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Measurement Systems for Electrical Machine Monitoring

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1. Introduction

Monitoring systems on electrical machines, nowadays largely present on new electrical rotating (synchronous generators) and non rotating machines (transformers) have to endure harsh conditions such as vibrations and electromagnetic disturbances. Also, especially for rotating machines, rotor physical quantities (temperature, strain, current…), have to be transferred to the standstill part of the measurement system without galvanic contact.

Therefore, monitoring systems should be, and usually are, designed for a specific purpose and for a specific machine. Some essential parts are the same but most of the monitoring system should be custom made especially if one takes into consideration that there is a small serial production of large electrical machines in the world and that most of the large units are unique.

Modern monitoring of big transformers covers permanent on-line monitoring of electrical, magnetic and mechanic quantities. It is specific when compared to rotational electrical machines because it also usually includes monitoring of dissolved gasses in transformer oil. This information, with proper interpretation, represents an important element for transformer state determination. However, transformer monitoring systems are not the focus of this chapter.

This chapter deals with all problems, obstacles and solutions applied to two measurement systems installed on a 35 MVA hydro-generator and a 250 MVA turbo-generator.

Large electric machines justify investment in measurement systems for several reasons. Usually, measurement systems for bearings are installed. In such systems vibrations and oil parameters (pressure and temperature) are monitored to help maintenance. Measurements of stator and less often rotor currents are also present as parts of different systems. For example, a differential stator current measurement is present for protection purposes and enables detection of current leakage (short circuit between phase windings). Monitoring systems that incorporate all necessary measurements and, of course, interpretations of those measurements are almost non existing and very rare. This chapter will concentrate on synchronous generators.

2. The monitoring system

The monitoring system is basically a data acquisition system with on line data processing and possible data interpretation. A standard data acquisition system consists of a sensor, signal transfer, A/D conversion, signal conditioning and data storage.

The sensor is usually analogue, like a Pt1000 probe for temperature measurement. The temperature is measured as a resistance over two, three or four wires. If resistance is measured over four wires, the current flows through two wires and the other two wires are used for voltage measurement. This system configuration is very sensitive to electromagnetic disturbances thus making measurement inherently inaccurate. In order to avoid that and to make measurement more accurate signal amplifiers and converters are designed. They enable steady current regardless temperature dependence of connecting wires. But still, voltage measurement is subjected to electromagnetic disturbances since the measured voltage has an mV range. Of course, all of these disturbances and most of their influence can be avoided by proper wiring. For example, bifilar wire configuration and shielded cables significantly reduce electromagnetic disturbances if the shield is properly grounded.

So, such configuration, for example the one installed in Plomin thermo power plant, has a sensor (a Pt1000 probe), a rather large amount of wire (15 m), a signal converter and amplifier (placed in the measurement cabinet), a ±10 VDC signal path (a 2 m cable), an acquisition system, communication (90 m Ethernet FTP cable) and finally a measurement computer.

The reasons for such configuration will be presented later in this chapter. Of course, if one has the opportunity and technical possibility, one should install a more advanced temperature measurement. For example, there are digital temperature probes on the market that are basically small chips with temperature probes and all the necessary signal conversion. All they need is power and communication. They obtain them both through a three wire system that is completely independent of electromagnetic disturbances. Such a system has a serial connection and can have up to 127 probes in one system.

This description shows one review of the acquisition system that, of course, can grow to an enormous size. For example, in CERN in Switzerland, there is a measurement system with over 175 000 channels.

The monitoring system incorporates data acquisition and enables instant data processing and interpretation. For instance, before information enters the PC, the analogue signal goes through the A/D conversion and scaling. With this, for example, a signal of 5.4 mV becomes 24.5 °C. After that, the information about the exact temperature enters a PC application that operates with it. The temperature, maybe, does not represent the physical quantity, so vibrations will be used from now on.

Vibrations are measured with accelerometers. They measure vibration accelerations and such information enters the PC. But for a reasonable vibration analysis different quantities should be obtained from vibration acceleration such as vibration velocity and vibration displacement. Furthermore, for all the three quantities (acceleration, velocity and displacement) a base harmonic and some higher harmonics should be known. All of this can be done within data acquisition unit but then this unit will be very expensive. So, the

general idea is that such advance data processing is done within application in the monitoring PC.

The monitoring system can now have access to all the necessary data and can conclude upon the electrical machine condition. Of course, this conclusion can be based on simple or complex algorithms. Simple algorithms will include allowed limits, alarm limits and shutdown limits for some or most of the physical quantities. Complex algorithms include monitoring of some physical quantity trend lines and from that info concludes on further actions. Those conclusions can lead to a well-timed maintenance action that is more efficient and cheaper than waiting for a fault to occur and lead to an unplanned stopping of electrical machine and process for which this machine is necessary.

In the following text three measurement systems and one monitoring system will be presented.

The general idea of building a measurement system, and further on, a monitoring system on synchronous generators started with a desire to build a user P-Q diagram of a synchronous aggregate. In order to adapt FEM and analytical models to a real generator a lot of measurement of different physical quantities should be done. This demanded a measurement system to be made. Such a measurement system should be able to measure magnetic inductances B (T), temperatures T (°C), acceleration of vibrations a (m/s²), stator and rotor voltages U (V) and currents I (A).

So the whole idea was tested on synchronous hydro-generator and synchronous turbo-generator.

3. Measurements on the hydro-generator

When research for a user P-Q diagram started, the access was approved to Vinodol hydropower plant where three generators (Fig. 1) are installed. Their rated data is: S_n=35 MVA, U_n=10.5 kV, f=50 Hz, n=500 rpm, $cos\varphi$=0.9.

Fig. 1. Hydro-generators in hydro power plant Vinodol - 35MVA each

A larger measurement system was installed on the first generator. This enables a reduction of measurement systems installed on the other two generators. This text will describe the larger measurement system.

The research demanded a magnetic induction measurement, so 22 Hall probes were installed in winding end part and in the air gap. Since calibrated Hall probes are very expensive it was decided to buy only three calibrated Hall probes with their calibration certificates. The rest of hall probes were cheap sensors (their cost was approx. $5 per probe).

