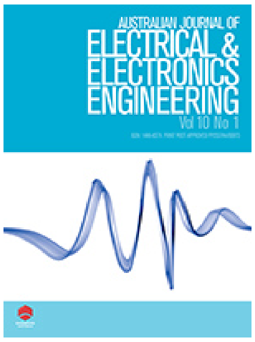

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Upgrading and Uprating of Hydro Generators: An Australian Perspective

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Upgrading and uprating of hydro generators: An Australian perspective*

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ABSTRACT: *Environmental concerns often preclude establishment of a new hydro generating plant. Hydro generators are still the main source of renewable energy that is available on a large scale. They are eminently suitable for peaking duty, which often provides attractive returns to the power utilities in privatised electricity markets. Many power utilities therefore resort to upgrading and uprating their ageing generating plants. The hydro generators designed and built around the middle of last century were generously sized by today's standards, and generally permit significant increases in machine output, when contemporary material technology and engineering designs are utilised. Large electrical machines were never manufactured in Australia, and thus locally based practical engineering design experience was never evolved. Over the last 30 years the author has researched and developed a unique domestically based engineering design knowledge and expertise required to test, analyse, redesign and upgrade/uprate existing Australian hydro generators. This paper outlines the approach and general engineering methodology the author has used to upgrade and uprate numerous hydro generators. The hydro generator life span and life cycle are considered, and the scope of possible upgrading and uprating is outlined. The methodology for hydro generator uprating is described, including generator data collection, pre-uprate generator performance testing, electromagnetic and performance analysis, and contents of the final design output.*

KEYWORDS: Hydroelectric generators; power generation; rotating machines; synchronous generators.

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1 INTRODUCTION

About 17% of global electricity is generated from hydro-power, which is still the only commercially viable renewable energy produced on a large scale (Hydro Power Upgrading Task Force, 2001). Only about 33% of earth's hydro potential has been developed so far, and given the increased environmental awareness and scrutiny, it is most unlikely that much of the world's available hydro potential will ever be realised. The ageing Australian installed hydro generating capacity of approximately 7600 MW is typically 30-60 years old and approaching its half-life refurbishment. Most of the generators of that vintage were generously sized by today's standards, and offer an opportunity for uprating of their output as part of the refurbishment process.

Considering environmental constraints, the uprating of existing hydro generation plants is the easiest and cheapest way of obtaining extra generation capacity, without embarking on a costly and uncertain environmental approval process. Uprated output, and in most cases increased plant efficiency can be obtained at a fraction of the cost of a new plant. Analysis of figures shows this cost to be in the order of 10% to 12.5% when compared to the cost of new plant installation (Hydro Power Upgrading Task Force, 2001; Blacken, 1997).

Government incentives for additional renewable energy generation capacity are available in most countries.

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Unlike thermal power stations, which need considerable time to be brought on-line, hydro generators are eminently suitable for peak power supply, since they can be brought online in a matter of a few minutes. This then provides an opportunity for hydro generation utilities to sell their power at a premium price, as they have the energy available when it is needed and at very short notice. Extra generation capacity in such situations makes a big difference in generation utility revenues, and provides easily justifiable impetus for machine refurbishment, upgrades, and uprates.

For the purposes of this paper, "upgrade" means bringing the hydro generator components or systems up to the contemporary standard, while "uprate" means increasing generator power output.

2 HYDRO GENERATOR LIFE SPAN

Hydro generators are extremely durable, and machines of up to 100 years of age can still be found in operation. Any human creation will begin to deteriorate the moment it is put into service, and will eventually cease its useful life due to a variety of degradation mechanisms it is exposed to. Hydro generators are no exception, and machine operators usually refer to the machine "half-life" and "end of useful life" (Blacken, 1997).

Depending on the robustness of its original design, and rigors of its operational life, the hydro generator half-life may be reached after 30 to 60 years of its operation. Generator half-life is indicated by the complete loss of functionality of all or some of its active electrical components (stator or rotor field winding), and/or static mechanical components (stator core and stator frame). This is most common, and a most opportune time to carry out hydro generator upgrading and uprating while conducting extensive generator refurbishment. This will usually extend generator functionality for the "second half-life".

The end of a hydro generator's useful life occurs at the end of its second half-life, and is indicated by complete failure of active electrical components, static mechanical components, as well as rotating components (rotor rim, rotor spider, etc.).

3 HYDRO GENERATOR OUTPUT COEFFICIENT

Since the early days of large scale commercial exploitation of electrical machines at the beginning of the last century, many authors and analysts have measured the progress in machine development by the so called "output coefficient". When related to any machine, the output coefficient gives the relationship of the machine output versus its physical size. In the case of hydro generators the output coefficient is given as the ratio of apparent power output versus the generator's physical size and speed (number of poles) (Walker, 1981), ie.:

$$\xi = 10^{12} \frac{S_{gen}}{D_g^2 L_c N} \tag{1}$$

where ξ is the generator output coefficient; S_{gen} is the generator output capacity (apparent power) [MVA]; D_g is the inside diameter of stator core [mm]; L_c is the gross stator core length [mm]; and N is the generator rated speed [revolutions/minute].

