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REFURBISHMENT OF GENERATORS IN RAMA HPP

REVITALIZACIJA GENERATORA U HE RAMA

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Abstract: The paper describes the project and design features of the refurbished and old generators as well as generator design and its main components. Technical data of old and refurbished generators such as temperature rise of active parts, excitation data, reactance and resistance of armature and field windings, power loss data, and generator efficiency are given.

In spite of output increasing by 10 MVA, the power losses on refurbished generators are lower than on the old generators by 478.5 kW, excluding bearings losses. Also, the temperature rise is lower on refurbished generators, even at maximum continuous load, which is by 21 MVA, or 23.3%, higher than the previous.

Keywords: refurbishment, synchronous generator, power losses, generator efficiency, reactances

Sažetak: U radu su opisane projektne i konstrukcijske značajke revitaliziranih i starih generatora te konstrukcija generatora i njegovih glavnih dijelova. Dati su osnovni tehnički podaci starih i revitaliziranih generatora kao što su podaci o zagrijavanju aktivnih dijelova, uzbudni podaci, reaktancije i otpori armaturnog i uzbudnog namota, podaci o gubicima i korisnosti generatora.

Unatoč povećanoj snazi za 10 MVA, gubici snage na revitaliziranim generatorima bez gubitaka u ležajima, su manji u odnosu na stare generatore za 478,5 kW. Također, i zagrijavanja su manja, čak i kod maksimalnog kontinuiranog opterećenja, što je za 21 MVA, za 23,3 %, veća snaga od prijašnje.

Ključne riječi: revitalizacija, sinkroni generator, gubici snage generatora, korisnost, reaktancije

INTRODUCTION

Hydro Power Plant Rama is the largest plant in the Neretva - Rama system and the largest in the power system of JP Elektroprivreda HZ Herceg Bosna d.d. Mostar. Its construction started in 1964 and was completed and commissioned in 1968. The plant is an accumulation-derivation type and uses the waters of the Rama River at a fall of 325 m. The engine room is located underground, together with a transformer cavern, an access and drainage tunnel of approximately 560 m long. Two main aggregates and a household aggregate are placed into the engine room. The main aggregates are vertical design, comprising The main aggregates (two units) are vertical design, comprising Francis turbine (turbine T1: type F2.75/100-15/ 81, power output 78.8 MW, water had 285 m, water flow 32 m^3/s, rated speed 375 min^{-1}; turbine T2: type FvT-1.96/100-17; power output 95.7 MW, water had 293.61 m, water flow 35.2 m^3/s, rated speed 375 min^{-1}), and two identical three-phase synchronous generators, type S 4,758-16, rated output 100 MVA, (111 MVA as MCR – maximum continuous rating)), voltage 15.65 +10%/-5% kV, rated speed 375 min-1, and frequency 50 Hz). The total installed power of the previous two units in HPP Rama was 160 MW (2×80 MW), before refurbishment, and the average annual production was 650 GWh.

The refurbishment of the generator started in 2011. Forty-five years since the old generator had been in operation, the first refurbished generator was commissioned at the end of 2013. At the end of 2014, the second refurbished generator was commissioned.

The power of the old generators was 90 MVA and the power refurbished was 100 MVA (MCR 111 MVA). Rated speed of rotation remained unchanged at 375 min^{-1} as well as 15.65 kV voltage, voltage regulation + 10%/-5%, frequency 50 Hz, cos φ = 0.9, runaway speed at 660 min^{-1}, and a flywheel effect 1560 tm^2.

Old excitation systems (main and auxiliary exciter and generator with permanent magnets for speed control and amplidine drive) were replaced by static thyristor type excitation system in 1996, which were upgraded during refurbishment of HE Rama (2013-2014). At the same time, in 1996, the electric braking system of the generator was installed.

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1. REFURBISHMENT SCOPE

The scope of the contract was refurbishment of the turbines, generators and online monitoring of aggregates and new step-up transformers of 111 MVA each. The contracted scope of deliveries and works includes the design of contracted equipment, the production of turbine models, the manufacture of new equipment, the dismantling of old equipment with repair and refurbishment of individual parts in the factory, delivery and installation of old and new equipment in the power plant, testing and commissioning, trial run in duration of two months, guarantee period of two years with two inspections of each aggregate.