Hall probes have 4 connections. Two of them need a steady current flow and on the other two voltage can be measured. The voltage corresponds to the magnetic induction. Both current (1 mA or 5 mA) and voltage (range of mV) have rather small values. To satisfy those conditions current sources were designed. The current range can be selected with a switch within the current source. The Hall probe voltage is amplified with a signal amplifier to a ±10 VDC signal range and as such prepared for data acquisition. Of course, there are still two problems: calibration and electromagnetic disturbances.

But before calibration, all Hall probes were placed on an electronic board (Fig. 2) that has two possible connection places. If there is enough room for probe placement, then Fig. 2 option a can be used, but if there is not enough place (air gap, cooling channel) then a minor board can be cut out from the bigger one (Fig. 2 option b) and wires can be connected to it.

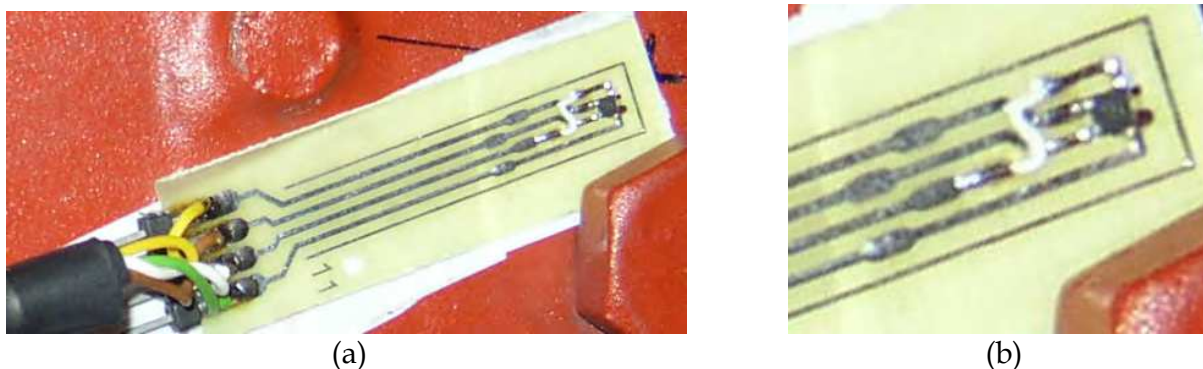| (a) | (b) |

Fig. 2. Hall probe board

The calibration problem was resolved when it was done in the laboratory. A three phase choke was used (Fig. 3) for that purpose. The air gap on the choke can be changed from 0 to 32 mm.

The calibrated Hall probe (the expensive one) was used as a reference probe and all the necessary calibrations (with AC and DC signals) for all the other Hall probes were made with it: the calibration constant, the DC offset and the thermal dependence. Several Hall probes were discarded because of their lack of linearity but most of the cheap hall probes were successfully calibrated.

Still, there was a problem of electromagnetic disturbances since the voltage signal from Hall probes is very small (range of mV). The distance from a probe to signal amplifiers is approx. 15 meters and that also contributes to the problem. This issue was minimized by using a 4 wire shielded cable. So there is one cable for each probe. Since those synchronous generators are air cooled there was no problem with the cable entrance through generator housing. Standard cable glands were used. All the cables were shielded on one side, near signal amplifiers. Such configuration ensures electromagnetic disturbance discharge thus minimizing their influence on the measured signal.
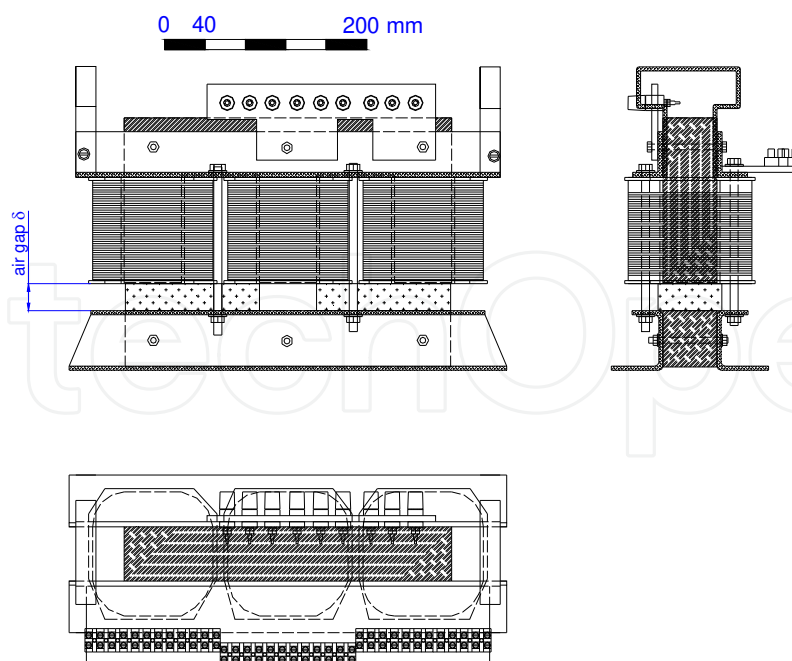
Fig. 3. Choke for Hall probe calibration

Similar measurement was made for temperature. Pt1000 probes and 2 wire measurement were used. Signal converters and amplifiers in one device were used to obtain a ±10 VDC signal for the data acquisition system. Two wire shielded cables were used for each signal and were grounded as the ones from Hall probes.

But a different problem was identified here. The problem was heat transfer from the surface to the probe. So before mounting Pt1000 probes onto the generator, the probes were conditioned. They were aligned on a thin pertinax base to ease mounting on the generator and as well as to assure the wanted relative position. Each probe was glued with super glue to pertinax (Fig. 4). After that isolation foil was glued over the probe. This foil assures electrical isolation but does not influence thermal transition. Cable wires were soldered on the Pt probe and the cable was glued on pertinax. When mounting on the generator, thermal paste was applied between the surface and the probe to ease thermal conductivity.

After that everything was suffused with thermal resistant glue.
In order to be able to obtain the exact wanted position of probes within the generator, Hall (A1, B1-B4, C1-C4, D1-D4, E1-E4, F1-F3, G1-G2) and Pt1000 (GTS1-GTS14) probes were placed on thin boards in the exact position (Fig. 5). The boards were then placed at the exact position within the generator (Fig. 6, Fig. 7 and Fig. 8). All probe positions were carefully recorded and later used when 2D and 3D FEM models were confirmed by measurements (Fig. 9).

