Abstract—The advanced age of electrical equipment from the high voltage power stations, correlated with the power sector restructure, the reduction of personnel, the increasing competition in the service market, and more recently with the economic crisis, determine the need to introduce new solutions and criteria for the correct on-line evaluation of the current technical condition of the electrical equipment in power stations, in order to assess correctly the withdrawal of the equipment from operation, to plan the need for maintenance works, to increase the financial and technical efficiency of these works, to support a correct operation risk evaluation. For the power companies, one of the main methods to obtain the mentioned benefits, including cost reduction, is to use intelligent systems for on-line monitoring of primary equipment from electrical power stations. The current paper describes the parts of the intelligent system, dedicated to on-line monitoring of primary equipment from high voltage electrical substations, respectively the components of the complex system NOVA EMCSIT, designed for the on-line monitoring of power transformers, shunt reactors, circuit breakers, disconnectors, voltage & current transformers and surge arresters. These intelligent monitoring systems can be used stand-alone or within an integrated system for on-line monitoring of electric power stations and substations – Smart Grids.

Index Terms-- Monitoring, Smart Grids, diagnose, maintenance, high voltage equipment, substations

I. INTRODUCTION

The age of the existing high voltage electrical equipment in operating in power system is continuously increasing and their failure rate grows with the increase in age. The great majority of failures appear as a result of the combined action of the thermal and electric stresses, to which mechanical stresses are added. In order to repair these equipments, it is often necessary to take them out of operation for a long period of time. The policy related to the management of the operation and maintenance of the existing high voltage electrical equipment is based on the following main principles:

- Their maintenance or even replacement should take into consideration their momentary technical condition in the first place and not their age;
- The on and/or off-line monitoring activity should discover (identify) the modification in the momentary technical condition in due time, in order to minimize the risk of major outages accompanied or not by fire-breaking;
- Extending the service lifetime in operation by the means of adequate maintenance.

The paper briefly describes the technological solutions and the experience gained by Nova Industrial and CN Transelectrica in the life management and maintenance of high voltage equipment.

II. INTELLIGENT MONITORING SYSTEMS FOR HIGH VOLTAGE ELECTRICAL EQUIPMENT

The Romanian Power Grid Company (CN Transelectrica) intends to implement "Smart Grids" networks based on on-line monitoring systems dedicated to: high voltage substations, overhead power lines and power quality. Systems for on-line monitoring of the weather parameters are considered for a later on stage.

Starting from this "Smart Grids" concept, Nova Industrial has developed several solutions - dedicated on-line monitoring systems (Figure 1), such as:

- on-line system for condition monitoring and diagnose of substation primary equipment – EMCSIT, that operates for:
  - power transformers: TRAFOMON monitoring system,
  - circuit breakers: EMCSIT- I monitoring equipment,
  - disconnectors: EMCSIT- S monitoring equipment,
  - instrument transformers (current transformers - TC and voltage transformers - TT): EMCSIT- TC/TT monitoring equipment;
- surge arresters: EMCSIT –D monitoring equipment,
- on-line system for power quality monitoring.
  - power quality: QA monitoring equipment;

A. TRAFOMON monitoring system

This system is designed for the on-line monitoring of power transformers and high voltage shunt reactors,
Fig. 1. EMCSIT complex system for the on-line monitoring and diagnostic of substation high voltage electrical equipment providing on-line data acquisition regarding:

a) Operating condition: transformer meets / does not meet the standards of operation; it is connected / disconnected to / from grid;

b) Operating parameters: currents, overloads, voltages, voltage increase, frequency, power factor; powers: active, reactive, apparent; temperatures, winding temperatures, oil temperature, hot spot temperature, power quality, etc.;

c) Operating condition for the active part (core + windings + inner connections) through on-line monitoring of:
   - Dissolved gas-in-oil concentrations: hydrogen (H2), acetylene (C2H2) - optional, carbon monoxide (CO) - optional, methane (CH4) - optional; ethane (C2H6) - optional, ethylene (C2H4) - optional, carbon dioxide (CO2) - optional, oxygen (O2) - optional, nitrogen (N2) - optional;

d) The moisture level of insulation by: on-line measurement of water-in-oil content and evaluation of the water content in the solid insulation;

e) Operating condition of the cooling system, by:
   - Displaying the number of the coolers (cooling batteries) in operation;
   - Highlighting the operating oil pumps and fans, evaluating the efficiency of the coolers activity, evaluating the total operating time or between overhauls / repairs of oil pumps and / or electric fans;
   - Displaying the proper or inadequate state of the cooling system;