As part of the refurbishment of the generators, complete stators were replaced with new ones. After the NDT tests have been carried out, replacement of the upper and lower brackets has been agreed. The existing poles of both rotors, including the pole windings have been retained. The pole windings were pre-insulated with modern insulating materials with the application of modern technology. Other parts on the rotors were retained. Along with the minor modernisation of the existing fan rings, new fan blades are installed on it. The size and shape of the blades differ from the previous ones on the old generators. There were 51 blades on each fan of the old generators, while 59 small blades were built on refurbished fans.

The reconstruction of the upper combined, thrust and guide bearing was done on both generators. On the thrust bearing, new segments, 9 pcs, have been built with new supports and segment fixing brackets. There were 12 segments on the old generators. Recasting of the 12 existing segments was carried out. A new support for guide segments has been installed. All new seals are installed. The finishing of the bearing collar was carried out and the height of the oil pot was increased. Complete new cooling system was installed, including oil coolers that are located outside the bearing.

The complete system for high pressure lubrication on both generators was replaced by a new one.

In the lower guide bearing, on both generators, recasting of 12 existing guide segments was carried out. A new reservoir, a new cooling system, including an oil cooler, was built in.

On the generator - turbine coupling flange, on both generators, the existing holes were reamed to the first clean dimension and the installation of new bolts hydraulic clamping.

A new oil vapour drainage system was installed on both generators, which is used for both bearings, and a new oil filling and discharge device that is also used for both bearings.

The cooling system of both generators was reconstructed by installing thermo-regulating valves on the cooling systems of the bearings and the electromotor control valve on the generator cooling system.

On both generators, new instruments and devices for controlling and monitoring bearings were installed on both bearings.

On both generators, an on-line monitoring system is installed.

2. SHORT DESCRIPTION OF GENERATOR DESIGN

Generators are designed for direct, rigid coupling with vertical FRANCIS turbines. Generators are suspended design form (IM 8425, IEC60034-7), with a combined (thrust and guide) bearing above and a guide bearing below the rotor. The generator lay out is shown in Figure 1.

The generator rotor consists of a single-piece shaft, rotor spider, rotor core, which is made as a package from the laminated segment sheets on the principle of the chain ring, the brake ring, the poles with a field and damping winding and the fans. At the lower part of the shaft there is a flange, made as an integral part of the shaft, intended for the connection with the appropriate flange on the turbine shaft. On the upper part of the generator shaft with a rigid connection, the shaft extension is provided for the installation of parts of the slip ring device. The slip ring device serves to power the generator's field winding and consists of slip rings, brushes, brush holders and parts for their attachment and to the power supply of the field winding. The slip ring device is housed in a separate housing, ventilated by a separate fan.

The stator is fixed by bolts to existing base blocks (base plates) built into concrete that are further fastened with anchor bolts into primary concrete. On the upper side of the stator frame, the upper bracket is fixed on which the upper cover and the slip ring cap are supported. In the central part of the upper bracket, the upper combined bearing is placed.

The lower bracket is supported by the arms on the base blocks embedded in secondary concrete. The lower generator guide bearing is placed in the central part of the lower bracket. Generator brakes are placed on the lower bracket arms.