According to data presented by Glew (1998), the electrical machine output coefficient has increased 12 times in the last 85 years, or 4.2 times in the last 33 years. This was mainly due to advances in electrical insulations and magnetic core materials. Figure 1, reproduced from Glew (1998), illustrates quite amazing progress with high voltage insulations,

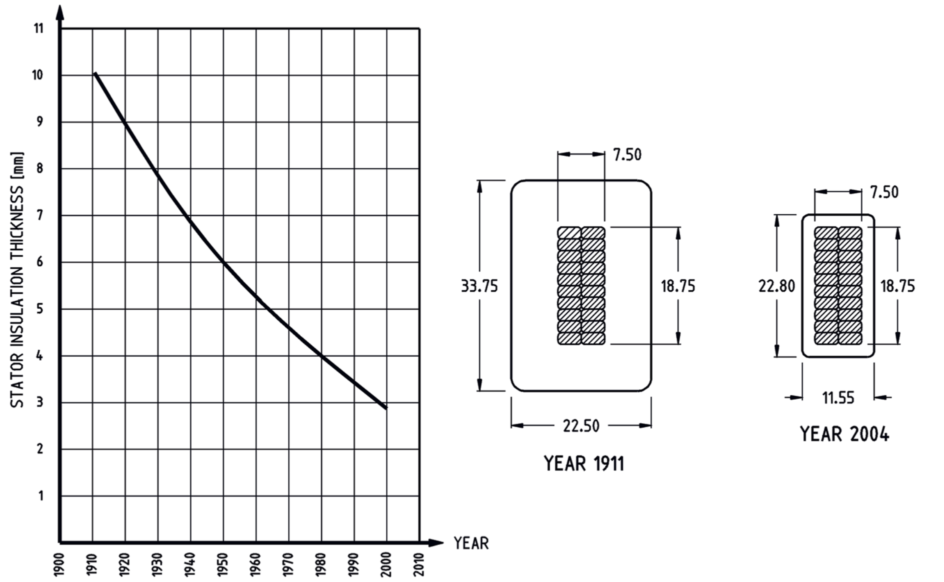


Figure 1: Decrease of high voltage ground insulation thickness during the last century.

particularly reduction in insulation thickness over the last 100 years.

Examination of figure 1 indicates that the possible magnitude of generator output uprate will be approximately inversely proportional to its age. The author's experience concurs with the above. In general, the author has found that 40-50 year old machines can almost always be uprated by 20%-30%, whereas older more generously sized machines will permit uprates of up to 50%. In most cases hydraulic system limitations will preclude higher uprate magnitudes.

4 HYDRO GENERATOR LIFE CYCLE

The life cycle of any machine can be represented by a classical bath tub curve, comprising early life, useful life, and wear-out stages (refer figure 2). Wear-out stage immediately precedes refurbishment and upgrade activities. During this period the machine becomes less reliable with service and is characterised with lower machine profitability and increased maintenance requirements. As described earlier, the end of wear-out stage for a hydro generator is symptomatically evident by loss of functionality of vital machine components, either at half-life or end of useful life stages.

The hydro generator wear-out stage can be statistically monitored and analysed using forced outage rate or total incapability factor methods presented in Hydro Power Upgrading Task Force (2001).

Statistical analysis for both methods should be carried out for at least 10 years approaching the wear-out stage, with the upward bend in the curve indicating its commencement. Forced outage rate provides an indication of the time the generating unit was forced out of service, while the incapability factor incorporates additional complexity of the maintenance and planned outage states.

Upward bending of the wear-out state of the bath tub curve will usually trigger refurbishment and upgrade feasibility studies, although some authors (Blacken, 1997) have proposed that economically justifiable upgrading and uprating projects could be carried out even on 20-30 years old machines, which are still in their useful life section of the bath tub curve.

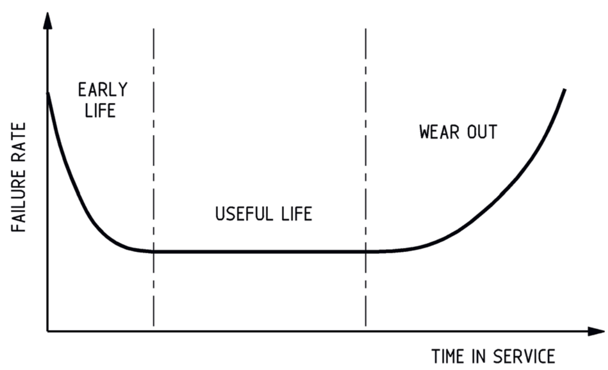


Figure 2: Machine life cycle bath tub curve.

4.1 Assessment of hydro generator condition

Having established that the generator is well into the wear-out stage, thorough assessment of its condition is necessary as a precursor to upgrade feasibility studies. Upgrade feasibility studies in the large part deal with economic justification of generator upgrade costs, and will not be covered in this paper. A very good tool for hydro generator condition assessment was provided by Hydro Power Upgrading Task Force (2001) and is titled *Multi-Factor Condition Assessment of a Hydroelectric Generator*. The author has used this tool for assessment of numerous hydro generators' conditions.