f) The insulation condition of high voltage bushings equipped with tap for measuring the power / dissipation factor, by:
   - Measuring of the current through C1 dielectric (bushing tap current); assessing the unbalance current resulted from the phase sum of the currents through the C1 dielectric of the bushings mounted on R, S, T phases of the same three-phase windings;
   - Measuring the capacity of the C1 dielectric on each high voltage bushing;
   - Measuring the tangent of the phase angle between the bushing insulation currents for each pair of bushings of the same three-phase winding;
   - Displaying the proper or inadequate state of the high voltage bushings;

g) The operating condition of the on-load tap changer (OLTC), by:
   - Monitoring the operation position of the tap changer;
   - Measuring the load current of the drive mechanism motor and its stamp;
   - Counting the cumulated number of OLTC operation;
   - Measuring the temperature difference between the temperature of oil in the diverter switch compartment and the temperature of oil in the transformer tank - optional;
   - Measuring the vibrations during OLTC operation - optional;
   - Displaying the proper or inadequate state of the tap changer.

h) The condition of the oil conservator associated to the transformer tank: oil level in the tank, the condition of oil protection membrane against the direct contact with the environment (for conservators with membrane) - optional; signaling of the moment when oil in conservator reaches the maximum or minimum level;

i) The condition of the oil conservator associated to the tap changer compartment: signaling of the moment when oil reaches the maximum or minimum level;

j) The operating condition of the Buchholz relay: the signaling step and the tripping step;

k) The operating condition of the pressure relay associated to the OLTC diverter switch compartment;

l) The operating condition of overpressure protection device associated to the main tank of the transformer.

The configuration of this monitoring system configuration is specific to each monitored transformer, taking into account many factors such as: the user requests, power transformer...
construction particularities, the transformer role in the power system, its age, its technical condition, etc.

Each TRAFOMON monitoring system contains one IED - Intelligent Electronic Device (Figure 2), that receives signals from sensors, transducers or monitoring subsystems, and sends the information regarding operating parameters and momentary status of the monitored equipment, to the control room or to the protection systems (Figure 3).

The dedicated software of TRAFOMON 5 is compatible with Microsoft Windows XP SP2 and it is designed on a client-server architecture.

The server software contains: a module for data acquisition, a module for viewing the parameters which are monitored on-line (Figure 4), a module for the diagnose of the monitored power transformer, a module for viewing previous measurements, stored in a database, and to graphically display their evolution in time and a module for the self-testing system.

The client software contains: a module for viewing the parameters which are monitored on-line, a module for the diagnose of the monitored power transformer, a module for viewing previous measurements, stored in a database, and to graphically display their evolution in time and a module to export the data monitored on-line in the RCM (Reliability Centered Maintenance) database for on-line and off-line analysis, a module for the technical expertise and prediction of the remaining lifetime, based on the information stored in the RCM database – using Nova Transpower PT and Nova Predict expert systems.

The TRAFOMON monitoring system may be connected to dedicated optional on-line monitoring equipment such as:

- the bushing monitoring equipment, the water content and gases dissolved in transformer oil monitoring equipment, partial discharge monitoring equipment, etc.
- SMT 5 equipment is designed for the on-line monitoring of the high voltage bushings of power transformers and shunt reactors in operation, continuously monitoring the leakage current through the bushings, the sum of the leakage current through three bushings of the same three phase transformer winding, respectively the relative power factor between the Ic1 currents through two bushings on adjacent phases $\delta_{IC1R,IC1S}$, $\delta_{IC1S,IC1T}$, $\delta_{IC1T,IC1S}$ of the same transformer winding (Figure 5).

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Based on user requests, the TRAFOMON monitoring system can be connected to an equipment for the on-line monitoring of the water content and of hydrogen plus other gases, such us: carbon monoxide (CO), acetylene (C2H2), methane (CH4) etc. (Figure 6).

Also for the on-line monitoring of the acoustic signals produced by partial discharges TRAFOMON monitoring system may be connected to a dedicated monitoring equipment (Figure 7).
In order to highlight how abnormal operating regimes (overloads or power frequency overvoltages) can change the operating conditions of the power transformer (with direct implications in terms of local overheatings and the quality parameters of the transferred energy), some of the monitoring systems also included NOVA QS or A subsystem for on-line power quality monitoring (Figure 8).

