APPLICATION OF THE MOST RECENT MONITORING SYSTEMS IN HYDRO POWER PLANTS

ABSTRACT

The paper describes main reasons for refurbishment of hydro power plants and summarizes the most frequent works during refurbishment. A special attention is paid to the process of refurbishment of the electric equipment, in the first line generators and excitation systems, and integration of the most contemporary monitoring system. The paper talks about some of the methods of estimation of the generator operating life time as well as possibilities of an increase of the power and the efficiency of revitalised machines. The paper describes possibilities of replacement of existing excitation DC rotating system with new static or brushless excitation systems with digital voltage regulators. Possibilities of application of new contemporary monitoring system to the refurbished and rehabilitated generators are also described. The paper also describes possible rehabilitation and refurbishment benefits

Keywords: refurbishment, rehabilitation, hydro power plant, generator, excitation system, monitoring system, residual operating life time, stator winding insulation condition

1 INTRODUCTION

Construction of hydro power plants started at the end of the 19^{th} century. The first power plant based on the principle of the alternate current invented by Nikola Tesla was put into operation on the Niagara Falls in 1881. Since the moment, the hydro power plant construction technology has been successfully spread all around the world and today hydro power plants generate about 15.8 % of the total global generation of the electric energy. The size of units has been gradually increased from starting small powers of a few kilowatts during the time to current powers of several hundred megawatts. Refurbishment of equipment enables a continuance of the generation of the electric power from the water potential by existing power plants in a safe manner at an acceptable investment. Investments into refurbishment of existing plants are significantly lower than investments into new hydro power plants since civil engineering facilities do not require any reinvestment and their value amounts up to 80 % of the investment into a new power plant.

Practically speaking, refurbishment comprises all the parts of a hydro power plant including civil engineering parts of the facility (dams, tunnels, power houses, input and output buildings, etc.), hydro-mechanical equipment and electric and mechanical equipment.

2 MAIN REASONS FOR HYDRO POWER PLANT REFURBISHMENT

There is a range of reasons to refurbish a hydro power plant. The most frequent are obsoleteness and worn out condition of the equipment resulting in a gradual decrease of generation of the electric power during years and in a lowered profitability of the hydro power plant.

Refurbishment of a hydro power plant and its equipment should be considered in following situations: when the availability of units is decreased, if there is a possibility to return the equipment performance to the initial ones or to improve them, when significant changes of plant operating conditions or operating units have been faced, if there is a possibility to automate the plant, when the operating capacity of the plant is decreased, if large failures of the main equipment are faced requiring large investments, when the plant of the equipment cannot stand possible earthquakes, when spare parts are not available any more, if the equipment maintenance cost is significantly increased and plant operating cost are high or if the operational safety of the equipment cannot be guaranteed.

3 REFURBISHMENT

3.1 Plant and equipment condition assessment

To perform a high quality refurbishment, the condition of the complete plant and its most important elements should be assessed at the beginning.

The main causes of problems at the hydro power plant should be found out as well types of standstills, their frequency and duration. Load of the equipment, flows, temperatures and cooling systems should be checked up since all of them influence the operational life time of the equipment.

Changes that have happened since the moment of construction of the plant should be taken into consideration for planning of the scope of refurbishment, selection of new equipment, decisions on the increase of the output power or possible extension with a new unit.

3.2 Possible approaches to refurbishment

There are two main possible approaches to refurbishment having the following aim:

a) Extension of the hydro power plant life time;

b) Extension of the hydro power plant life time together with an increase of the output power or upgrade.

In the first case the existing equipment is replaced with new, more recent equipment while the plant output power remains the same. In the second case the existing equipment is being replaced with the new equipment with a higher output power. A detailed technical feasibility study is to be made for both cases as well as an economic profitability analysis of investment of additional assets into the increase of the output power regarding additional revenue generated by the increased generation during the extended life time of the refurbished hydro power plant.

3.3 Scope of refurbishment

A decision on a partial refurbishment of individual parts of the hydro power plant or on complete replacement is made on the basis of the condition of the equipment.

