NEW CONCEPT
OF HIGH-VOLTAGE SWITCHGEAR ON-LINE MONITORING SYSTEM

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Abstract: A new concept of a high-voltage switchgear on-line monitoring system (BMS - Bay Monitoring System) is described. Main features and benefits of BMS are simple ethernet-based communication which means simple LAN connectivity with other systems in a switchgear, reliable data collection, reliable controller operation, reliable power supply, quick access to data and a quick and simple retrieval of stored data via graphic user interface (wave shapes, measured values etc.). BMS is modular based system. It can be used as independent system or as a subsystem of integrated on-line monitoring system (PEM-Power Equipment Monitoring). PEM is a complex on-line monitoring system. It has three integrated on-line monitoring subsystems: rotated machines, power transformers and high-voltage switchgear.

1. INTRODUCTION

In power system one of the key element is high voltage switchgear. Switchgear contains numerous types of high voltage equipment: circuit-breakers, disconnectors, earthing switches, current and voltage transformers and surge arresters.
On-line monitoring of high voltage switchgear provides: insight into real-time switchgear condition, condition based maintenance, incipient fault detection, prevention and reduction of fault consequences (cost reductions), continuous information on switchgear condition, information about high voltage switchgear operating conditions (loads at switching operations, assessment of the residual life), increased availability and fault cause analysis.
In this paper a new concept of a high voltage switchgear on-line monitoring system, called Bay Monitoring System (BMS) is described, Figure 1.

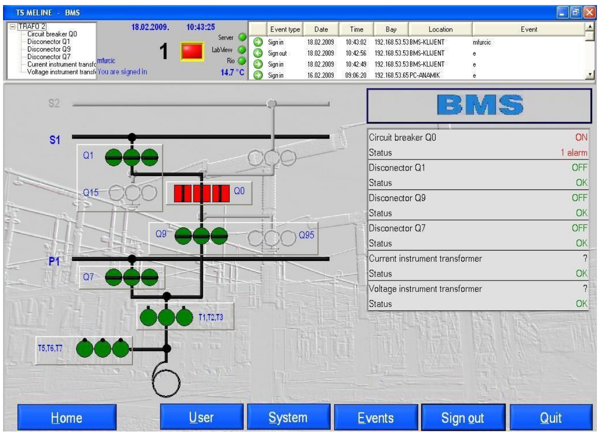

Figure 1: Switchgear on-line monitoring system - interface

BMS is installed and tested in a transformer switchgear bay of 400 kV transformer substation in a Croatian Power System, Figure 2.

Figure 2: 400 kV switchgear

A various operational quantities of high voltage circuit breaker, disconnectors, earthing switches, instrument voltage and current transformers are on-line monitored. The monitored quantities are compared with the quantities from diagnostic testing.

2. DEVELOPMENT

A laboratory model is made which consists of monitoring equipment used for completely functional system (front edge, controller), and the model of one high voltage switchgear bay which gave all signal types and sizes (although smaller number of signals) expected in the real high voltage switchgear. The model consisted of a controller, circuit-breaker model, disconnector model, devices for measuring pressure and temperature, devices for measuring tripping and closing coils currents and device for measuring motor current.
FPGA chip was configured for software tasks and the application was made in real time (RT) for the signal acquisition and primary data processing on the controller. Software application was also created (in

the program language LabVIEW) consisting of two parts, i.e. one for final data processing and the other which sorts and saves data in the data base as well as allows the user access to all data. An adequate data base has been created and installed on the server together with the software application already mentioned. For data inspection and analysis (visualization) in the base, the client application (CVI) has been created which enables the user to monitor on local or remote computer current conditions, switching operation data either in numerical or graphical format, as well as for any other group of data, for the chosen time period, and trends of all sizes. Communication between system components is based on TCP/IP protocol, while „shared" variables or „xml strings" are used on application level.