5 SCOPE OF HYDRO GENERATOR UPGRADE AND UPRATE

Depending on machine condition assessment, level of required output uprate, and economic and commercial issues, the scope of a hydro generator upgrade and uprate may include uprated stator winding, re-insulation of rotor field excitation winding, new stator core, upgrade to static excitation system, provision of digital turbine governor, stator frame modifications, rotor rim modifications, generator bearing upgrades, improvements to the cooling air circuit, and provision of additional condition monitoring equipment.

5.1 Uprating stator winding

Advances in insulation technology over the last 35 years and in particular the change from "thermoplastic" organic binders to the "thermoset" synthetic epoxy systems provide the largest scope for hydro generator output uprates.

Continuous development of synthetic epoxy resins made it possible to produce insulations which can be exposed to much higher dielectric stresses (Draper & Moore, 1997; McDermid, 1997). In addition, due to their increased density, homogeneity, and reduced thickness, the new insulations have much better thermal conductivity/heat transfer properties, resulting in enhanced heat dissipation and reduced winding temperature rises. The new insulations also possess higher thermal rating (Class B 130 °C for thermoplastics versus Class F 155 °C for thermosets) (Harder, 1999).

Typically, thermoplastic insulations produced mid-last century were designed with voltage stresses to ground of 1378-1575 V/mm (35-40 VPM), while new generation insulations' standard designed voltage stress to earth is between 2560-2756 V/mm (65-70 VPM). For typical 11 kV coil, where voltage to ground is 6.35 kV, the ground wall insulation thickness has typically decreased from 4.6 to 2.48 mm, ie. the ground insulation thickness has reduced to approximately 54% of the value used with thermoplastic systems. The better quality of the turn to turn and strand to strand insulations has also resulted in reduction of their thickness (refer to figures 3, 4 and 5). Reduction in insulation thickness provides an opportunity for high voltage coil designs of substantially increased coil winding copper content, with marked reduction in winding DC resistance and a resulting decrease in DC I^2R losses. The author has often found that increases in copper CSA of up to 40% are possible for machines produced mid last century. This means that machine upgrades of up to 30% may be possible without exceeding the stator winding copper losses and temperature rise at a machine's originally rated output.

During the new winding design process, further substantial reductions in extra copper losses (strand eddy current losses, and circulating current losses) can be achieved by appropriate sizing of copper strands and implementation of winding transpositions (Lyons, 1930; Summers, 1927). In most cases these loss reduction techniques may not have been available or implemented at the time of original winding production (Gentilini, 1977).

With machine uprates approaching 50%, the new winding losses and temperature rises will be higher when compared to the original machine. Given that most of the hydro generators employing thermoplastic insulation systems were designed with a 60 °C temperature rise, the author has never needed to exceed a 80 °C temperature rise, even for the windings of machines being uprated by up to 50%. The commonly accepted opinion among hydro generator operators worldwide is that the Class B temperature rise for the stator winding should not be exceeded, and that requirement is often part of hydro generator upgrade and uprate specification.

Further subtle enhancements with stator winding uprate design may involve changes to a higher number of parallel circuits for reduction of unbalanced magnetic pull. If a new stator core is part of the

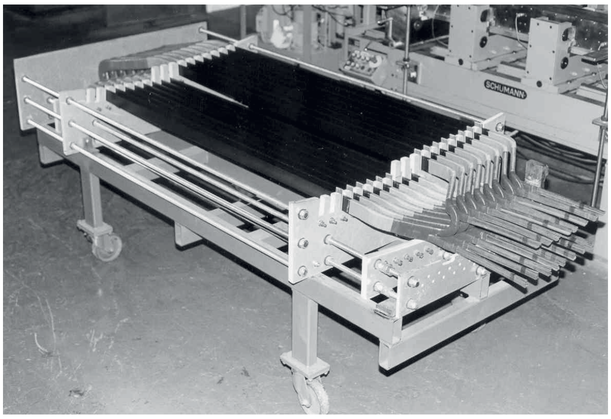


Figure 4: New hydro generator high voltage coils.

Figure 5: Hydro generator rewind uprate from 44.444 to 50 MVA.