One of the important factors lobbying for the complete replacement of the equipment is its age. Some of the electric equipment features such as insulation are weakening during the time and it is hard to determine their changes by inspections and non-destructive testing. Therefore the safest thing to do is replacement of such equipment after a certain number of years.

3.4 Refurbishment of generators

Key parts when a refurbishment of a generator is in question are stator winding, rotor winding, stator core, exciter and losses. An analysis of the condition of all the generator parts should be made to assess the generator refurbishment scope. In addition to the condition of the stator and the rotor whose failures cause the longest standstills, a care should be taken on the condition of auxiliary systems that tear and wear during the normal operation such as slip rings, brake shoes, oil-water and water-air coolers that can also cause significant outages. A special attention should be paid to the replacement of parts that are possibly made of asbestos or similar materials whose usage is forbidden nowadays.

When the condition of a generator is being assessed, in addition to the electrical features, mechanical features of the machines should be estimated as well.

The generator stator winding is considered to be a key indicator of the condition of the generator. The majority of studies and expert literature are dedicated to the understanding of factors influencing the operating life time of the stator winding. Figure 1 shows that the largest number of failures of hydro generators is bound to the fails of insulation.

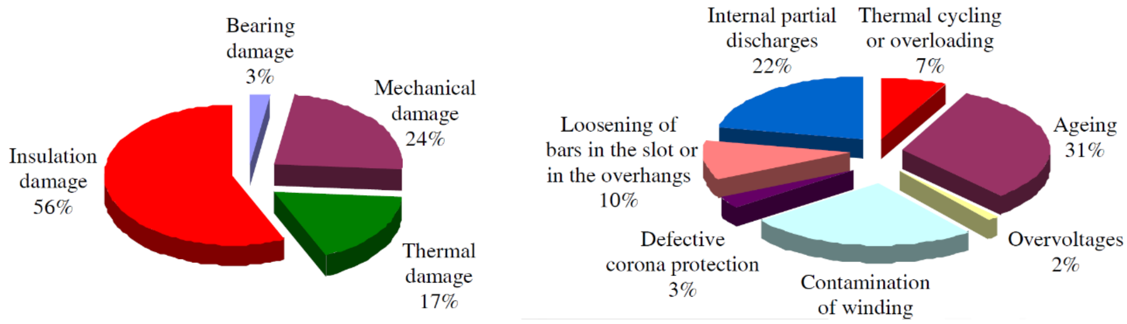

Figure 1 Damages of hydro generators (left) and root causes of insulation damages (right) [10]

Numerous longstanding generator standstills are caused by problems with bearings. Therefore the condition of existing bearings should be considered seriously as well. Existing bearings should be refurbished or reconstructed decreasing the possibility of their failure in the future. Oil and grease lubrication systems are bound to bearings. After a long time operation they can start leaking resulting in insufficient lubrication that can cause serious damages and environmental pollution. Therefore stated systems shall be necessarily refurbished and upgraded whenever it is possible.

Refurbishment is also a chance to replace existing DC or AC rotating machine exciters with technologically improved static excitation systems.

When the diagnostic tests are completed and certain calculations made, the complete condition of the existing generator can be estimated on the basis of collected data and a conclusion on the necessary scope of refurbishment and replacement of parts of the generator can be reached from the technical point of view. Economic circumstances of the referred project should be also taken into consideration to make a final decision on the stated scope of the refurbishment. It is clear that a complete replacement of the whole generator is the best solution, but it is also the most expensive solution as well and in some cases it has no economic justification. Other solutions understand a partial replacement of generator parts that depends on the above described analyses, economic circumstances, aimed operating life time of the refurbished generator, decrease of some risks, etc.

When a partial refurbishment of the generator is performed, a larger part of machine active parts or all machine active parts are almost always replaced:

- Stator winding – almost always
- Stator core – very often
- Re-insulation of pole winding – almost always
- Replacement of pole winding – sometimes
- Complete replacement of poles – often

A complete stator can be replaced additionally (and relatively often) or a complete rotor (rarely). The scope of refurbishment frequently comprises refurbishment of bearings, braking system, ventilation system, cooling system, etc. as well.