One of the instruments developed during the measurement system design was an instrument for measuring the load angle (δ). During the designing period several devices were designed and commissioned. The method of load angle measurement is based on time measurement between zero crossing of the generator voltage and the rotor position represented by positive edge of proximity switch impulse. At first, this operation was carried out with a laboratory device and then after the production of a more professional version, the third, compact and universal model was produced.
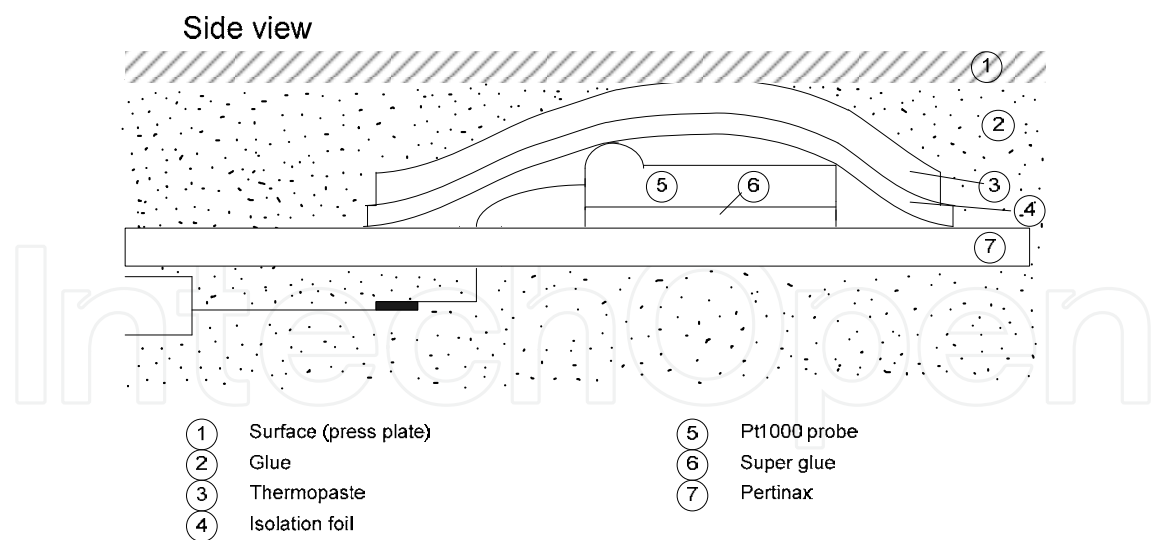
Side view

① Surface (press plate)	⑤ Pt1000 probe
② Glue	⑥ Super glue
③ Thermopaste	⑦ Pertinax
④ Isolation foil	

Fig. 4. Mounting scheme of Pt1000 probes

(a)   (b)
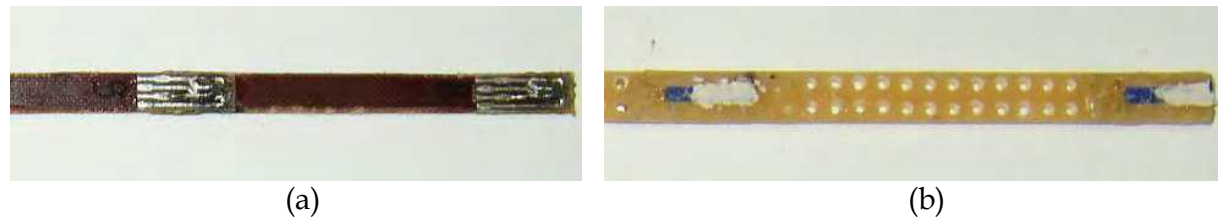
Fig. 5. Prepared probes: a) Hall probes; b) Pt1000 probes