Model and system prototype functioning have been tested by means of switching operations, and in so doing static and dynamic measurements of analog and digital signals have been carried out.

The chosen monitor system concept can accept a hundred digital and app. 70 analog physical signals from the monitored switchgear bay.

After the successful testing of the on-line monitoring system on a laboratory model, the system was built into a 400 kV transformer switchgear bay. In the transformer switchgear bay there is a single pole operated circuit-breaker, two busbars and one line disconnector, three earthing switches and instrument current and voltage transformers.

The mounting of BMS system prototype in a 400 kV transformer substation was carried out in two phases, i.e. before the switchgear bay revitalization the equipment on the new circuit breaker had been mounted while it was still in the storehouse, and the monitoring system cubicles were built in the transformer switchgear bay, but on the earth potential. Then, while revitalizing (voltage free) the equipment built-in sensors, signaling and communication cables as well as the other system elements are connected. The BMS system server was installed in the relay box which is connected, together with the controller, by the Ethernet connection to the local (internal) Croatian utility network of the transformer substation Melina. All the necessary testing of the complete monitoring system has been carried out. The testing includes status value checks during the acceptance and signal processing phase, as well as result presentation. A close attention has been paid to acceptance and analysis of the dynamic phenomena (transients), i.e. their storing on the controller itself as a transfer and storing in the base. After successful testing of the monitoring system and the completion of the revitalization works for the 400 kV transformer substation, the monitoring system was put into operation.

3. ON-LINE MONITORING SYSTEM

The on-line monitoring system is presented in Figure 3.

All values of the condition and phenomena occurring on high voltage switchgear elements are registered by means of adequate sensors in real time and are forwarded to the processing unit. The processing unit