In addition to stated causes of refurbishment, effects of the refurbishment in the form of a possible increase of the generator power or in other words an increase of the generation of the electric power should be taken into consideration as well. More significant increase is possible if other parts of the hydro power plant allow that in the first line. The most important element here is the turbine that gives the necessary increase of power as well as the system that transmits the power into the gird (busbars, transformers, switches). Power increase is achieved through application of new windings having the insulation significantly thinner compared to the thickness of older insulations and therefore they can work at higher temperatures. Possibilities of the increase of the generator output power are described below in connection with replacement of some older insulation technologies with the most recent insulation technologies:

- From 1930 to 1955 lacquer and asphalt glued mica was used as insulation. When windings with modern insulation are used on generators manufactured before 1955, it is possible to increase the generator output power by 15 % if the same dimensions are kept;
- From 1955 to 1970 synthetic resins were gradually introduced for insulation with the improvement of the insulation from the class B to the class F. The output power can be increased from 7.5 to 10 % for generators manufactured between 1955 and 1970, since the thin "hard" F class insulation was not applied then;
- Since 1970 advanced polyester resins or epoxy resins have been applied to almost all the stator windings having the class F of "hard" insulation systems. For generators manufactured after 1970 minimum increases of power are possible decreasing the thickness of insulation and improvement of other insulation characteristics such as voltage gradients, thermal transfer, etc. [2].

In addition to the above stated increase of the generator output power, the power can be also increased on the basis of an improvement of the generator efficiency. Possibilities of the efficiency improvement depend directly on the decision regarding the scope of refurbishment, installed materials and optimization of the complete machine. We can say that the efficiency improvement is frequently connected directly to assets invested into the refurbishment. A more significant improvement of refurbished generator efficiency can be achieved by a decrease of losses in the iron and losses of the ventilation. New materials enable lower iron losses in the stator core compared to older generations of materials. When ventilation losses are being decreased the main challenge is decreasing of the cooling air flow without increasing of the temperature of machine active parts (stator and rotor windings). Such an approach can be generally applied to generators of middle / high speed (> 250 rotations per minute) designed with the old ventilation system concept. Potential of decrease of those losses when improving efficiency amounts up to 0.3 %. The typical total increase of the refurbished generator is from 0.2 % to over 1 %. In such a way the increase of the efficiency on projects in Scandinavia were the following: Imatra 7 HPP (Finland) over 1.5 %; Batfors HPP (Sweden) almost 1 % (0.98 %) [11].

3.4.1 Assessment of the residual operating life time of generator

Methods for assessment of the residual operation life of generators are mostly based on measuring, data on installed materials and calculations that require certain input data. In addition to input data on characteristics of installed materials, certain presumptions are also often taken into consideration not only regarding past events, but also regarding future events for making calculations.

Parts of the generator that are mostly subject to aging and that should be treated in a special way when the operating life time is being assessed can be divided into two basic "branches":

- Insulation (or more generally we can say active generator parts comprising stator winding, stator core and rotor winding);
- Mechanical parts or in other words rotational mechanical parts comprising pole cores, laminated rotor rim, rotor spider and shaft.

The spent operational life time of the insulation is determined by comparison of measured values to the previous condition (if we have previously measured values), analyses of collected data on passed operation of the machine and analyses of diagnostic test results.

Some of diagnostic tests of the stator winding are: measuring of the winding insulation resistance, measuring of the polarisation index, measuring of partial discharges per phase, visual inspection of the winding and finding out of corona effect traces on the winding, visual inspection and measuring of hardness of wedging of keys fixing the winding in the slot, measuring of the winding operating resistance, measuring of the loss angle of the winding insulation, measuring of the stator winding insulation capacity, measuring of the insulation output current during a linear voltage increase (Ramp Test), testing of the winding insulation with high direct voltage, testing of the stator winding inter-turn insulation with impulse voltage, checking of the winding insulation with high alternated voltage and a range of other measuring.