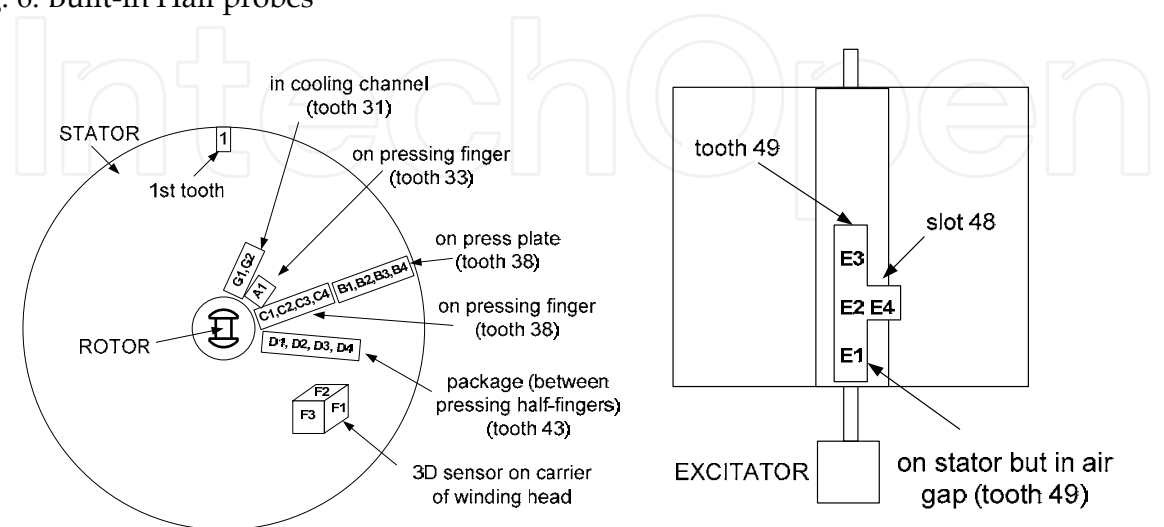Fig. 6. Built-in Hall probes

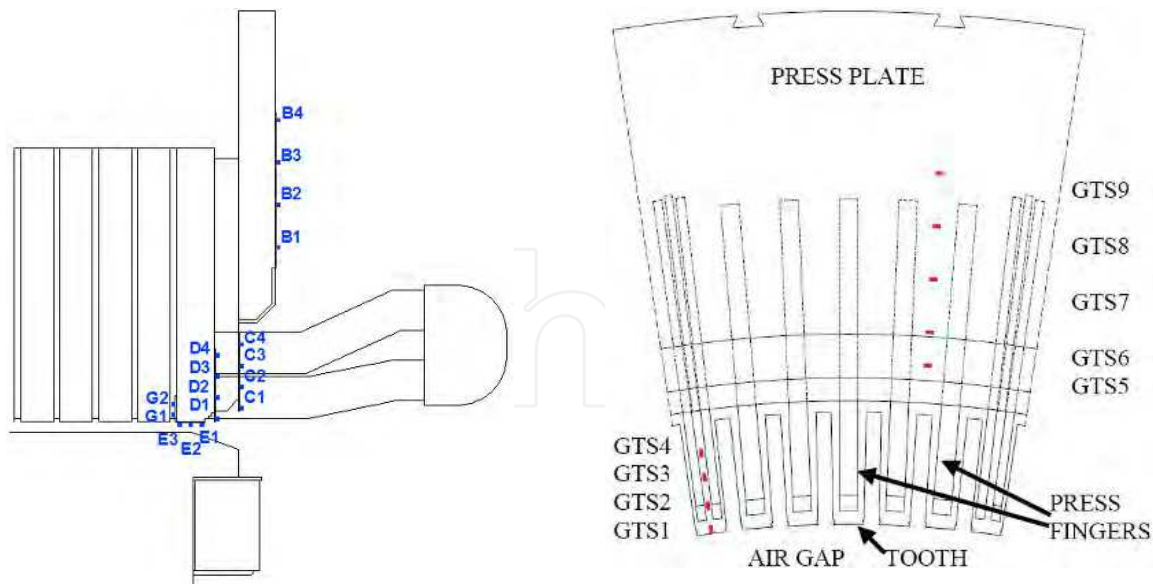Fig. 7. Placement of Hall probes in generator
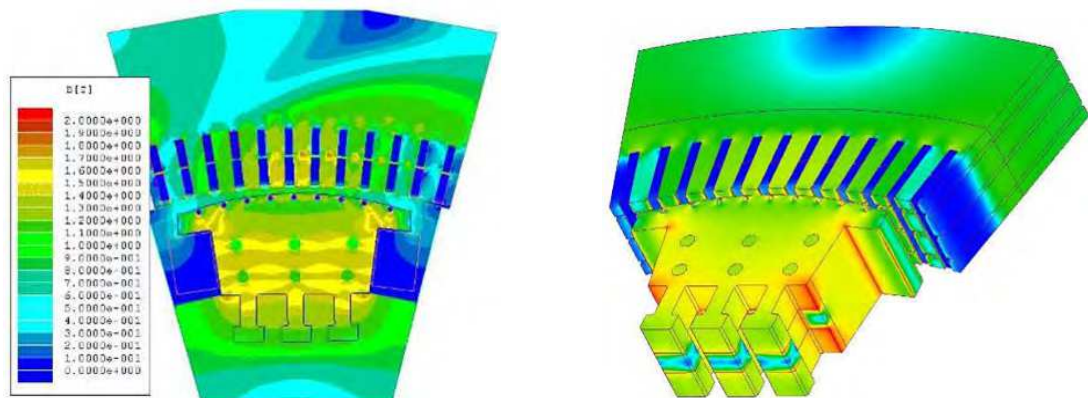
Fig. 8. Placement of Hall and Pt1000 probes

Fig. 9. 2D and 3D FEM induction calculations for no load operation

Also, as previously mentioned, two vibration probes (accelerometers) were installed on the stator package (Fig. 10).

Fig. 10. Vibration accelerometer installed on the stator package

After all of that, the measurement system needed to be designed and built. Since, at the time, only 16 channel data acquisition systems were available to us, 4 different data acquisition systems (Iotech) were used for complex measurements. All together there were a total of 51 signals (22 Hall probes, 14 Pt1000 probes, 3 armature currents, 3 armature voltages, 1 excitation current, 1 excitation voltage, 1 impulse per rotation, 1 load angle, 3 grid voltages, 2 vibration accelerations). All data acquisition systems had trigger possibility on one channel so this was used for synchronous start of data acquisition. Since there were so many signals there are lots of cables present. Most measurements were made with a temporary measurement system (Fig. 11). In order to be sure that electromagnetic