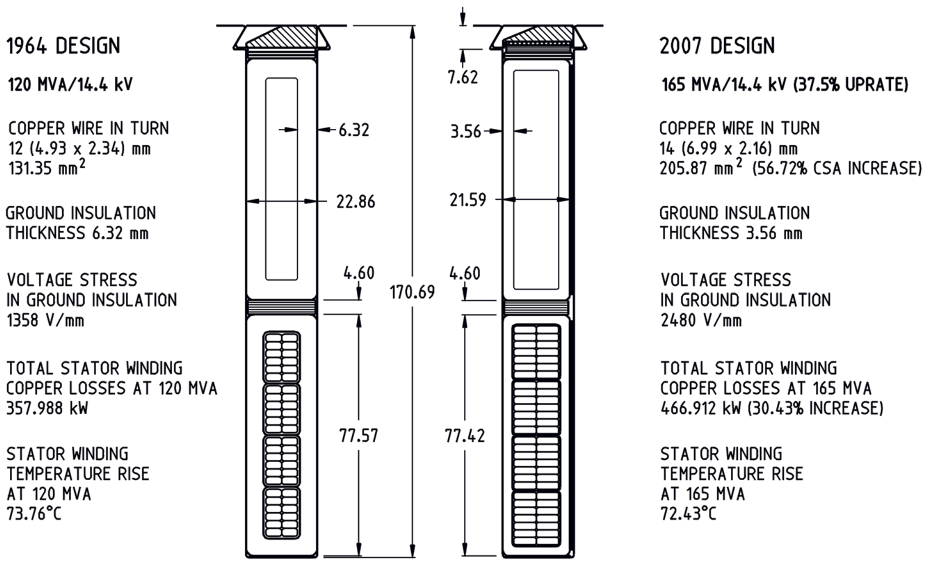


Figure 3: Comparison between old and new insulation technology.

generator upgrade, the opportunity may be taken to employ a winding with fractional slotting for reduction of harmonics.

5.2 Re-insulation of rotor field excitation winding

The field windings designed mid last century operated with 40-50 °C temperature rises, while employing Class B turn-to-turn and ground insulations. The hydro generator uprate will invariably involve a higher excitation current, but the increase in excitation current is not directly proportional to the amount of machine uprate as is the case with the stator current. Depending on the machine configuration, the author has found that even for uprates of 50%, the increase in excitation current requirement is in the order of only 20%. In all cases encountered so far, the author was able to use existing field windings, which required only re-insulation with Class F insulation materials (refer to figure 6). The re-insulated windings never exceeded a 80 °C temperature rise, even for the highest level of hydro generator uprates. Asbestos abatement provides secondary impetus for field coil insulation upgrade, since all field coils manufactured mid last century contained at least asbestos turn-to-turn insulation, which is no longer acceptable. Further to that, re-insulation of field coils is mandatory if static excitation equipment is being implemented, since DC excitation current produced by static inverters contains steep voltage gradients which may overstress field coil turn-to-turn insulation, particularly end turns of the end coils (Blacken, 1997).

If efficiency improvements are a higher order of priority, the rotor field coils may be partially remanufactured or fully replaced. Partial remanufacturing may involve replacement of a certain number of field coil turns with wider copper sections so that extra cooling fins are created. This will further reduce field winding operational temperature and I^2R losses, thus making a small contribution to increasing the machine efficiency. The full replacement of field coils will take this one step further, since copper content and geometry of a field coils can be fully optimised in line with contemporary engineering practice and full utilisation of modern insulation materials.

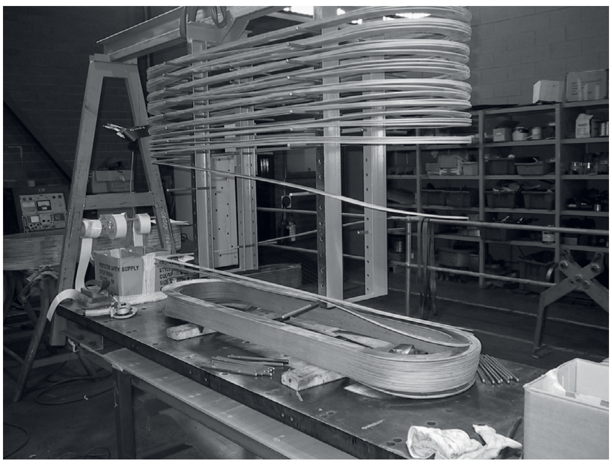


Figure 6: Re-insulation of rotor field poles.

The last thing to consider is optimisation of inter-polar cooling air space by the addition of displacement fillets for better direction of cooling air flow (Blacken, 1997).

5.3 Provision of new stator core

Quite often 50-60 year old stator cores will be in an advanced state of deterioration, and a new stator core may be specified as a part of the hydro generator upgrade process. Since stator core losses are among the machines highest, the new stator core manufactured from modern low loss materials may significantly contribute to the overall machine loss reduction, and hence improved efficiency. For machines built 50-60 years ago, Epstein test losses were in the order of 5-6 W/kg, whereas modern materials are typically 2.5-3.0 W/kg. Since the stator winding is embedded into the stator core, lower core losses and lower core temperature rises will also result in lower stator winding temperature rise.

Additional reductions in core losses are achieved by contemporary stator core design incorporating core end support fingers, and radial air duct separators manufactured from austenitic (non-magnetic) stainless steel.

Substantial improvements in stator core cooling are implemented by changing the number and size of stator core radial ventilation ducts. Older machines were built with a certain number of 10 mm wide radial ventilation ducts. The contemporary stator core design practice favours 6 or 8 mm wide radial ventilation ducts. A typical hydro generator stator core 1,300 mm long would have approximately 25 radial ventilation ducts 10 mm long. This is now typically replaced by 41 radial ventilation ducts 6 mm long. This results in about a 64% increase of radial ventilation duct cooling surface area, while still maintaining the same effective stator core axial length and machine flux densities.