Useful information that can help to determine the condition of the insulations are for example the number of outages due to possible replacement of bars / coils, results of previously performed tests, findings of the user and similar.

The most frequent diagnostic tests of the stator core are: magnetization of the stator core and thermo-vision – seeking of stator core hot spots (damages of the insulation), stator core visual inspection – finding of any irregularities on the stator core (excessive ruggedness, stator core damages, damages on the stator core fixing system).

The most frequent diagnostic tests of the rotor winding are: measuring of the insulation resistance, measuring of the polarisation index, testing of the rotor winding inter-turn insulation, rotor winding high voltage tests, testing of the rotor winding inter-turn insulation with impulse voltage, measuring of rotor winding operation resistance, checking of the rotor winding insulation with high alternate voltage.

Mechanical tests are generally reduced to non-destructing tests of materials such as tests of welds and materials and finding of cracks. If any crack is found out, it shall be analysed in great details.

Nowadays the finite element method can be used for making of numerous mechanical calculations that can determine the residual operating life time of mechanically loaded parts on the basis of data on the material, previous loading of the material, features of the installed materials and expected loads in the future.

There are also several methods of assessment of the residual stator winding life time. The aim of the assessment is an exact determination of the term in which it is necessary to plan replacement of the winding that should not be earlier than when the replacement is necessary and that should not be later than a possible damage that could cause any unplanned standstills and costs.

One of the methods invented by Japanese authors is based on the residual breakdown voltage on the basis of which the residual life time is assessed. [9]

Other authors calculate the residual operating life time combining the influence of diagnostic measuring measured values, the total generator operating time, the number of starts and stops and applying certain statistic methods. [7]

Some authors consider that a complex analysis is necessary to assess the residual operating life time comprising a range of diagnostic tests due to a large number of insulation weakening processes that cannot be found out by only one type of diagnostic measuring. Some of insulation collapsing processes are slow, while some of them are very quick (for example damaging and sparkling due to vibrations), and the results of their diagnostic measuring can be similar. Besides, the real moment of an insulation breakdown does not depend on the weakened condition of the insulation due to aging process and other unfavourable processes only, but also on outside stressing factors coming from the environment and the grid such as over voltages and various transient phenomena. Under the circumstances when no additional outside stresses exist, even the significantly weakened insulation can survive a range of additional years without a breakdown. Some of processes leading into a breakdown such as for example end winding vibrations do not show significant changes of dielectric characteristics as long as no insulation braking and its breakdown happens. To assess the residual operational life time the experience in correct interpretation of diagnostic measuring results is of a great importance. [8]

It has been also proved that the design and the quality of the construction of the winding have also a significant influence on the winding operating life time [10].

A data base regarding the operation of the unit and results of various diagnostic measuring that can be provided for by the installation of a modern monitoring system has an important role in the assessment of the life time.

3.5 Refurbishment of the excitation system

Expected aims of replacement of the excitation systems are in the first line: replacement of obsolete equipment with new equipment that is at the level of state of the art technological and technical solutions, decrease of costs and simplification of maintenance, achievement of better generator behaviour characteristics, increasing of the flexibility of the plant and assurance of a higher operational reliability and availability.

Due to the obsoleteness of the solution, direct current or alternate current excitation systems are most frequently replaced with static excitation systems.

All static excitation system components are static, i.e. stationary. Static rectifiers, controllable or uncontrollable, deliver the excitation current directly to the excitation circuit of the main synchronous generator over brushes or slip rings. Rectifiers are power supplied by the main generator line up terminals (or by auxiliary busbars) over the excitation transformer or in some cases with the help of generator auxiliary windings.

Recent excitation systems fulfil significantly bigger task than a simple voltage governor since they comprise a significant number of regulatory, limiting and protection functions. Micro processing control systems enable not only the basic voltage regulation, but also logic and sequence control, monitoring and protection, diagnosis and signalling as well as communication. Systems are completely automatic, foreseen for crewless power plants and adjusted to the remote control from master control centres. The state of the art digital excitation systems also comprise solutions that could not be implemented into the old excitation systems as transient phenomena register, chronological event register; power system stabilizer (PSS), reactive power regulator (*Q*-regulator), power factor regulator (cos fi-regulator) and remote supervision of the excitation system operation.