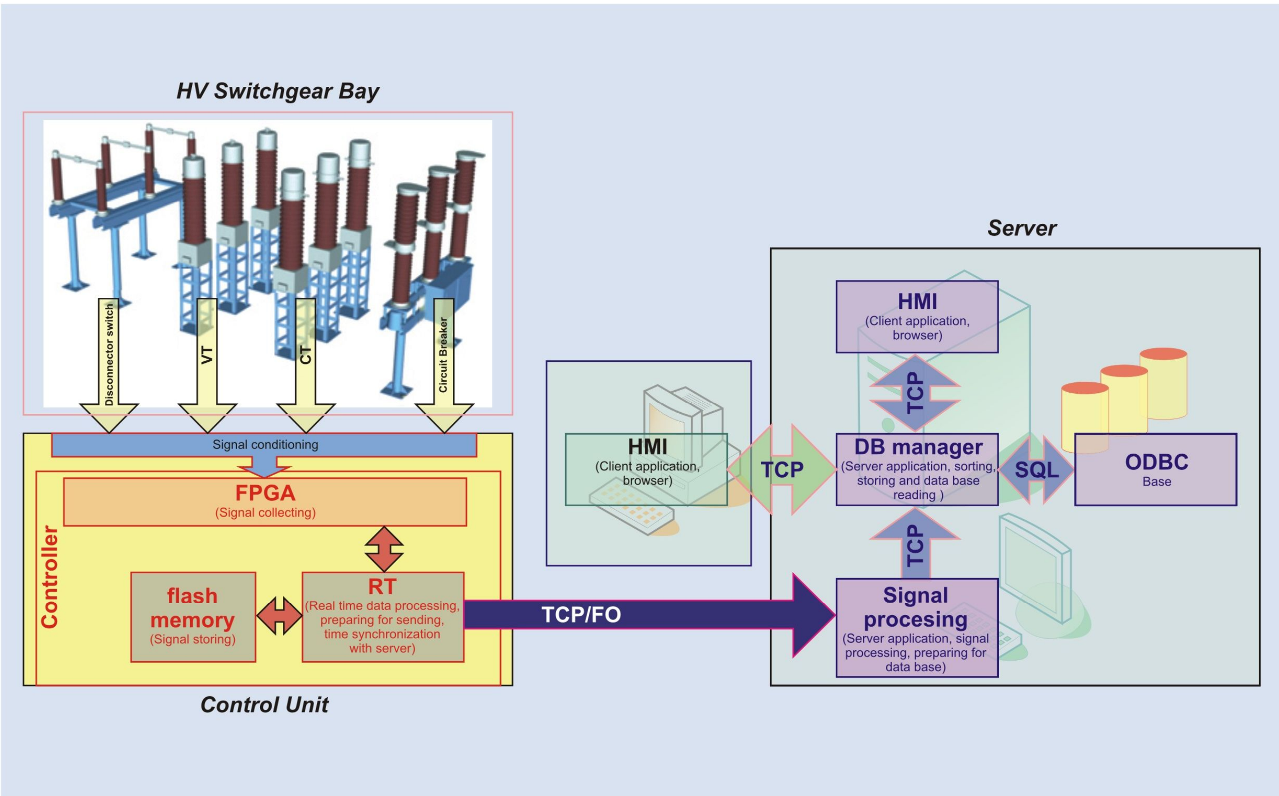

Figure 3: Switchgear on-line monitoring system - fundamentals

sends the processed signals by standard communication protocol to the computer (server) where the signals are sorted and stored in the relevant data base. By the data access from the base, analysis and presentation of all phenomena and conditions introduced in the system are carried out. Analysis results are presented on the server in both graphical and numerical form, and may be available remotely through global network or modem access, Figure 4, 5, and 6.

Monitoring system uses one central unit, i.e. PAC type (Programmable Automation Controller). Inputs are modular (analog, digital, RTD for Pt100 temperature probes), and the entire system is built according to the signal number needed for the server. The equipment used is National Instruments cRIO model, and the software is based on LabVIEW program language.

Circuit-breaker monitored quantities are:

· Status: circuit breaker close/open, trigger, lockout,
· Phase voltage,
· Main circuit current,
· Close coil and trip coil currents,
· Control circuit voltage,
· Motor current,
· Frequency and duration of motor operation,
· Contact and/or drive travel,
· Switching times (make, closing, close-open),
· Hydraulic drive pressure,
· Oil loss in hydraulic cylinder,
· Spring drive tension,
· SF_6 temperature,
· SF_6 dew point,
· SF_6 density,
· SF_6 pressure, and
· Variation of SF_6 gas pressure at various circuit-breaker switching operations.

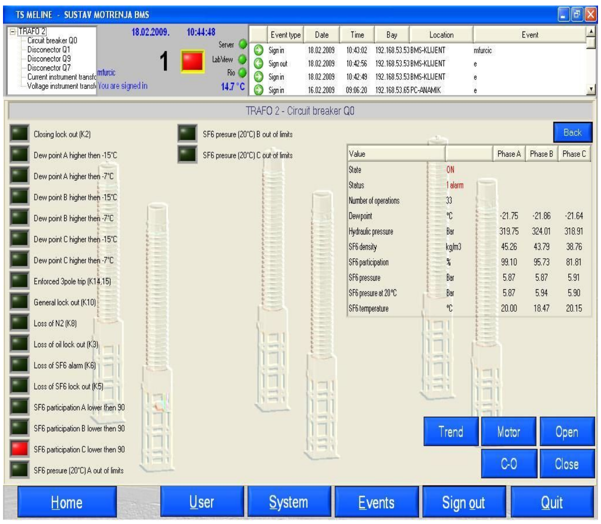

Figure 4: Switchgear on-line monitoring system - alarms

Disconnector monitored quantities are:

· Status: disconnector close/open, trigger,
· Motor current,
· Contact travel, and
· Switching times (make, closing).

Instrument current and voltage transformers monitored quantities are:

· Hydrostatic pressure,
· Main circuit current, and
· Main circuit voltage.

Earthing switch monitored quantities is status: close/open.