New stator cores are built with C5 grade core plate, which provides durability at elevated temperatures. Due to its reduced thickness when compared to older type core plate insulations, it may provide some further small improvements in core losses, since the effective core length may be increased within boundaries of existing core parameters, leading to a slight reduction in machine flux densities and core losses.

When replacing a stator core, which is always installed at site (refer to figure 7), the opportunity is always taken to specify a continuously stacked

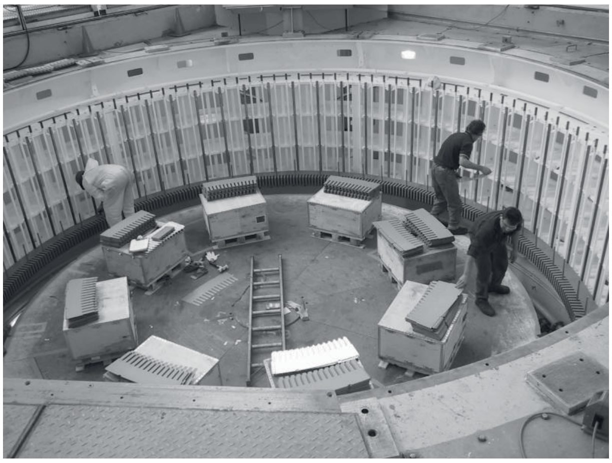


Figure 7: On-site installation of new stator core.

core, rather than a segmented core used in the past, which commonly provided operational troubles due to uneven thermal expansion ("clover leafing"), deviation from bore circularity, uneven air gaps, unbalanced magnetic pull, vibrations, and arcing and shorting of core laminations at the joints.

Further opportunities may be taken to optimise stator core slot shape relative to extra copper loss issues (cross slot leakage fluxes), and sometimes to change machine reactances if required. The shape of the slot wedge groove may also need changing to accommodate modern slot wedging systems.

Finally, an opportunity may be taken to change the number of core slots, by employing fractional slotting for the reduction of higher order harmonics. Some machines built at the beginning of the last century did not incorporate this feature, since the theory behind its functionality was not fully understood at that time.

5.4 Upgrade to static excitation system

Replacement of old style rotating exciters with new generation static excitation inverters is almost standard practice for most hydro generator upgrades and uprates. Undisputable advantages achieved are a reduction in maintenance efforts and costs, and improved reliability. The new solid state systems are considerably more efficient, since there are no windage and friction losses associated with rotating equipment, as well as weight reduction of the rotating assembly. Common mechanical vibration problems associated with rotating exciters mounted at the end of the hydro generator shaft are also eliminated. The most important advantages of modern static excitation systems, however, are much faster control action responses (IEEE Committee, 1973; 1981; Dandeno et al, 1968), which provide good generator stability right through the complete area of a somewhat compromised upgraded generator reactive capability chart (IEEE, 1990).

Rotor winding re-insulation and upgrade to static excitation systems are almost always accompanied

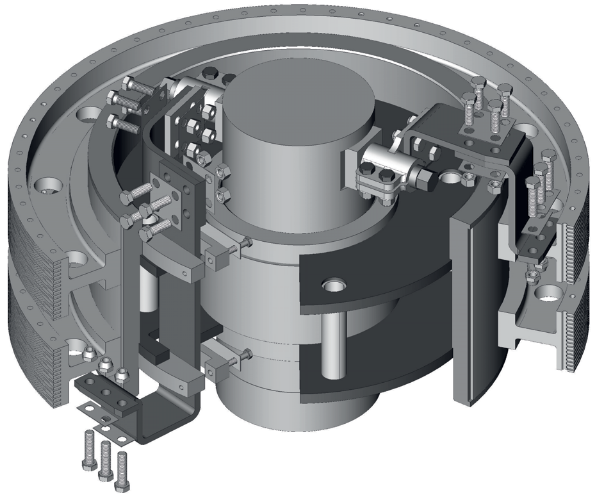


Figure 8: 3D assembly of uprated slip rings for 200 MVA hydro generator.

by redesigned and uprated rotor slip rings, which are capable of carrying additional excitation current without overheating (refer to figure 8).

5.5 Provision of digital turbine governor

Conventional mechanical turbine governors are often replaced with new generation digital governors. Among the advantages are reliability improvements and reduced maintenance requirements, enhanced response by utilising more complex control algorithms, increased reserve response, and enhanced ability to tune the control to achieve stability limits and maintain this tuning (IEEE, 1988).

5.6 Stator frame modifications

If the uprated machine having hard fixed stator frame sole plates is expected to operate with increased temperature rises, consideration should be given to a change to special keyed sole plates to provide for even stator frame thermal expansion at its top and bottom sides. On some machines problems were encountered where constrained uneven stator frame expansions reflected the same way on stator core thermal expansion, leading to stator core degradation and relaxation.