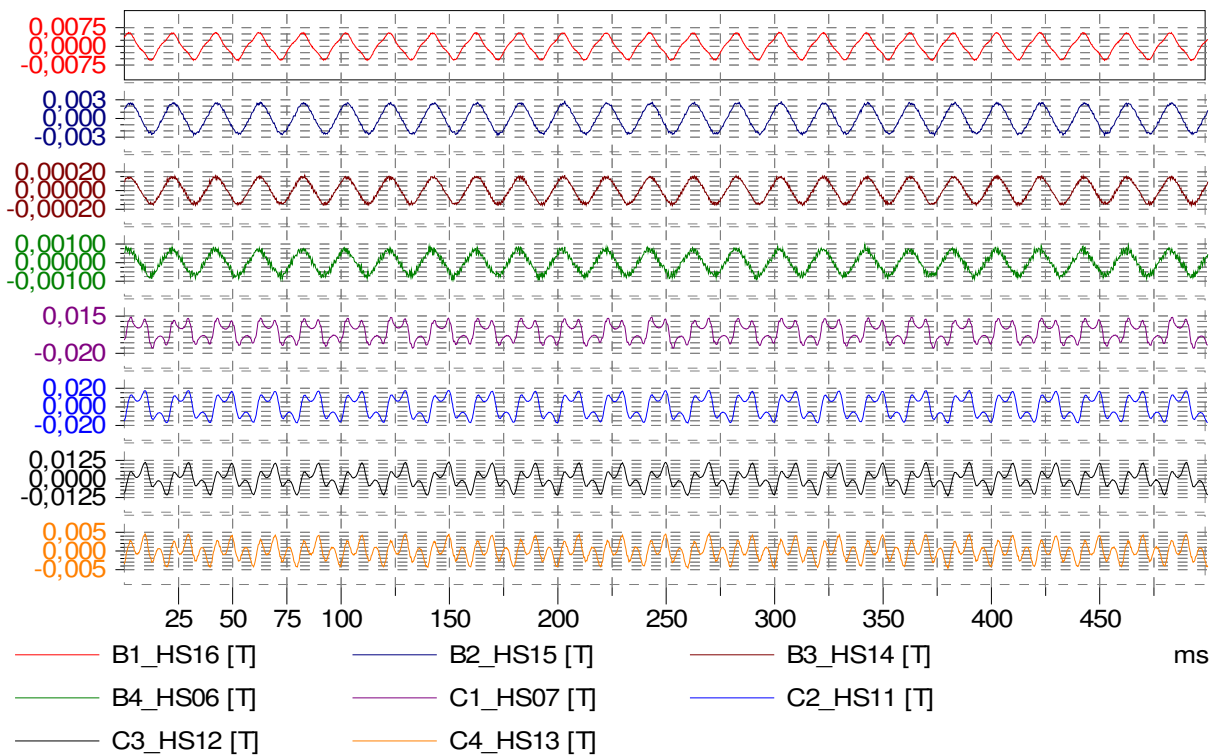Fig. 11. Temporary measurement system

Fig. 12. Hall probe measurements – signals of different probes

disturbances are not present, or at least are acceptable, each signal was checked several times and compared to the theory. For example, each magnetic induction signal was checked separately and together with the rest of them. If two signals are the same and their probes are not in the position that can give the same signals (for example the same radial position on the press plate) this is the indication that one signal is copied to the other channel. Also, most of signals must have some angular difference and this is the other way to check them (Fig. 12).

After several measurements with the temporary measurement system there was a 3 year delay with this power plant due to circumstances beyond our influence. So, the measurement and monitoring system development for this power plant was halted. But all designs have been done and the equipment has been bought and installed in the electrical cabinet (Fig. 13). This cabinet (measurement cabinet) will be installed in the power plant during the first half of next year. Data acquisition will be realised with National instruments Compact RIO product. The main interface will be touch panel. The plan is to place a PC near this cabinet and connect the system to the Internet.

Fig. 13. Measurement cabinet for measurement systems installed on all three generators in hydro power plant Vinodol

4. Measurements on the turbo-generator

A measurement system was also installed on one turbo-generator (Fig. 14). This generator is installed in Plomin 2 thermo power plant. Its rated data are 250 MVA, 3000 rpm.

A similar set of probes was installed in this generator as it was in the generator in HPP Vinodol. In total, 55 probes were installed in the generator: 30 Hall probes, 14 Pt1000 probes and 11 accelerometers. All armature and excitation voltages and currents are measured together with one grid voltage. All those currents and voltages are measured in such a way that a malfunction in the measurement system does not influence systems in the power plant. For instance, armature currents are measured with current transformers (5A/333mV)

Fig. 14. Turbo-generator 250 MVA in Plomin 2 thermo power plant

placed around the wires from the secondary windings of the major current measurement transformers (2000A/5A) of the generator. Voltages are also measured on the secondary windings of major voltage measurement transformers. This connection was made over 250mA fuses. Major voltage transformers have the ability to burn those fuses (in case of a measurement system malfunction) without jeopardizing their primary function.

This generator is cooled with hydrogen. Since this is a highly explosive coolant all signals were checked for energy level they import in the generator. The energy level must be lower than the energy that is high enough for sparking and that may ignite hydrogen. This is the first step to ensure that the measurement system can do no harm to the generator. The next step was to shut down all the measurements and cut off the power in the measurement cabinet in case of hydrogen leakage. So, if sensors detect hydrogen outside of generator, the main contactor used for powering the measurement cabinet switches off. The third step was installation of a hydrogen detection probe within the measurement cabinet since signal cables can lead hydrogen from the generator to the measurement cabinet in case of cable glands malfunction. The fourth step was to design special cable glands to ensure absence of hydrogen leakage. Cable glands (Fig. 15) were designed, tested, installed and they have been functioning flawlessly for two years.

Signals from the generator were conducted through a signal cable. This cable has 16 twisted pair wires. Each twisted pair is shielded and the whole cable is shielded, too. This double shielding ensures better protection from electromagnetic disturbances. The measurement system is similar to the one in HPP Vinodol. The difference occurs in the data acquisition system.

After conditioning all the signals go to one device (NIcDAQ9188) and not to four different data acquisition systems. The conditions and customer demanded that the PC should be positioned in the control room approximately 90m away from the measurement cabinet (Fig. 16) so Ethernet cable FTP cat.6 was used for that connection.

Fig. 15. Signal cable glands

Fig. 16. Measurement cabinet with NIcDAQ9188 data acquisition system

Unlike the measurement system in HPP Vinodol, where measurement and monitoring systems should be finished, everything is finished in TPP Plomin2. A lot of work was done in order to produce the application in LabVIEW for measurement, signal processing and data storage.

The front panel application was developed in LabVIEW and consists of several tabs. All of the measurements are divided between multiple tabs. The first three tabs are used for graphical view of the measured signals. It is possible to observe waveforms of all of the acquired signals (magnetic field flux density, vibration accelerations and electrical signals such as stator currents, voltages, field current, voltage etc.). The user is also able to read the exact value of the waveform using a cursor tool and move over the waveform using zoom in/out and drag tools (Fig. 17).

After successful acquisition of the all the signals the application computes all the necessary quantities such as rms, peak-to-peak, base harmonics of the acceleration, velocity and
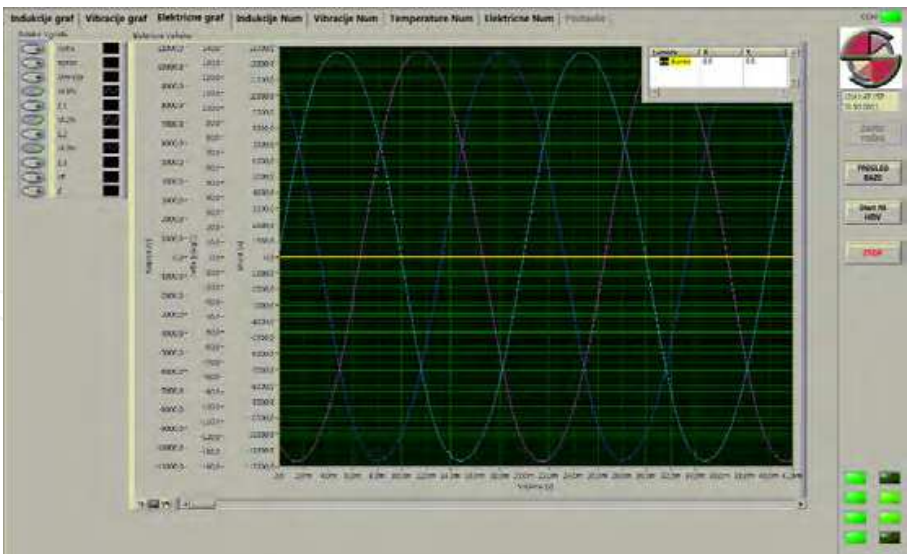
Fig. 17. Front panel of the application, showing real time waveforms of the 3-phase system voltage

