩ) and low-resistance (1 kΩ) input terminations (assuming the Thevenin Equivalent Circuit with negligible impedance's imaginary part) both models in the Standards could be reconstructed.

By means of high internal resistance, ESP map measuring became faster by gaining the source voltage directly through neglecting the equivalent circuit resistances, and more robust regarding different probe deepness. Disadvantages of the method concerning phantom voltages due to the various interferences have been avoided by using the Heavy Current Injection Method.

6. CONCLUSIONS

The proposed system for ESP measuring is based on structured measuring procedures, most convenient in large substation grounding systems supposing the Heavy Current Injection Method is applicable. The major benefit can be gained by consistent measurement planning, performed in well defined phases, which encompasses full measuring project analysis and documentation.

The measuring device as a subsystem has a crucial role in measurement simplification and acceleration due to the following properties:

- autoranging, autozeroing and autocalibration assuring accurate measurement in an optimal measuring range
- high internal resistance measurements enabling fast ESP map determination
- automatic incrementing or decrementing of measuring point identifiers following the user-defined template strategy
- input selector driven by measuring point type for manipulation-free probe selection for Touch and Step voltage measuring
- capability of splitting and merging projects
- customizations of measuring procedures
- stand-alone measuring unit capability
- ergonomic user interface conceived with an alphanumerical LCD and a customized keyboard layout

ESP measurements are carried out using both high-resistance (1 MΩ) and low-resistance (1 kΩ) terminations introducing additional measuring parameters which can be calculated from the equivalent circuit model. Finally, visual analysis of these two measurements provides the on-site information of correct probe placement.

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