5.7 Rotor rim modifications

Increased uprated generator temperature rises may lead to additional rotor rim thermal expansion, and possible loosening of rotor rim fit relative to the rotor spider. It is often necessary to examine tightness of this fit, and in some cases to refit the rotor rim with increased interference shrink fit, which will not loosen in operation at the new level of machine temperature rise.

5.8 Generator bearing upgrades

New technology utilising PTFE (Teflon) coated thrust and journal bearing pads is fast gaining momentum.

Due to the lower frictional losses and higher permissible operating temperatures, PTFE bearing pads permit higher thrust bearing loads with reduction in frictional losses, and noticeable improvements in generator efficiency. Other advantages are total insulation of rotating members for reduction of shaft bearing currents (PTFE is an insulator for electrical current), a high pressure oil lifting system is no longer required, and possibilities of catastrophic bearing failures due to white metal wiping are greatly reduced. With conventional white metal bearings, rotor braking was necessary at about 20% of the rated speed due to instability of the oil film at that speed and the possibility of bearing damage. PTFE bearings permit commencement of braking at about 10% of the rated speed, thus reducing stator winding contamination by brake pad dusting (Blacken, 1997).

5.9 Improvements to the cooling air circuit

Technological advances in manufacturing air to water generator coolers result in improved efficiency of their operation, ie. a higher amount of heat extraction from cooling air, with the same amount of cooling water flow. Air flow can be adjusted by setting appropriate angles to the rotor mounted fan blades, and advances in fan technology and 3D finite element analysis provide for increased rotor mounted fan efficiencies by advanced modelling of aero foil shape. Auxiliary fans, controlled either by generator load or winding temperatures, can be added for maintenance of optimum air flow through the machine. Additional control of machine temperature can be achieved by automatically controlled valves fitted into the cooling water circuit. It is well known that operating a generator at too low a temperature can also be detrimental to the insulation life, mainly due to the possibility of moisture condensation on exposed winding surfaces.

5.10 Provision of new condition monitoring equipment

With advancements in electronics, the condition monitoring equipment has evolved to a higher level of sophistication, while becoming more affordable. It is a common requirement of generator upgrade specification to add a substantial number of condition monitoring sensors, such as increased number of temperature sensors for stator winding, stator core, cooling air, bearing pads etc., and more sophisticated bearing vibration analysis systems. In addition, partial discharge capacitive couplers for on-line monitoring of partial discharges have become a standard requirement. In some cases air gap monitors may be fitted for continuous monitoring of air gap shape and short circuits in the rotor field winding.

6 EFFECT OF STATOR AND ROTOR WINDING UPRATING ON GENERATOR POWER CHART

Synchronous generator reactive capability curves (also known as operating or power charts) (Brosan & Hayden, 1966; Adibi & Milanicz, 1994; Nilsson & Mercurio, 1995; Panvini & Yohn, 1995), define the allowable spectrum of machine operation without exceeding the designed operational temperatures, mechanical stresses, and allowable electrical loadings. For any point within the capability curve area, the relationship is defined between active (MW), reactive (MVAr), and apparent (MVA) powers, power factor, stator current, and excitation current (refer to figure 9). The load angle δ can also be determined by measurement. Operation anywhere outside of the reactive capability curve area may lead to machine overloading or instability.

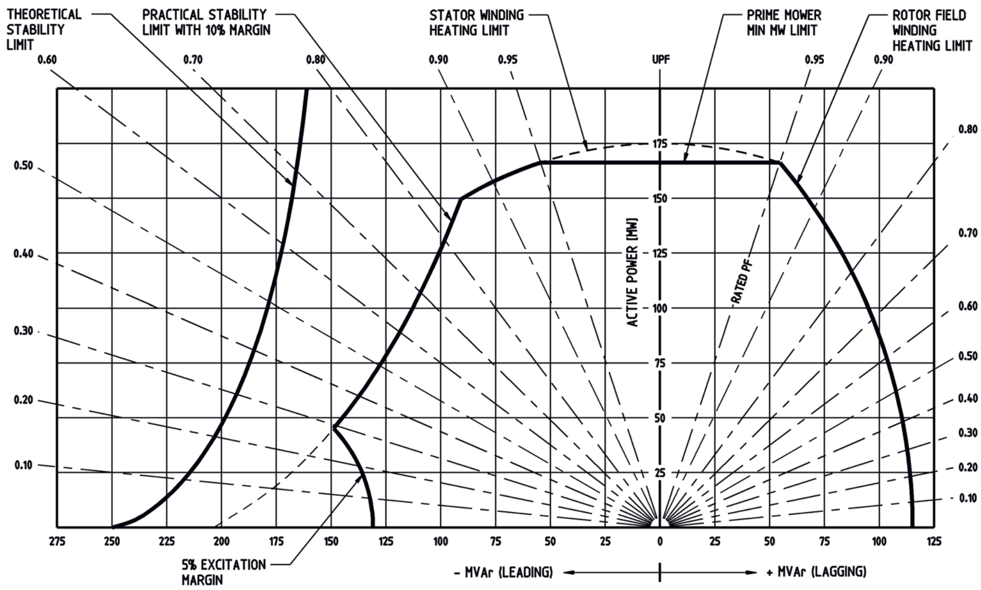


Figure 9: Typical hydro generator reactive capability chart.