Fig. 8 Power quality parameters monitored on-line by QX equipment at a 100 MVAr 400 kV shunt reactor

B. EMCSIT I monitoring equipment

EMCSIT - I equipment is designed for the on-line monitoring of high voltage circuit breakers, ensuring on-line data acquisition regarding the operating parameters and the condition of the monitored apparatus, such as: circuit breaker technical condition, close / open operating condition, operating times, lack of synchronization of operation between poles, arcing times, contact speed, re-ignition, number of operations, wearing of the contacts, pressure of the insulating fluid, the ambient temperature, the operating condition of the operating mechanism (current through motor, operating times), etc. (Figure 9).

The equipment allows the on-line monitoring of the condition and operation of a circuit breaker. The equipment operation can be divided into three sections, namely:

a) Section for measuring the parameters in stand-by, where there are measured the following parameters: battery voltage, ambient temperature, SF6 gas pressure, etc.;

b) Section for operating parameters, where there are measured the following parameters: currents (through opening and closing coils), each phase line current, dynamic characteristics of the circuit breaker (calculated by software, based on parameters measured directly). Each measurement lasts 3 seconds, the whole event being completely recorded. In this section the digital signals are also included - opening, closing, end of stroke, etc..

c) Section for signaling, where there are monitored signalization events generated by incorrect operation of the monitored circuit breaker (including switchgear), for example: lack or fall below a certain limit of the battery voltage, fall below a certain limit of the SF6 gas pressure, the lack of some mandatory digital signals - end of stroke after a close or open operation, etc.

The software dedicated to EMCSIT - I (the on-line monitoring system for high voltage circuit breakers) is structured in the following modules:

a) server application software, for data acquisition and database storage - “EMCSIT - I Server”,

b) client application software, for viewing analog and digital parameters (states) - “EMCSIT - I Client”,

c) application software for viewing and analyzing events - “EMCSIT - I Event graphics”,

d) application software for viewing history information recorded in the database “EMCSIT - I History”.

The selection of the monitored parameters is done based on the diagnosis scheme. The normal variation domain, pre-alarm and alarm selection is done based on normal operating values specified by the manufacturer of the circuit breaker, and the limits of the variation allowed by the operating norms.

The equipment has 13 analog inputs: five inputs with the sampling rate of 10 ks / s per channel and 8 with the sampling rate of 1 ks / s / channel and 10 digital inputs. Also, the equipment has four outputs (4 relay contacts - NO - dry contact).
The interface of client/server application software allows the user to view values for the monitored analog and digital parameters (Figure 10) and to view information on the events that involved the monitored circuit breaker.

C. EMCSIT S monitoring equipment

EMCSIT - S equipment provides the on-line monitoring of high voltage disconnectors (Figure 11), ensuring on-line data acquisition regarding the operating parameters and the condition of the monitored device, such as: technical condition of the disconnector, close / open operating condition, operation times, lack of synchronization of operation between poles, contact speed, number of operations, the ambient temperature, the operating condition of the driver mechanism (current through motor, operating times, etc.).

The EMCSIT S equipment has eight analog inputs with the sample rate of 1.6 ks / s / channel and 10 digital inputs. Also, the equipment has four outputs (4 relay contacts - NO - dry contact).

The selection of the monitored parameters is done based on the diagnosis scheme. Normal variation domain, pre-alarm and alarm selection is done based on normal operating values specified by the manufacturer of the equipment (disconnecter) and the limits of the variation allowed by the operating norms.

Depending on the type of disconnector, in order to monitor a three phase disconnector, it is required the installation of one or three monitoring equipment NOVA EMCSIT - S.

EMCSIT - S equipment allows the monitoring of a single phase disconnector with three disconnectors (main and earthing switches, one at each end) or a three phase disconnector with simultaneous action on three phases, with one or two grounding systems.

EMCSIT - S equipment works connected to a local data processing unit. The processing unit may provide recording and processing of data coming from several disconnectors on-line monitoring systems EMCSIT - S. The processing unit stores the data and then transmits them through the LAN, to the control room of the station, or through WAN to the Regional Monitoring Center.