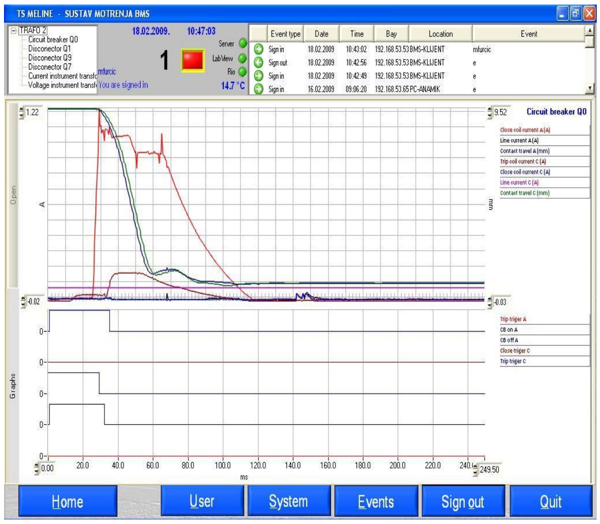

Figure 5: Switchgear on-line monitoring system - monitored quantities

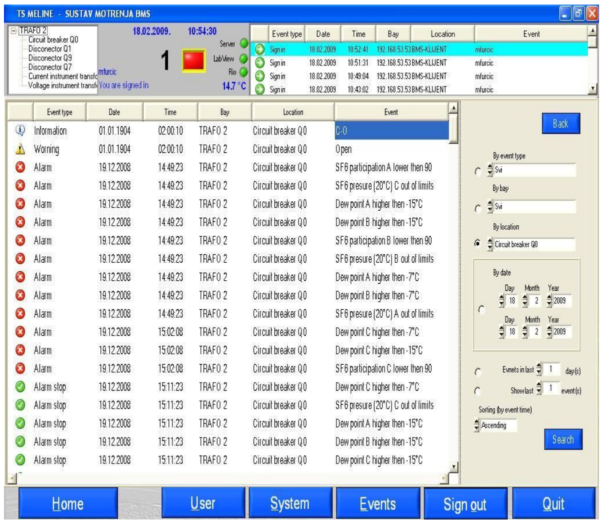

Figure 6: Switchgear on-line monitoring system - operation events

Beside values obtained from the sensor directly, there are values which are calculated by mathematical methods.

Circuit-breaker calculation gives the amount:

· Main and control circuits operating times,
· Contact travel and contact velocity during closing and making operations,
· Arc integral (I^2 t) during making operations,
· SF_6 pressure at 20°C, and
· SF_6 percentage.

For disconnector the following values are calculated: Main contact arms opening and closing time,

· Travel and angular velocity of main contact arms.

For instrument voltage and current transformer calculations are made:

· Hydrostatic pressure at 20°C.

The above parameters are monitored through all three phases and they may be presented by single amount or by their wave forms.

4. SIMULATION AND TESTING

In order to understand and predict the possible failure mechanism of particular high-voltage circuit breaker structure elements, SIMULINK model for the high-voltage SF_6 circuit breaker was designed. SIMULINK is a graphic simulation tool which uses so-called MATLAB mathematical shell for carrying out the dynamic analysis of a system. A high voltage circuit breaker model [7] is used as base and it is supplemented and adopted for the high voltage SF_6 circuit breaker 7F1 – 123 kV with hydraulic-mechanical drive.

The model has got 46 input and 27 output parameters which can be monitored in real time during simulation. In order to adopt the simulation model to other types of high-voltage circuit breakers, the model is normalized, i.e. normal value of all input and output parameters is 1. The circuit breaker is presented with three basic functional values: control circuit, operating mechanism and interrupter. Each of them is modeled independently and consists of different sub circuits which are modeled separately. All sub circuits are connected through corresponding input and output data connections into a complete circuit breaker model. The developed model can simulate circuit breaker operation as well as each of its components. This is very important when circuit breaker irregularities have to be diagnosed. Due to manual regulation of model parameters, it is easier to describe the monitored circuit breaker. The model is used to simulate all possible failure on the circuit breaker and the results are stored in the data base. This data base can be used in circuit-breaker on-line monitoring system. Therefore it is easier to diagnose the deviation and failure of the circuit breaker. Figure 7 gives the simulation of the 400 A_{eff} circuit breaker opening.