Figure 2 New Končar excitation system of the synchronous generator at Varaždin HPP, Croatia

Requirements for the operation of the unit regarding the excitation system are frequently different from requirements before the refurbishment. First of all it refers to the following facts: units do not operate as basic, but as peak ones and it understands more frequent starts and stops, a wider range of reactive power regulation, requirement for a higher stability of the unit, as well as a higher influence to the stability of the electric energy system itself. All the listed requirements should be taken into consideration when a new excitation system is being designed. Possible new parameters of the synchronous machine should be also taken into consideration, especially when the output power of the generator is increased. The selection of the main technical characteristics of the new excitation system (nominal current, nominal voltage, maximum continuous excitation current, forcing factor, etc.) shall be coordinated with the data of the existing or a new synchronous machine.

In case a new excitation is implemented to the existing machine, the rotor circle insulation condition should be checked up due to applications of higher (peak) excitation voltages, and also due to the wave form of the excitation voltage caused by the directional thyristor preventing unwanted breakdowns. In some cases regulated slowed don increase of the voltage is applied (slowed down excitation) to decrease the speed of voltage increase on the insulation.

3.6 Installation of monitoring system

Regarding the time before the most contemporary monitoring systems, the data base with automatic reports represents a big step forward in the technology of recording of machine operation parameters. Only individual states of the interest had to be recorded earlier and the obtained data were subsequently compared. That hard work is done as a back ground process on a server computer today. You only have to click the mouse several time on the web application you will obtain relevant data such as number of operating hours of the generator, number of starts and stops, operating regimes of the machine, frequency of appearance of the vibrations, etc. on the basis of which the current condition of the machine can be assessed as well as its residual life time, time period by the following overhaul or the necessity of a repair or refurbishment.

In addition to the generator and the turbine the hydro power plant monitoring system can comprise the block transformer, switchgear, HV cables to obtain a complete image of the condition of the power plant.

Every modern monitoring system consists of 3 major parts:

1. a front edge, i.e. measuring sensors,
2. a processing unit for acquisition and processing of data from measuring sensors,
3. a server computer comprising the data base.

Sensors transform one physical unit into another and they can, but they do not have to comprise signal conditioning.

Signals are transmitted from sensors to the processing unit through cables. They are processed there and sent to the permanent data base in the server computer. The computer equipment development has enabled the processing unit to perform the role of the server including the data base as well in smaller systems. In such a manner the total costs of the system is further decreased.

The server computer is a central place for storage of all measured and processed values from processing units. During recent times, a web server is established on the server computer to enable the access to the monitoring system from any computer within the local area network. Application software should not be installed on each computer from which the monitoring system is going to be used, but a web application that communicates with the web server on the server computer is opened simply from the web browser. That means that simultaneous values of measured units can be examined over a web application as well as their trends in the real time or historical data, orbits and other presentations agreed pursuant special user specifications. More sophisticated monitoring systems have an integrated automatic report function that are periodically generated from the system and comprise important statistic data helping the user monitor the machine operation selected parameters. Automation of power plants that has also contributed to the development of the monitoring system enables a safer usage and control of the plant.

The main task of the monitoring system is permanent collection of data on the condition of the machine and alarming and/or trigging protection relays in case of more significant changes in the system. Alarming is usually performed at two levels out of which the first one represents a *warning signal* – meaning that the measured value has reached the set amount and that the machine can operate under such conditions for some time until the reasons causing sending of the warning signals are examined and a *danger signal* – meaning that any further operation of the machine can cause more significant damages and it is necessary to take measures to lower the value causing the danger or to stop the machine. When alarming is designed the care should be taken about differentiation of the level of warning and dangers under various operating regimes (start, operation, and stop).