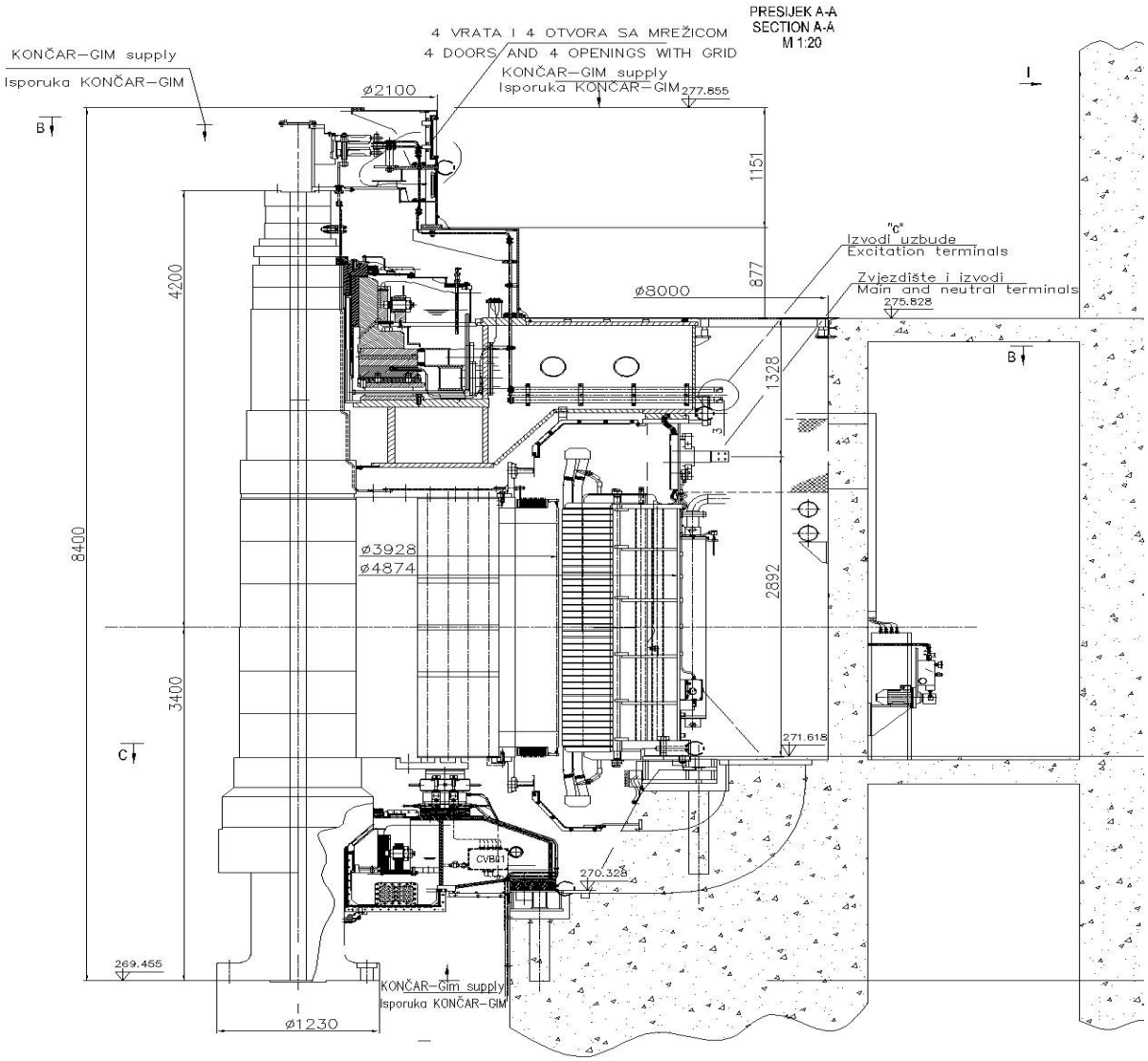


Figure 1: Generator longitudinal section 100 MVA, 15.65 kV, +10%/-5%, 50 Hz, p.f. = 0.9, 375 rpm/ 660 rpm

Ventilation and cooling of the generator active parts is achieved by circulating the cooling air in the closed circuit. The air circulation is ensured by ventilation acting of the rotor (rotor, wheel and pole) and two fans, one mounted on each side of the rotor.

The generator is placed in a concrete barrel, on the upper and lower sides closed with the top and bottom cover. The bottom cover, which is located below the lower bracket, closes the generator space towards the turbine compartment.

3. PRESENTATION OF IMPLEMENTING PROJECT SOLUTIONS

In the process of designing of the refurbished generators, in the first step, the design of the old generators was analysed, their characteristics and operation experience during their utilization. Since the certain assemblies are retained and that some are replaced by new ones, all new assemblies should be adapted to parts and assemblies that will continue to be used. Also, all new parts and generator assemblies should be adapted to the civil structure and its conditions and to conditions on the delivery interfaces. New assemblies and generators as a whole should meet all requirements set out in the technical specifications of the tender documentation. While in the new generators there is complete freedom in the choice of main dimensions, in the refurbishment of existing generators this freedom is limited in all these aspects. Refurbishment from the aspect of choice of technical solutions and their economic valorisation is described in [1]-[3]. In principle, if it is not necessary, the aim is to not change anything on the building.