displacement for vibration signals; dc-offset, rms value, base harmonics for magnetic flux density signals; mean value for temperature signals; full 3 phase power analysis for electrical signals. The signals that can also be measured on the synchronous machine are field current, voltage and load angle of the machine. The computed quantities are also divided in four separate tabs (magnetic flux density, vibrations, temperature and electrical), (Fig. 18).
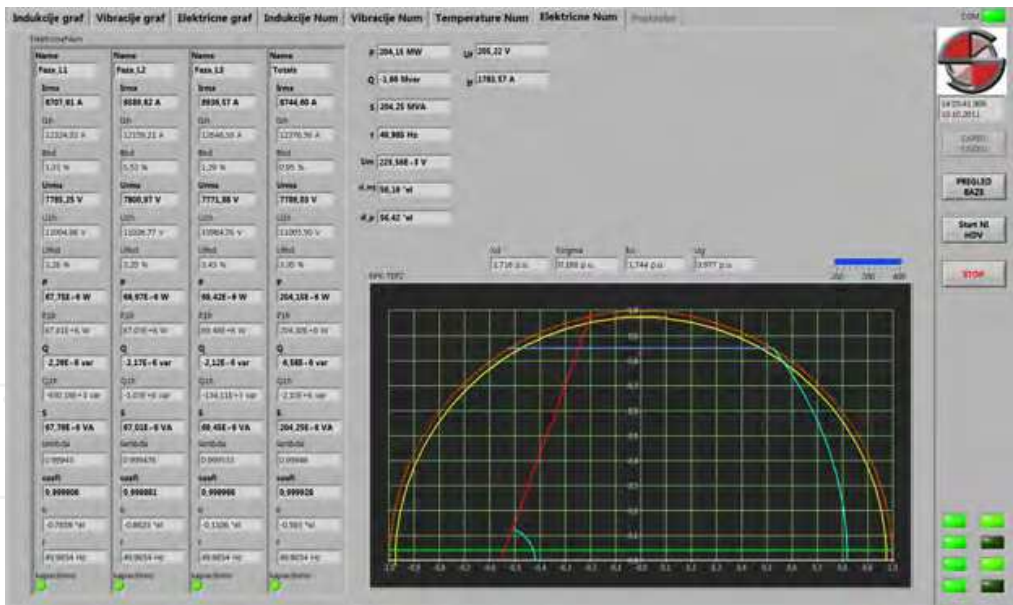
Fig. 18. Front panel of the application, showing real time electrical measurements and capability diagram

After a successful calculation, all of the calculated quantities are logged into the historical database (Fig. 19). A user can access the database from the application GUI, and observe variations or trends of the selected quantities over a desired time period. Trend analysis is especially valuable tool in vibration monitoring. Based on the trend of the calculated vibrations user can predict a maintenance of the machine.

Fig. 19. Historical data view of computed variables (red-active power, green- reactive, white- tangential end winding vibration, violet-axial end winding vibration)

The described method of monitoring incorporates measurement of the signal waveforms. All of the data logged into the database are just physical quantities calculated from those waveforms. There are cases when a user demands to log the waveform data for further, more detailed, analysis. A continuous waveform logging requires a large storage capacity as all of the waveforms are sampled at rather a high frequency (more than 10 kHz). To lower the demands on storage capacity the application must be able to decide which of the waveforms to store. The stationary waveforms are no of interest for most of the users so the application must detect only a change in the signal and based on that change it has to trigger storing of the waveform. When designing such an application one has to be careful that it records a certain amount of signal before the actual trigger event. Furthermore, in this type of measurement the acquisition system and the data processing have to be able to withstand the continuous sampling of the signal to ensure that none of the samples are lost due to the buffer overrun or the slow data processing. Fig. 20 shows an armature current transient properly recorded with pre-buffer time set to 5 s and total transient time set to 20 s.

5. Measurements on the rotor

Modern synchronous generator monitoring and controlling systems require measurement of various physical quantities. One of those is the temperature of the machine. It is relatively easy to measure temperature of the stationary part of the machine, but the difficulties arise with the measurement of the rotor temperature. Conventional temperature measurement requires slip-rings for each sensor. The measurement system which uses digital wireless data transfer and digital temperature sensors will be described in short.

The DS18B20 digital sensors were chosen for the temperature measurement. The accuracy of the temperature sensors is ±0.5 °C. Sensors use a 1-wire protocol for communication with the microcontroller. Bluetooth communication was selected because of the high operating frequency 2.4 GHz, low power requirement and wide usage in various IT equipments. A special embedded device was developed to convert data from temperature sensors. The measurement system consists of several specific parts:

- Bluetooth communication module
- Microcontroller
- Battery charge management
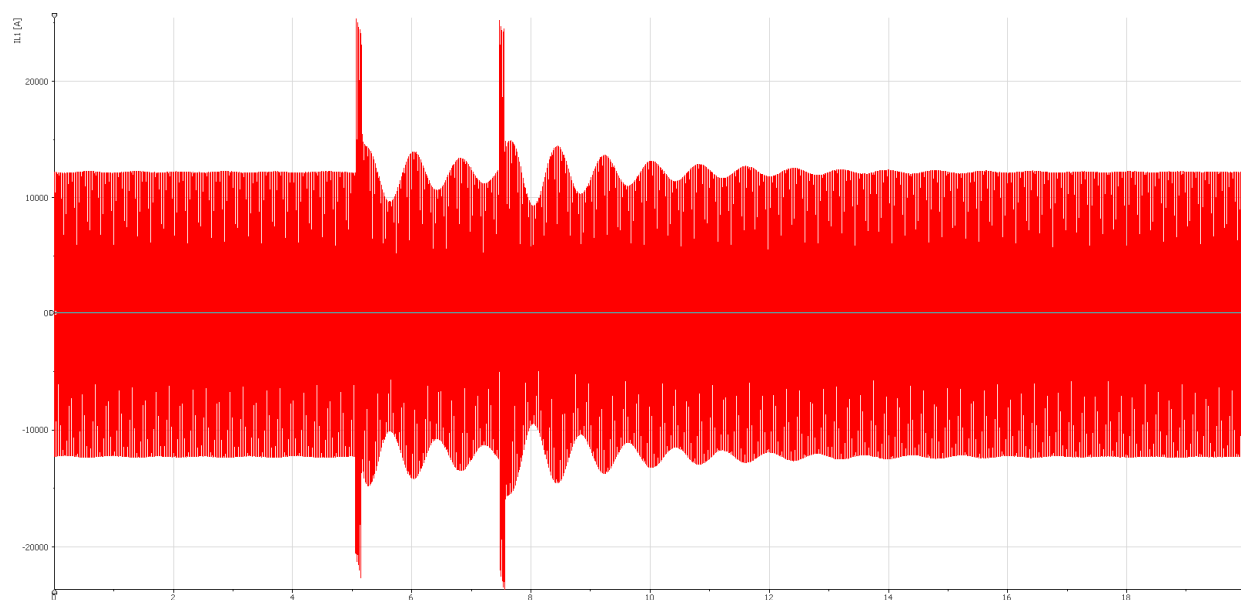- 14-bit ADC
- Li-ion battery