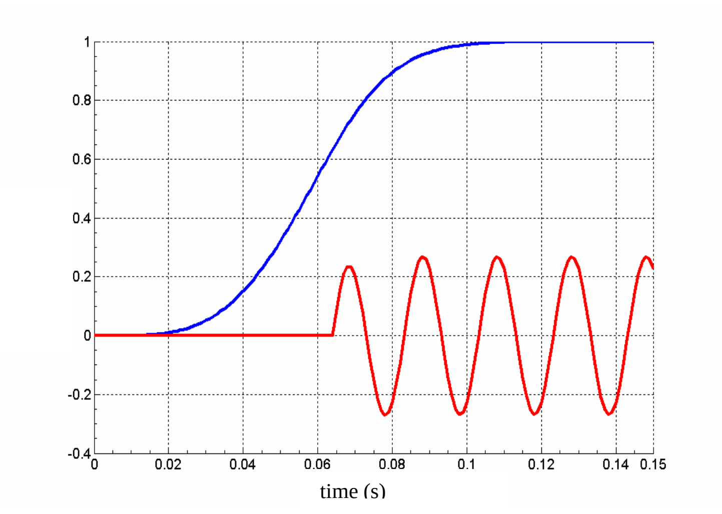

Figure 7: Simulation of circuit breaker opening

Simulation results show good agreement with results obtained on 7F1 circuit breaker during diagnostic tests, Figure 8 and on-line monitoring, Figure 9.

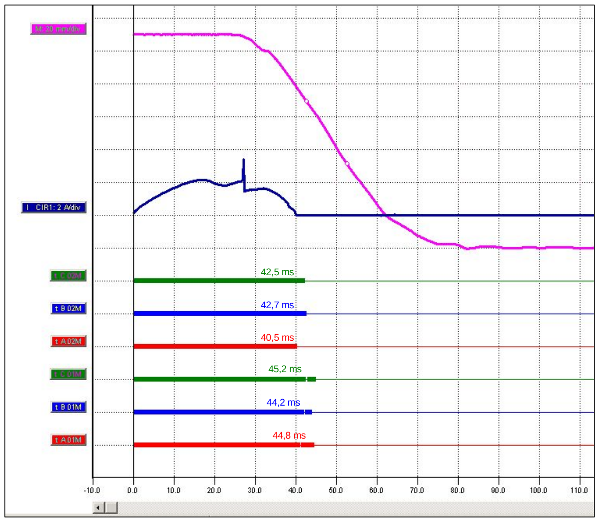

Figure 8: Diagnostic tests - circuit breaker opening

Simulation model of the high voltage circuit-breaker gives a good base for investigation of high voltage circuit-breaker functioning and the base for making expert monitoring system for high voltage switchgear, respectively.

The best results are shown during process analysis which cause significant deviations and changes so the model has to be built up by adding adequate algorithms for the analysis of slowly changing conditions, such as SF_6 gas leakage.