Despite of the increase in power output compared to the old generators, from 90 to 100 MVA of rated output, or to 111 MVA of maximum continuous rating (*MCR*), the design of the generator frame and lower bracket enabled

them to be installed on existing foundations. To allow the stator to be installed on existing foundations, the outer diameter of the stator core remained the same as on the old generators, 4750 mm. The internal diameter of the old generators was 4000 mm and the refurbished 3991 mm because the air gap was reduced by 4.5 mm, it was 36 mm and now it is 31.5 mm. The core height is the same as the previous 2300 mm. On the old generators, the effective length of the iron was 1930 mm, and on the refurbished generators of 2013 mm, which is 4.3% larger the effective length of the old core. Therefore, it is expected that, with this title, the induction in some parts of the magnetic circuit will be less by 4.3%, and the losses in the iron, with only that title, will be less 8.8%. Even if the iron space factor is added to the old generators, due to the greater thickness of sheet insulation and the worse flatness, less than 2% then iron losses, with the same specific losses, are lower by 13.2%. On old generators, DL 37 has a specific loss of 3.7 W/kg, while refurbished generators are 2.5 W/kg, 22.5% lower specific losses. Altogether, iron losses on old generators are about 115.5%, or 2.155 times higher than on refurbished generators. Having this in mind, as well as the changed winding diagram, and the larger cross section of the stator winding conductor, as will be more mentioned below, it is reasonable to choose a smaller number of coolant ducts in the stator core, 36 compared to the previous 37 and smaller duct widths, 8 mm compared to the previous 10 mm.

The poles are retained existing including the pole winding coil. The pole winding is reinsulated with modern insulating materials, and modern technology is used (pre-insulation and installation on existing poles).

There was effectively no freedom in selecting the stator winding slot number, because the existing poles with the existing damping winding were retained. Thus, the existing number of slots has been retained. For the number of slots 258, due to the possibility of matching the segmented sheets and to adjusted number of stator core key-bars to the number of segmental sheets in one layer, by means of which the stator sheets of the stator core to be fixed to the frame, all three stator segments are not completely identical in dimensions.

One segment differs from the other two. So it was on old generators.

The old generator winding diagram was analysed as well as possible diagrams with the same number of slots. After that, it came to the conclusion that the diagram needs to be changed because better generator characteristics are obtained.

An old stator winding diagram is based on a wave, two layers bar type. The winding pitch is on the drive side y_1=16, on the non-drive side y_2=16. The winding sequence relatively good damping of the 5th and 7th harmonics, the winding pitch should be approximately 85% of the pole pitch (for total damping of the 5th harmonic, the winding pitch should be 4/5, and for the 7th harmonic should be 6/7). Winding spread factor according to the diagram of the old generators of the base harmonic is smaller than for the diagram with equal and fixed phase zones, 60° el., but due to the variable phase zones it is smaller and is 0.934635, the spread factor of the 5th harmonic is 0.285148, 7th harmonic is 0.12517, 11th harmonic is 0.115776, 13th harmonic is 0.05583, etc. The winding pitch factor of all the first is 83747383. This sequence is repeated 6 times. This means that the first 8 slots belong to phase A, conditional to the north pole, the other three slots belong to phase C' (phase C to the north pole) followed by 7 slots of phase B (north pole), 4 slots of phase A' (phase A under the south pole) 7 slots of phase C (under the south pole), 3 slots of phase B' (Phase B under the south pole), 8 slots of phase A and 3 slots of phase C'. For the aforementioned winding sequence, the fact that in the groups of coils whose slots are greater than 6 indicates that the phase zone extends beyond 60 degrees el., whereas in the groups of coils whose slots are smaller than the 5, phase zone narrows to less than 60 degrees el. Due to limited space, it is not possible to show a complete winding diagram.

We assume that this kind of winding sequence, extending or narrowing of certain phase zones or their overlapping, has resulted in the reduction of the number of connection bus-bars, which are only two and are relatively short lengths of 14 slots.

Since the pitch of y_1 is very close to the pole pitch 16 1/8, damping of the higher harmonics is very weak. For a 11 harmonics is greater than 0.99, only the 13th harmonic is 0.9875. The winding factor for basic harmonic is 0.934566, the 5th harmonic is 0.284606, the 7th harmonic is -0.12307, the 11th harmonic is -0.11473, the 13th harmonic is 0.055634, etc.

The refurbished generator winding diagram is based on the winding sequence 65655655 and with the fixed and equal distribution of phase zones 60° el. The winding step is on the drive side y_1=15, on the side of the joints y_2=17. And by this diagram, the connection bus-bars are also two per phase and also of relatively short lengths of 16 slot pitches.

The spread winding factor of the base harmonic, for the refurbished generator winding diagram is 0.955, the pitch factor 0.994, the total winding factor 0.9492. Spread winding factor for 5th harmonic is 0.1911, 7th harmonic is - 0.0137, 11th harmonic is - 0.087, 13th harmonic is 0.0738.