The software dedicated to EMCSIT – S (the on-line monitoring system for high voltage disconnectors) is structured in the following modules:

a) server application software for data acquisition and database storage - “EMCSIT - S Server” (Figure 12),

b) client application software for viewing analog and digital parameters (states) - “EMCSIT - S Client”,

c) application software for viewing and analyzing events - “EMCSIT - S Event graphics”,

d) application software for viewing history information recorded in the database – “EMCSIT - S History”.

The “EMCSIT - S server” uses a fix time interval (ex. 1 minute), to acquire the latest information on the monitored parameters. The data is displayed on the main screen of the application software and it is stored in an Oracle database.

D. EMCSIT TC/TT monitoring equipment

EMCSIT - TC/TT equipment is designed for the on-line monitoring of current and/or voltage instrument transformers, ensuring on-line data acquisition regarding the operating parameters and the condition of the monitored device, such as: the technical condition of the transformer, the operating condition, the pressure of the insulating fluid, etc. The equipment can also ensure data on current and/or voltage over-stresses (the estimated amplitude, the occurrence time, the event duration, etc.) in the power network where the transformer which is on-line monitored (Figure 13).

The equipment has 6 analog inputs with the sample rate of: 10 ks / s / channel (phase currents: IR, IS, IT, voltage phases: UR, US, UT), 8 analog inputs with the sampling rate of 1 ks / s / channel (for ambient temperature, SF6 gas pressure, etc..) and 8 digital inputs. Also, the equipment has four outputs (4 relay contacts - NO - dry contact).

The software dedicated to EMCSIT – TC/TT (the on-line monitoring system for instrument transformers) is structured in the following modules:

a) server application software for data acquisition and database storage “EMCSIT - TC / TT Server”;

b) client application software for viewing analog and digital parameters (states) - “EMCSIT - TC / TT Client”;

c) application software for viewing and analyzing events - “EMCSIT - TC / TT Event graphics”;

d) application software for viewing history information recorded in the database – “EMCSIT - TC / TT History”.

The “EMCSIT - TC/TT server” uses a fix time interval (ex. 1 minute), to acquire the latest information on the monitored parameters. The data is displayed on the main screen of the application software and it is stored in an Oracle database.
b) client application software for viewing analog and digital parameters (states) - “EMCSIT – TC / TT Client”;
c) application software for viewing and analyzing events - “EMCSIT - TC / TT Event graphics”; 
d) application software for viewing history information recorded in the database “EMCSIT - TC / TT History”.

The interface of the server/client application software allows the view of the monitored parameters: 14 analog and 10 digital parameters (states) (Figure 14).

The main window also shows information on events recorded by the “EMCSIT TC / TT server”.

E. EMCSIT - D monitoring equipment

EMCSIT - D equipment provides the on-line monitoring of high voltage surge arresters, ensuring on-line data acquisition regarding the operating parameters and the condition of the monitored device, such as: the technical condition of the surge arrester, the total current passing through each surge arrester on the R, S, T phases of the same power network, the unbalance current resulting from the total currents passing through the surge arresters on the three phases of the network, the third harmonics of the total current through each surge arrester, the number of operations for each surge arrester on R, S, T phases (Figure 15).

The equipment has 5 analog inputs: 3 x total current inputs through each surge arrester on R, S, T phases of the same three-phase network; 2 x current inputs (4-20mA), available for input configuration. Sampling rate is 10 kS/s/channel. Also, the equipment has 4 outputs (4 relay contacts – NO - dry contact).

The software dedicated to EMCSIT – D (the on-line monitoring system for surge arresters) is structured in the following modules:

- a) server application software for data acquisition and database storage - “EMCSIT - D Server”;
- b) client application software for viewing analog and digital parameters (states) - “EMCSIT - D Client”,
- c) application software for viewing history information recorded in the database - “EMCSIT - D History”.

The “EMCSIT - D Server” uses a fixed time interval (ex. 1 minute), to acquire the latest information on the monitored parameters. The data is displayed on the main screen of the application software and it is stored in an Oracle database.

III. INTEGRATING INTELLIGENT EMCSIT SYSTEMS IN A COMPLEX ON-LINE STATION MONITORING SYSTEM

On-line monitoring equipments EMCSIT TRAFOMON, I, S, TC / TT and D can be integrated into the SCADA system, can be integrated into the user’s intranet (fiber optic network or GSM network), can be used as standalone equipment or integrated into an on-line monitoring system of primary equipment in high voltage substations - Smart Grids. In addition to that, they may also constitute a viable solution when using on-line monitoring systems for substations without personnel, remotely controlled (Figure 16).