Fig. 20. TEP2 armature current transient caused by the short circuit on the power-line (5 s of pre-buffer time and 20 s of total signal time)
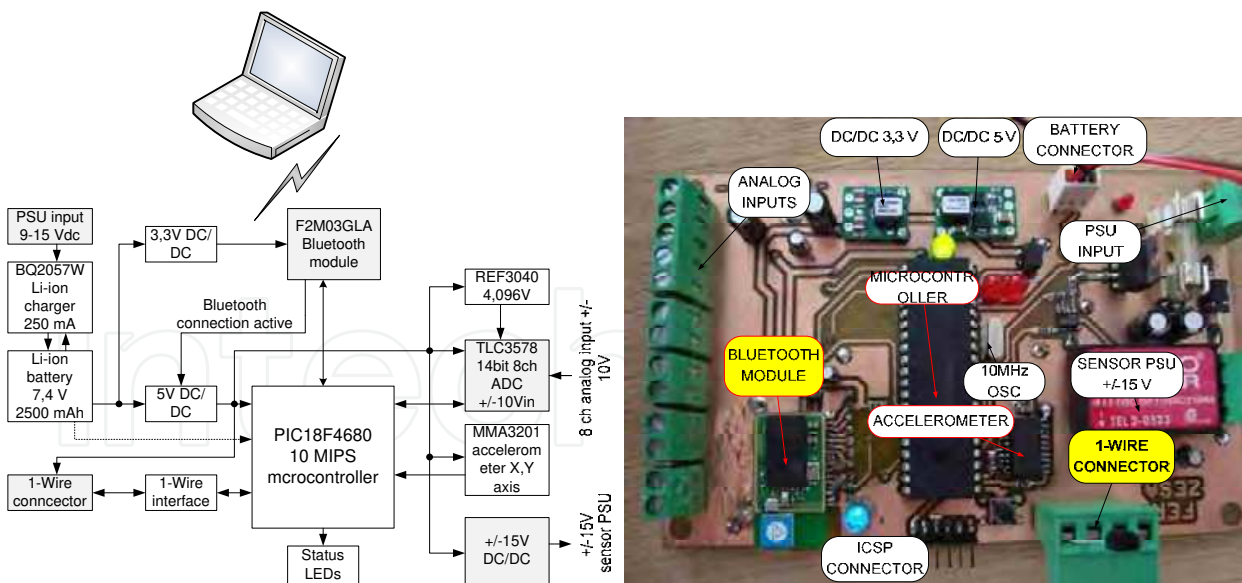

Fig. 21. Block diagram and PCB of the wireless measurement system

The heart of the measurement system is a microcontroller which routes data from the sensors to the Bluetooth interface. Each DS18B20 has a unique 64-bit serial code, which allows multiple DS18B20 to function on the same 1-Wire bus. A parallel connection of the sensors simplifies wire routing over the machine rotor. Routines for searching, addressing and reading 1-Wire temperature sensors are integrated in the embedded code of the microcontroller.

The Bluetooth module is connected with the microcontroller via a USART interface so the system acts as a virtual serial port on the host computer. It is advisable that the microcontroller has a pre-programmed bootloader, a part of software which enables updating of firmware in the rotation through the Bluetooth link.

Because the system operates on the rotating part of the machine it had to be battery supplied. An absence of the alternating magnetic field on the rotor side of the synchronous generator excluded the usage of coils for parasite battery charge. Instead, batteries can be charged via a DC/DC converter connected to the synchronous machine excitation. This procedure has to be performed with caution due to the high voltage spikes generated by the excitation system.

To save the battery, only the Bluetooth module has to be powered while the connection is inactive while all other circuits (microcontroller, sensor supply) should be powered after a successful Bluetooth connection to the host system is established.

The measurement system has additional features intended for future use, such as a 2-axsis accelerometer, an 8 channel 14-bit analogue to digital converter and a ±15V sensor power supply.

Data from all the sensors had to be monitored and logged on to the host computer. The GUI application sends commands to the measurement system via the Bluetooth and waits for its response. The time base of the measurement is generated by the host system. The application searches for sensors on the 1-Wire bus and monitors the temperature of each sensor. Temperatures of each sensor together with time base are logged in a textual file which is used for further analysis. The GUI application can also read the battery voltage and battery charge status via the analogue input of the microcontroller. After a successful sensor search, the application enters in the temperature polling mode. A small database which joins names to the unique 64-bit address of a specific sensor can be incorporated into the application. This way, it is easier to monitor temperature of each sensor during an experiment.

It can be useful if the application has an ability to render 3D temperature distribution over the surface. The 3D representation greatly improves visualization of temperature distribution, especially locations of the hot-spots. The 3D model of the salient, shown in Fig. 22 (right), has been drawn and imported in LABView using "3D Sensor Mapping Tool". Sensors were positioned on the same coordinates as on the real salient pole. Temperature distribution over the surface between sensors is calculated using interpolation.