The winding factor for 5th harmonic is 0.1631, 7th harmonic is 0.0983, 11th harmonic is 0.0311, 13th harmonica is 0.0107 etc.

From the presentation of the winding factor of the base and the higher harmonics, with the changed winding diagram, significant contribution to the improvement of generator characteristics is visible. The basic harmonic

winding factor is higher in refurbished generators for 0.9492/0.934566, i.e. 1.57%. From this aspect, there was a bigger induction in all parts of the magnetic circuit on old generators for the same percentage. This means that there are larger excitation currents for a variety of service conditions. Due to the iron saturation of the magnetic circuit, the increase in the excitation current is higher by more than 1.57%. Let's say, if the induction in the stator core tooth of refurbished generators is 1.95 T, in the old is 1.98 T. The increase of the magneto motive force (increase in magnetic force drop) in the tooth will be due to the reduced winding factor by 26% (290 vs. 230 A/cm). Due to higher induction, older generators have higher losses in iron and in copper of the field winding.

The winding factors of all the higher harmonics on older generators are higher than those on refurbished ones; 5^{th} harmonic by 74.5%, 7^{th} by 25.2%, 11^{th} by 267%, 13^{th} by 422% etc. These considerably larger of higher harmonics affect to generator losses and generator voltage wave shape. Losses in iron, and also in copper of stator windings due to considerably larger of higher harmonics are considerably higher in old ones than in refurbished ones. This can be seen from the data on additional losses in copper and iron. The voltage wave shape on older generators shows a greater deviation than ideal sinusoids than on refurbished generators, *THD* factor, *THF* factor and deviation factor are considerably higher than on refurbished generator.

The cross section of the stator winding copper was increased from the previous 497 mm^2 to 583 mm^2, an increase of 17.3%. The stator winding resistance on the old generators was 6.3 mΩ, and the refurbished 5.05 mΩ, which is a 20% reduction. In the same value, will be reduced losses in copper, count for DC current at the same load. Due to the larger cross-section of the strands in the stator winding bars on the old generators compared to the cross section of copper strands on the refurbished generators, additional losses in the stator winding copper on older generators are higher than those on the refurbished, 44.6 kW on the old, 22.4 kW on the refurbished at same power output - 90 MVA. So the stray load copper losses are cut by a half at the same output.

On the existing fan rings, with new adapters, new fan blades were installed. The size and shape of blades differs from blades on the old generators. On the old generators 51 blades were built on each fan, and on refurbished there were built 59 smaller blades. By this reconstruction of the fans, ventilation losses have been reduced, while the effect of cooling is increased, as will be seen in the text below.

The reconstruction of the upper combined, thrust and guide, bearing was carried out. On the thrust bearing, new segments, 9 pcs, have been built with new supports and segments fixing brackets. There were 12 segments on the old generators. Recasting of the 12 existing segments was carried out in the upper guide bearing. A new support for guide segments has been installed. All new seals are installed. Machining of the bearing collar was carried out and the height of the oil pot was increased. A completely new cooling system is installed, including oil coolers that are located outside the bearing.

The complete system for high pressure lubrication has been replaced by a new one.

In the lower guide bearing, recasting of 12 existing guide segments was carried out. A new oil reservoir, a new cooling system, including an oil cooler, was built in.

A new oil vapour discharge system is installed, which is used for both bearings, and a new oil filling and discharge device that is also used for both bearings.

On both bearings new instruments and devices have been installed in purpose to control and monitor the bearings operation.

In addition to renewing of worn out of bearing white metal by new bearing design it is possible to change the bearing segments without bearing disassembly, and lowering of the bearing temperature, reducing cooling water consumption, and preventing oil leakage.

4. PROJECT FEATURES OF THE GENERATOR

After all analyses, the calculated values of the characteristic features of the refurbished generator have been shown in Table I; magnetic induction for partial parts of the magnetic circuit, electric load, A/m, on stator bore, output coefficient – defined as volume utilization, KVA/(m^3×rpm) (Essons' constant), Carter' factor and current density in armature and field windings .The design data of excitation currents for no-load, short-circuit, rated load and load with voltage regulation, current density, reactance, resistances, time constants, losses, generator efficiency, ventilation and thermal calculation data obtained by analytical model are given in item 5 where they are compared with measured data and data measured on the old generators.

Figure 2 shows the no-load, short circuit and regulation characteristics, Figure 3 shows *V*-curves, and Figure 4 shows generator capability diagram. Figure 5 shows efficiency curves based on calculated generator losses.