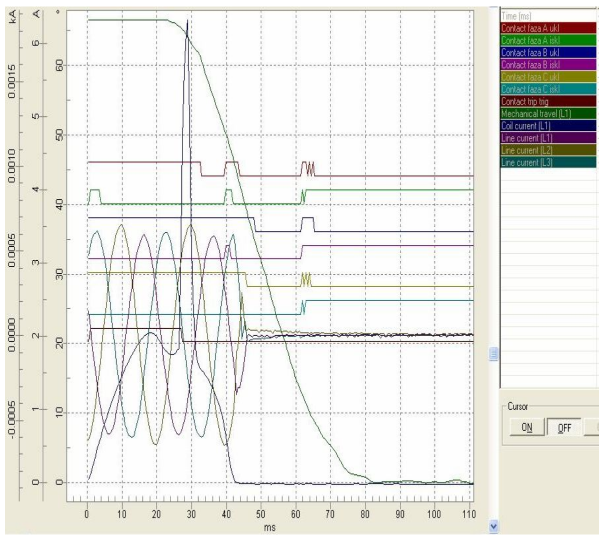

Figure 9: On-line monitoring, circuit breaker opening

By circuit breaker simulation model the most frequent possible mistakes and failures should be simulated first and then, the results obtained store in the data base. After that, the data base is used in real time for finding the best diagnosis when the deviations are observed.

Here, of course the knowledge and experience of the staff dealing with high voltage switchgear should be used and that knowledge should be applied when building up the expert system.

The expert system should help the staff in identifying problems while analyzing the monitored values in the same way as humans would do. In so doing, significant hazardous states and failures can be prevented and the problems are detected even before they become critical.

5. INTEGRATED HV EQUIPMENT ON-LINE MONITORING SYSTEM

A high-voltage switchgear on-line monitoring system described in this paper is modular based system. It can be used as independent system or as a subsystem of an integrated HV equipment system, Figure 10. This is a complex system with three subsystems for on-line monitoring of rotated machines, power transformers and high voltage switchgear. The advantages of this integrated HV equipment system are:

- All three monitoring systems (generators, transformers and switchgear) are unified and integrated in a single system,
- Only one server is needed,
- All three entire systems have the same communication infrastructure (LAN),
- Unified remote access to the monitoring system, with only one communication link from maintenance centre, control centre or from any user's location,
- Easier usage and maintenance of the monitoring system,
- Only one person with one set of tools can take care of the maintenance of generators, power transformers and switchgear in a whole power system.
- Better planning of maintenance and control quality.

6. CONCLUSION

The benefits of the on-line monitoring system are:

- Insight in the state of equipment and its real-time service conditions,
- Detection of emerging faults,
- Prevention of fault consequences (cost saving),
- Condition-based maintenance (cost savings),
- Optimum equipment management (overloading, residual lifetime assessment, lifetime extension, delayed replacements etc.),
- Improvement of personal and environment safety,
- Improvement of availability (more reliable operation – less unplanned outages and better managing of planned outages, and
- Easier fault cause analysis.

The on-line monitoring system has specific tasks during the whole lifetime of equipment:

- During the normal state – insight the state of equipment and its real-time service condition,
- During fault progress – diagnose of fault progress and warning the user, and
- In case of fault – support for fault analysis.

Bay monitoring system has been developed in order to evaluate the state of monitored high voltage apparatuses and equipment at any time, and bring about the right decision regarding the necessary maintenance activity and further exploitation. The system is based on Programmable Automation Controller Compact RIO, which collects measurement results from sensors built-in the equipment and sends them to the server. Measurement results are processed on the computer in LabVIEW program which is configured according to the specific high voltage switchgear bay. The data processed are sorted and stored in the base and are presented through graphical interface on the computer which can be accessed remotely (local network or the Internet).
System front rap consists of free signals and sensors built-in monitoring equipment. Standard sensors are used, such as current measuring transformers, shunts, pressure sensors, Pt100 probes for temperature measurements, analog and digital encoders for recording path and speed, sensors for SF_6 dew point and sensors for SF_6 density and other. The central part of the system is Compact RIO controller, into which, depending on the monitored functions desired number and type modules are built in for particular purposes. One controller can accept up to eight different modules and cover the number of signals needed for up to two switchgear bay. One or more controllers are connected to the server by means of optical cables which sends signals, the signals are processed and stored on the server.