The area of generator reactive capability is enclosed by the limits of field excitation current (rotor heating limit), stator current (stator heating limit), minimum prime mover power, stability limit for leading power factor operation and under excitation limit.

Figure 10 provides a rather interesting visual feedback on how stator and rotor winding uprates reflect on the machine reactive capability diagram.

An uprate of the stator winding alone will provide higher MVA capability, but without additional reactive capability the machine may need to operate at a higher lagging power factor (figure 10(a)). An uprate of rotor winding alone will provide extra reactive capability, and the machine will be able to operate at lower lagging power factors, without any increase in MVA capability (figure 10(b)). An uprate of both stator and rotor windings, will increase generator's apparent and reactive power capabilities, and in most cases the machine will be able to continue to operate with the original rated power factor (figure 10(c)).

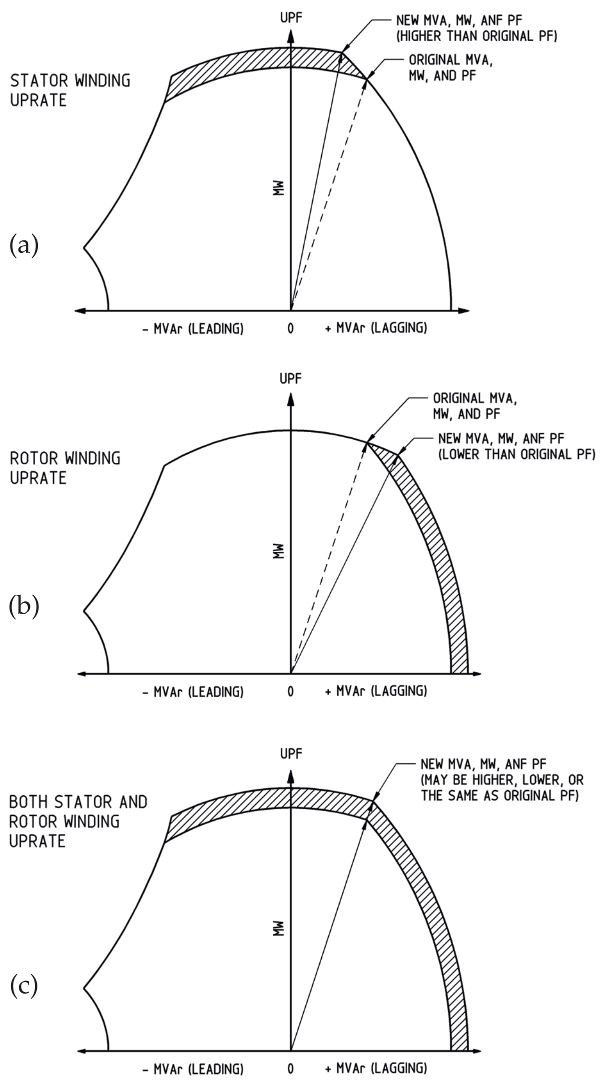


Figure 10: (a) Uprated generator reactive capability diagram, stator winding uprate; (b) rotor winding uprate; and (c) both stator and rotor winding uprates.

7 METHODOLOGY FOR HYDRO GENERATOR UPRATING

The methodology the author has successfully used for numerous hydro generator upgrades is outlined below. It essentially consists of generator data collection, on-site generator performance testing, complete machine electromagnetic and performance analysis, and final design output.

7.1 Generator data collection

This is often a rather problematic part of the process. With machines commonly more than half a century old, a lot of original information may have been lost or never provided by the original equipment manufacturer (OEM). What is required is as much machine OEM data as possible, such as manufacturing drawings, machine description, operational instructions, etc. A real "prize" for an uprate designer is if original machine performance testing and commissioning data can be found. If the machine was assembled and tested in the factory before installation, which is often the case, good accurate data will exist relative to the original machine parameters (reactances and time constants), losses and efficiencies, temperature rises, etc.

Recent operational data from the generator should be requested from the machine operators. The most important data are operational temperatures for stator and rotor windings, and field excitation parameters at various loads and power factors. These data are usually recorded by station SCADA (supervisory control and data acquisition) systems, and are readily available in the format that is easily graphed and analysed by computer software.

If the generator is available for a few days, an opportunity may be taken to carry out thorough physical inspection and data collection. This will confirm the accuracy of the data given on OEM's drawings, and may highlight some peculiarities or degradation modes and mechanisms that the upgrade designer should be aware of. Often generator upgrade tenders place full responsibility for machine data accuracy onto the upgrade tenderer, and in such cases physical machine data collection and measurements are mandatory as a contractor's risk mitigation measure.

7.2 Pre-uprate generator performance testing

With most hydro generator uprates carried out so far, the author has insisted on carrying out pre-uprate generator performance testing, often referred to as "footprint testing". This testing establishes a snapshot of the machine condition and performance "as found", and can often indicate inherent problems the machine designer should be aware of. The footprint testing is usually of 2-3 days duration, and involves most performance tests that will be carried out during the post uprate final commissioning, so that a good comparison of machine performance before and after uprate can be derived.