According to the generator thermal calculation results in all operation modes, the variation of the voltage +10% /-5% and the frequency of ±2% are within the thermal class B limits. According to the technical specifications of the tender documentation, nominal load permits the thermal of 80 K for stator and 90 K for rotor, and at the rated power with the voltage regulation of 90 K for stator and 100 K for rotor.

Table I: Characteristic values of the refurbished generator executable project

Winding factors for basic harmonic (Spread / Pitch / Total)	0.955 / 0.994 / 0.9492
The basic harmonic magn. induction in the air gap, NL / RL / REGmax (T)	0.882 / 0.913 / 0.999
Magnetic induction in the air gap, NL / RL / REGmax (T)	0.768 / 0.794 / 0.867
The current stator line density on the stator bore RL (A/mm)	75.91
Volume utilization, (Esson's constant), (KVA/(m^3×rpm))	7.279
Rotor peripheral speed - rated / runaway (m/s)	77.1 / 135.7
Carter's factor (Total)	1.058
Magn. induction in the stator tooth, NL / RL / REGmax (T) – at 1/3 of the tooth height (T)	1.58 / 1.689 / 1.919
Magnetic induction in the stator yoke, NL / RL / REGmax (T)	1.207 / 1.285 / 1.398
Magnetic induction in the rotor pole, NL / RL / REGmax (T)	1.42 / 1.69 / 1.812
Stator winding current density, NL / RL / REGmax (A/mm^2)	- / 3.16 / 3.4
Stator winding current density, NL / RL / REGmax (A/mm^2)	1.56 / 2.94 / 3.07