The system is designed for the continuous monitoring of the following equipment: high voltage circuit-breakers, disconnectors, earthing switches, instrument voltage and current transformers.

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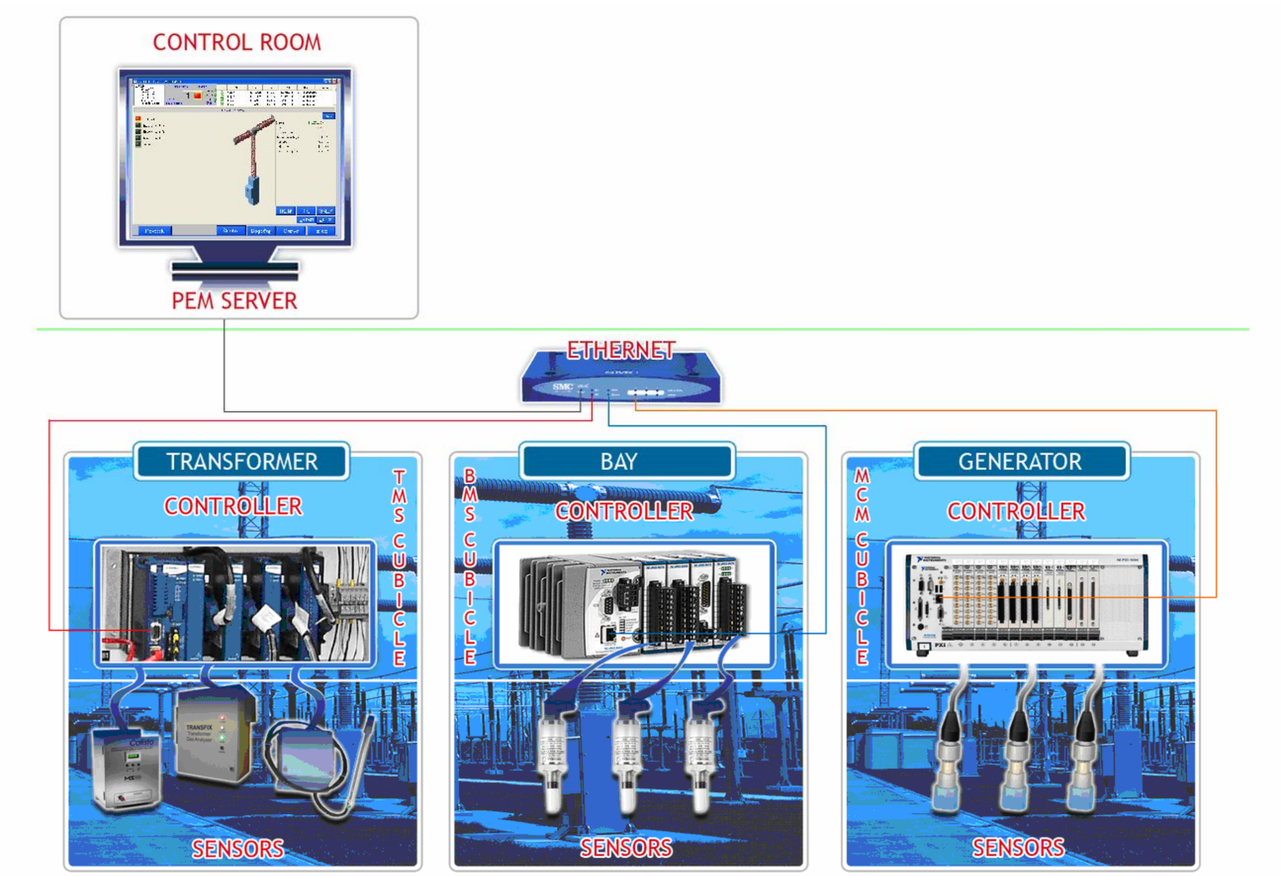

Figure 10: Integrated on-line monitoring system (PEM - Power Equipment Monitoring)