Another important design input derived from pre-uprate testing is a record of the machine thermal performance, particularly of the stator and rotor winding temperature rises at various loads. Since machine temperature rises are notoriously difficult to predict even with the most rigorous analysis, the trend in temperature rises derived from tests is always used for comparison with calculated empirical values, and extrapolation for the new rating (refer figure 11).

The pre-uprate generator performance testing will include at least the following (IEEE, 1995):

- open circuit saturation and short circuit impedance curves
- load rejection tests (at ¼, ½, ¾ and full load)
- heat run test (at ¼, ½, ¾ and full load), with comprehensive temperature trend monitoring of stator winding, rotor field winding, bearings, cooling water, inlet and outlet cooling air, exciter temperatures, etc.
- governor tests (frequency excursion and governor accumulator cycle)
- mechanical vibration footprint
- hydraulic component tests (wicket gate forces operating times and leakage, turbine head cover pressures, etc.).

7.3 Electromagnetic and performance analysis

Based on physical machine data and results of pre-uprate performance testing, the complete original machine electromagnetic and performance analysis is carried out.

The machine parameter and performance analyses are carried out for steady state and fault conditions. The comprehensive analyses output includes machine electromagnetic relationships, derivation of machine parameters (reactances and time constants), prediction of temperature rises, and computation of machine losses and efficiencies. The original machine characteristic curves are computed, including open circuit saturation and short circuit impedance curves; Vee curves; short circuit decrement and three-phase sudden short circuit waveforms; generator efficiency curves; voltage regulation curves; load saturation curves; synchronising power curves; and generator reactive capability diagram.

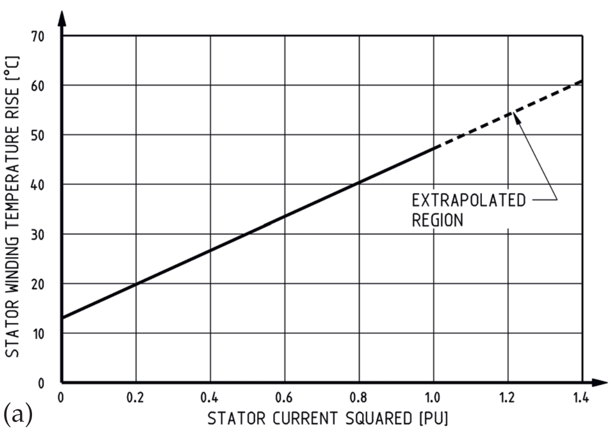
The biggest unknown are the characteristics of the original machine magnetic circuit materials, and these are adjusted from the choice of magnetic core materials available until good agreement is reached with the open circuit saturation curve obtained either from OEM drawings or pre-uprate testing. Machine air flow is also adjusted until good agreement is reached with original machine losses, efficiencies and temperature rises.

Having established machine performance as is, the next step is to carry out analysis of the uprated machine, with characteristics of all uprated components (stator winding, stator core, cooling circuit, excitation system, etc.) substituted in the computation input. The computation output is then complete prediction of up-rated machine performance.

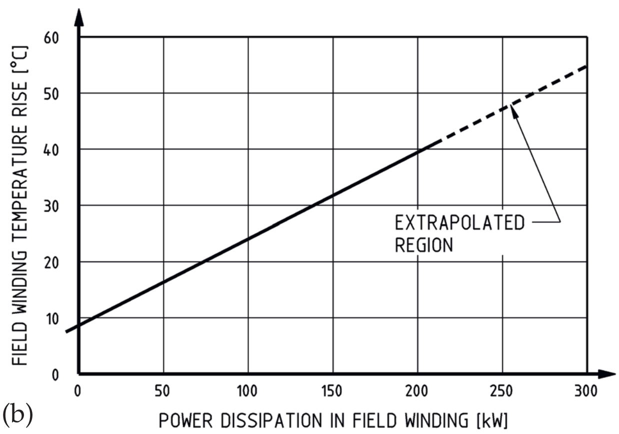
7.4 Final design output

With all generator characteristics confirmed and meeting required uprate parameters, the detailed design is proceeded with.

The detailed design output includes full engineering definition, part schedules, installation instructions, and testing requirement instructions for all components that are upgraded and uprated within the scope of a particular project.



(a)



(b)

Figure 11: (a) Extrapolation of stator winding temperature rise, and (b) rotor winding temperature rise, based on the results of pre-uprate tests on original machine (IEEE, 1995).

8 CONCLUSIONS

A detailed review of the methodology to carry out upgrading and uprating of hydro generators, including examples of particular engineering challenges at each step of the process, has been presented. Comparisons of past and present hydroelectric design trends have been made, including their merits and drawbacks. The importance of obtaining a good match between calculated data and actual measurements had been highlighted. A series of important points have been explained to help hydro-power plant owners, developers, and equipment providers with better informed decision making and specifications when carrying out refurbishment, upgrading and uprating of hydro generators.

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