NL – No-Load, RL – Rated load, REGmax – Maximum values for voltage regulation

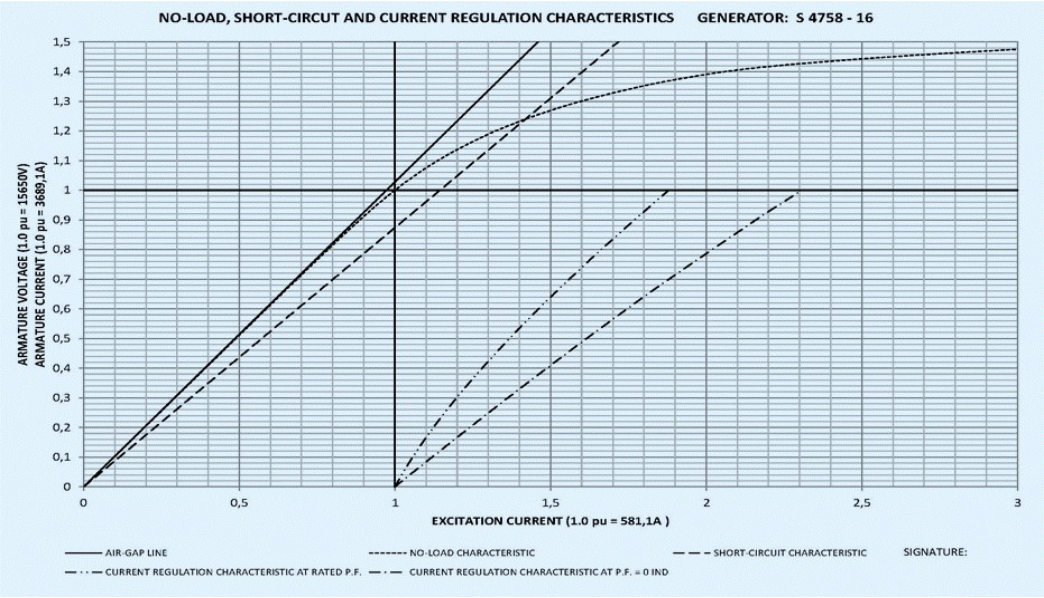


Figure 2: Design of no-load, short circuit and regulation characteristics

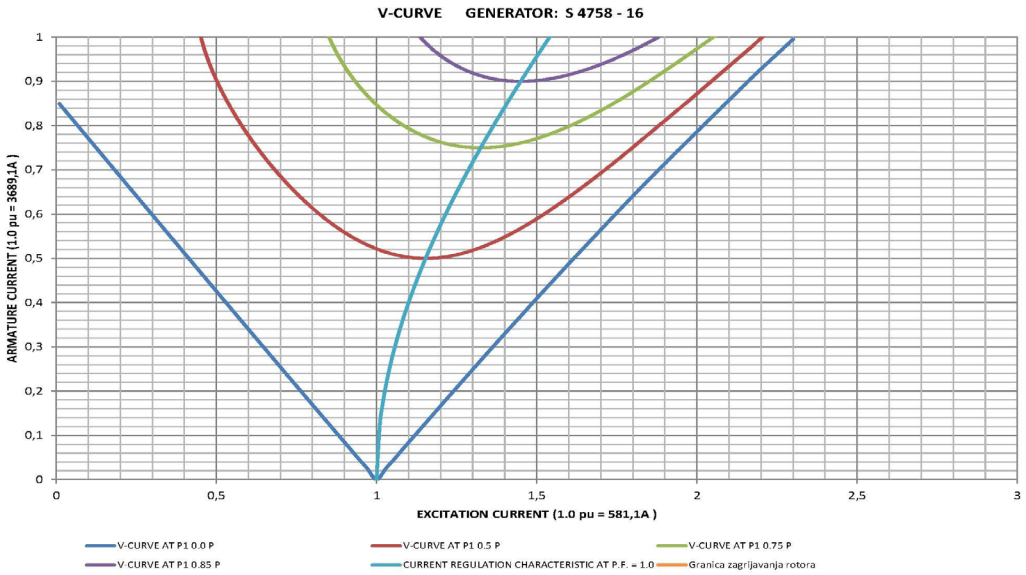


Figure 3: *V* - Curves

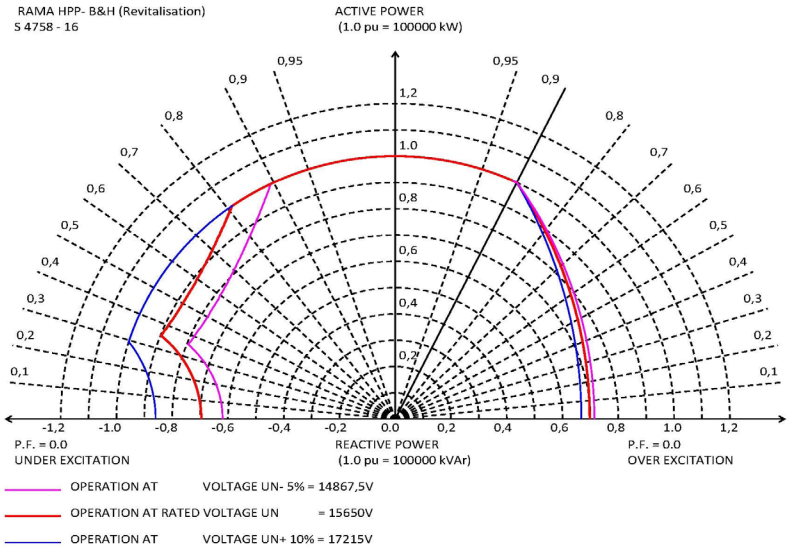


Figure 4: Capability diagram for rated power, rated voltage and rated p.f.

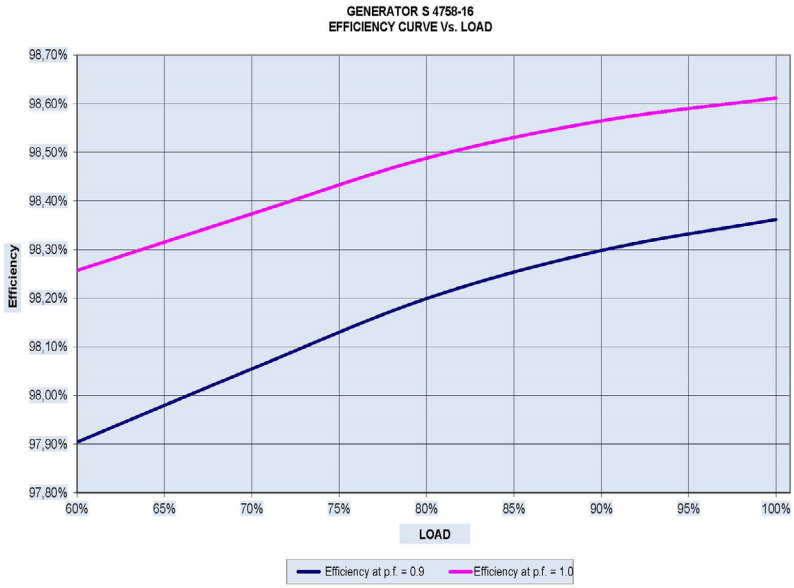


Figure 5: Efficiency curve with calculated generator losses

5. COMPARISON MEASURED AND DESIGN VALUES

Heat runtests were performed on several occasions. In this paper data on the generator 1 of the tests performed on 18.10.2013 and on the generator 2 of 10.12.2014 is given.