In order to integrate the EMCSIT systems into a complex system for monitoring high voltage substations, a dedicated software application - “EMCSIT station” was developed. “EMCSIT station” offers the customer a simple, easy to use
graphical interface, allowing the user to acquire information on the monitored parameters from the local servers corresponding to systems that individually monitor primary equipment of the on-line monitored substation.

“EMCSIT station” software is installed on the central server situated in the control room, which is in the same LAN with the local servers from the substation relay room.

The graphical interface of “EMCSIT station” presents the monitored substation’s schematic electrical circuit diagram. This schematic contains the following types of graphic elements: electric line, electrical connection (node); circuit breaker, disconnector, surge arrester, current and/or voltage transformer, voltage power transformer, shunt reactor, ground.

Images with “EMCSIT station” software in operation are taken from 400/110 kV Darste substation, the CNTEE Transelectrica pilot power substation for on-line monitoring using EMCSIT system (Figure 17).

In order to highlight voltage on overhead line or equipment, it is used a certain color code, that can be established in the “EMCSIT station” software.

The application software updates the information displayed every minute, so any change in the value of monitored parameters or states, for each one of the types of items displayed can be viewed.

When the user moves the mouse cursor over the graphic element that represents a type of primary equipment, information such as name, most recent measured values for the monitored parameters will be displayed.

If user requests a detailed view for a specific device, by clicking with the mouse on the graphic element corresponding to that device, a new window will appear, containing the client software for that specific equipment.

If a disconnector was selected, “EMCSIT Station” software will connect to the server database, will make the correlation between name of the device and the id recorded in the database for that equipment and will open a new window for the dedicated “EMCSIT - S Client” application software (Figure 18).

“EMCSIT - S Client” runs within the same LA with “EMCSIT - S Server” application and acquires the latest information recorded in the database for the selected device.

In terms of connecting all EMCSIT monitoring equipment in the substation, the software can acquire signals in real time and update the substation’s schematic electrical circuit diagram, in accordance with the information received.

IV. CONDITION ASSESSMENT OF HV ELECTRICAL EQUIPMENT

The integrated operations and maintenance (O&M) management system of CN Transelectrica is based on the on-line and/or off-line monitoring of the HV electric equipment and TRANSPOWER expert system dedicated to the evaluation of the momentary condition of these equipment, on-line and/or off-line monitoring, respectively [3].

The TRANSPOWER expert system is a modular system designed for evaluating the condition and maintenance, respectively, of the 110 – 750 kV primary electric equipment, namely the power transformers, instrument and voltage transformers, circuit breakers, disconnectors (switchgear), surge arresters.

Each module of the system is basically made up of three components: relational database for the respective primary equipment; unitary graphic interface for different modules, common to all the categories of users; management and communications software.

The software for the management of the specific databases specific to the TRANSPOWER expert system modules ensures: the precise identification of the managed primary equipment; interactive taking over, validation and storage of
the descriptive information on the operational procedures, standards, etc., in the database; database query (display, editing, reports, statistics, etc.); control of the access to the database content; a distinct module enabling a service company to supply the test results in an electronic format, compatible with the other software modules; loading of files (of any type) relating to different entities in the database for their subsequent viewing, etc.

For the purpose of calculating the reliability indicators and estimating the momentary condition of HV equipment, it uses Nova Predict software application which receives as input data, the on and/or off line measurements and the general characteristics of the equipment, and it calculates the main reliability indicators and estimates the lifetime of the equipment in question [4].

V. CONCLUSIONS

The EMCSIT intelligent monitoring systems described above and currently used within CN Transelectrica provide quick and correct information - an optimal support for best real time decisions, on the management and safe operation of power substations, with reduced costs.

These intelligent monitoring systems can be used stand-alone or within an integrated system for on-line monitoring of high voltage equipment from electric power stations and substations – Smart Grids.

VI. REFERENCES

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BIographies

Constantin Moldoveanu was born in Fetesti, Romania, on October 23, 1945. He graduated the Electrotechnical Faculty of the Bucharest Politechnical Institute where he obtained a Dipl. Ing. degree and received the Ph.D. degree in electrical engineering from the Polytechnic Institute of Jassy, in 1968 and 1980 respectively. Mr. Moldoveanu joined the Energy Research and Modernizing Institute – ICMENERG of Bucharest, in 1968 and has been engaged in numerous research projects on power transformers and high voltage equipment.

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