Some of basic values supervised by the monitoring system are vibrations. Vibrations are monitored on all the important unit parts, radially (more rarely axially on the bearing housing) on two axis that are rectangular to each other in the direction of the water and in the direction turned by 90º from the direction of the water, radially on the stator frame, one measuring on each segment and additionally vibrations can be measured on the stator end winding fixing. Vibrations of rotating parts (the shaft) are also monitored in the form of radial relative movements of the shaft in relation to the bearing housing in two axis that are rectangular to each other. Absolute vibrations are usually monitored by piezoelectric sensors although the development of the technology has enabled also optical measuring of vibrations. Due to economic calculations such measuring is most frequently used only at points where conventional accelerometers are not applicable (mostly due to high voltage).

Vibrations alone are not sufficient for a high quality assessment of the conditions of a unit. Therefore other values important for recognising of faulty conditions of the machine are also monitored:

a) Speed of rotation that is measured by an inductive sensor and a marker that is used as a synchronisation probe for individual measuring, in the first vector measuring, among the other things;

b) Clearness and magnetic induction on the stator core due to identification of eccentricity and asymmetry as well as inter-turn short circuits on the rotor and the stator;

c) Shaft currents and voltages that can cause damaging of the bearing if not detected;

d) Continuous measuring of the load angle during the operation due to control and protection of the stability;

e) Partial discharges due to identification of the winding insulation and end winding insulation problems;

f) Temperature in the stator core and in bearing as well as optical measuring of the temperature on the HV equipment (where conventional sensors, thermal couples or Pt100 probes are not applicable);

g) Hydraulic values, in the first line pressures, levels and flows, that give the data on turbine operating parameters, and that can be a useful indicator of deviations of reference operating parameters of the generator;

h) Cavitation that can cause an increase erosion of the machine parts placed in the circulating channel;

i) Operational electric values of the machine such as powers, currents, voltages, power factors, etc. can be measured directly from the generator by appropriate equipment or more frequently transferred by agreed communication protocols from the control system (MODBUS, PROFIBUS, IEC104, etc.).

Contemporary monitoring systems are characterised by modularity not only of the hardware, but also of the software meaning that such a system can be installed at a minimum economic price at the beginning and it can be simply extended and upgraded with necessary modules as necessary. During refurbishment a new monitoring systems are usually installed or the existing ones are upgraded with new modules. The example of such upgrading is the refurbishment of Senj HPP when all the correct sensors were kept and incorrect ones were replaced with new sensors- The processing unit was kept, while the server computer was replaced with a more contemporary one together with the belonging software. The data base was kept with all the data up to date, while the existing application programme was replaced with a new web application.

4 CONCLUSION

Since a long time period has elapsed from the beginning of construction of the first hydro power plants and that the installed equipment has its operating life time, the equipment of a large number of plants has been and will be necessary to replace in the future with new equipment due to its obsoleteness and worn out condition. Refurbishment of any hydro power plant should result in a prolonged operating life time of the plant, improved safety and security of operation of the equipment, improved environmental protection and human health protection, advanced performance of the equipment adjusted to new operating regimes (increased power, increased efficiency, larger generation of the electric energy), improved reliability, increased availability, bettered monitoring of the operation of the machine and condition of the equipment, decrease of operating cost and decrease of maintenance costs.

The scope of refurbishment of generators varies from a case to a case and depends on the aims wished to be achieved by the refurbishment. In most of the cases, refurbishment results in the increased generator power and almost always in the increased efficiency of the generator.

Obsoleteness of the technology, expensive maintenance due to unavailability of spare parts and worn out condition of components resulting in a lower reliability of systems represent main reasons for the need of replacement and refurbishment of the excitation system. New state of the art micro processing excitation systems improve monitoring of the condition of processes, control and diagnostics. All the stated results in decreased operating costs and simpler excitation system maintenance.

Safer usage and control of hydro power plants are achieved by the application of a contemporary monitoring system enabling permanent monitoring of a range of operating parameters of the machine as well as monitoring of trends and changes of stated parameters. Development of higher quality sensors, probes and micro processing units enables maintenance of the machine in operation on the basis of its real condition found out with the help of monitored values and supported with characteristic processing and diagnostic tools. In such a way the maintenance and the control of the hydro power plant operating life is significantly facilitated.

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