The measurement system was mounted on the 400 kVA, 1000 rpm synchronous generator, Fig. 23. Because of the Bluetooth transceiver it had to be placed in a non metal case. It was decided that the measurement system would be mounted on a shaft using a custom made holder. It was mounted in such a way that centrifugal force pushes the plastic case of the measurement system towards the metal holder and provides reliable fixation. Balancing weights were mounted on the opposite side of the shaft to reduce vibrations.

After a successful installation of the measurement system prototype on the laboratory synchronous generator, various experiments have been conducted. Fig. 24 shows an example of a measurement recorded by the measurement system. The excitation winding was first heated in standstill and afterwards in the rotation.
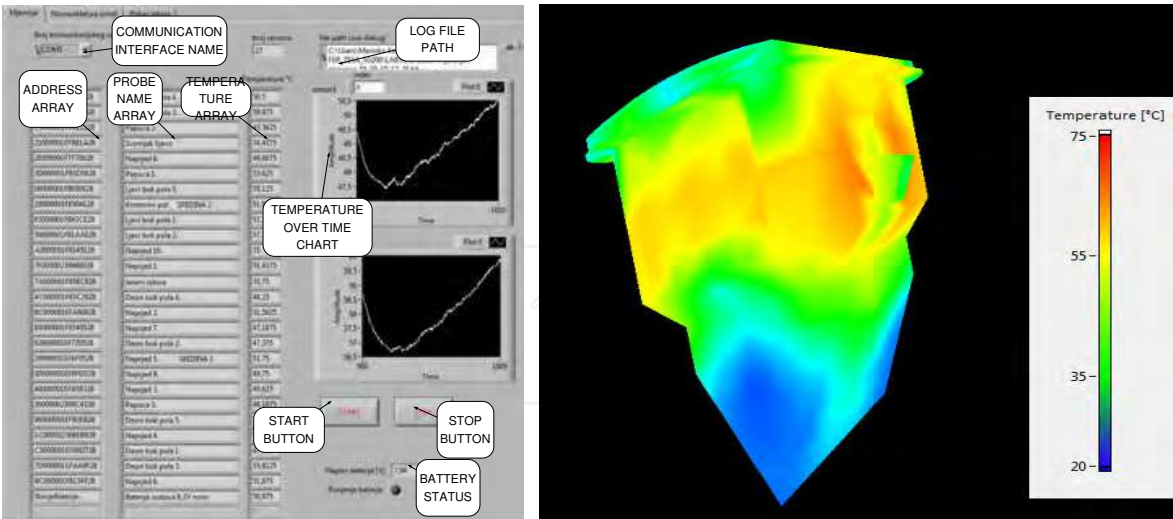
Fig. 22. GUI application and 3D temperature field representation

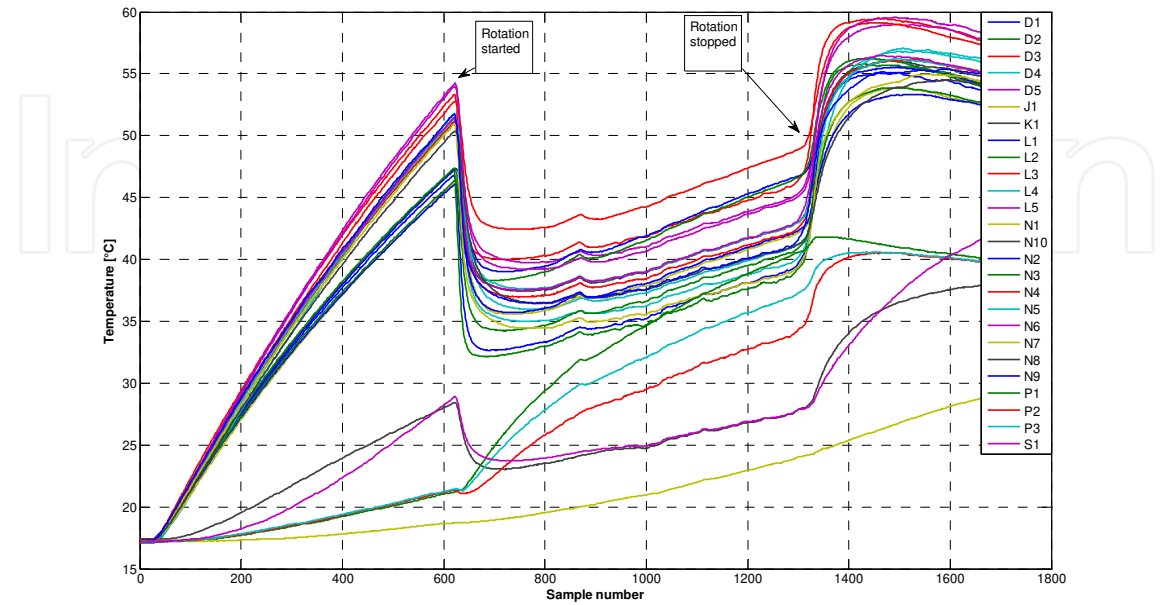Fig. 23. Mounting of the temperature probes (left); measurement system in rotation (right)

Fig. 24. Temperatures from 27 sensors placed on synchronous generator rotor (2 s sampling time)

6. Conclusion

Measurement systems described in this chapter show measurement of most of necessary physical quantities needed for proper rotating electric machine monitoring. Of course, measurement is not everything. A good monitoring system should be based on expert knowledge so that the monitoring system can give advice for maintenance. For large units such as synchronous generators monitoring systems are different for each machine. During the creation of such monitoring systems electric machine manufacturer should at least be present, because he did, during the design process, lots of modelling (analytically, with FEM etc.) and knows most of limitations of the produced electric machine. It would be the best if the manufacturer also produces such a monitoring system and has a permanent access to measurements. In such a way the manufacturer can improve his product, correct some flaws and optimize it.

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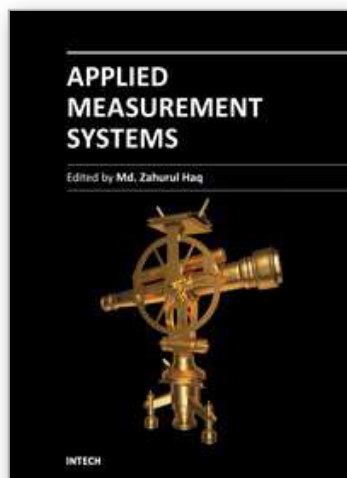
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Edited by Prof. Zahurul Haq

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