Load data of the old generator G1 at which the heat run test was heat run, protocol of 08.10.1971: 82 MW, 40 MVAr, 3.3 kA, 15,7 kV, excitation current 1170 A.

The load data at which the heat run was test was performed on generator 1: 100.2 MVA, 86.77 MW, 50.23 MVAr, 16570 V, 3465.4 A, cosφ = 0.863 and on generator 2: 110.4 MVA, 100, 9 MW, 43.6 MVAr, 16550 V, 3836.9 A, cosφ=0.908. Measured values are given in Table II. Based on the heat-run test for said load, the temperature rise of the field winding in all operation regimes are within the limits of insulation class B, including operation regimes for which temperature rise is contracted over class B.

If the temperature rise of the refurbished generators G1 and G2 is compared with the temperature rise of the old generators, it can be seen that the temperature rises of all active parts, despite the increase in rated power for 10 MVA, is lower; stator winding for about 15 K, stator core for about 13 K, and rotor winding for about 20 K.

As can be seen from the table, the temperature rise of refurbished generators is lower also at maximum continuous rating (*MCR*).

To estimate the effect of the cooling system of the generator, it should be noted that the flow of cooling air and water on refurbished generators is considerably smaller than that of the old generators. This fact suggests that the efficiency of the ventilation and cooling system, which can be seen from the air and water flow, the temperature rise of the active parts, and the difference between the temperature of the hot and cold air, is substantially improved. The air coolers of the refurbished generators are also

greatly improved, which is confirmed by the temperature rise of the cooling air and the lower flow of water.

In addition to heat-run test, vibration, noise, geometric values, isolation resistances and other characteristic values relevant to the generator takeover, the recording of no-load and load magnetization curves was performed.

Table III lists the designed and measured values of excitation data for refurbished generator. For comparison the refurbished with the old generators, the table lists the excitation data also of the old generators.

Refurbished generators, despite an increase in power of 90 to 100 MVA, which is an increase of 11.1%, have less exciting currents and voltages, and losses in the field winding recorded by measurements (201 kW at 95°C versus 264.8 kW at 95°C) is lower for 63.9 kW or for 24.1%.

Table IV shows the design and some of the measured values; armature and field winding resistances reactance and capacities.

If the same design was retained as it is on old generators, all reactances would rise linearly with output increasing, meaning 10/9 or 11.1%. Due to the reduction of the air gap from 36 to 31.5 mm synchronous reactance would be further increased by 14.3%, which would be in total of 26.85%. Therefore, direct synchronous reactance, with reduced air gap, as expected would be 114.45%. However, as measured, 110.6%, and designed, 110%, it can still be argued that the new design has managed to reduce this reactance by about 4%, which is considered to be a certain improvement. What is the cause of this? In the author's opinion leakage reactance and change of winding diagram contribute to this.

The transitional reactants at the old generators were 29.7%, the new ones should be 11% higher, which is expected to be 33%. The designed value of 32.2%, and especially measured 28.06%, is lower than expected, which is a certain contribution to the improvement of dynamic stability.

Unfortunately the sub-transient reactances on the old generators were not measured so that they cannot be compared.

It should be emphasized that the operation of generators with the reactances taken from conceptual design of refurbishment was analysed from the aspect of transient and static stability and after that the tender documentation was made. All reactances, designed and measured on refurbished generators, comply with the requirements of the tender documentation.

Table II: Load Warm-up test data (Heat-run test data)
G1 old: 82 MW, 40 MVAr, 3.3 kA, 15.7 kV, exc. current 1170 A
G1: 100.2 MVA, 86.77 MW, 50.23 MVAr, 16570 V, 3465.4 A, p.f. = 0.863
G2: 110-4 MVA, 100.9 MW, 43.6 MVAr, 16550 V, 3836.9 A, p.f. = 0.908

	Old generator 1		Revitalized generators	
	Temp. (ºC)	Temperature rise (K)	Temp. (ºC) G1 / G2	Tem. rise (K) G1 / G2
Static winding	90	58	64 / 75.2	44.2 /53.4
Rotor winding	101	69	82.6 / 89.7	62.8 / 59.6
Stator core	77	45	53.6 / 59.7	33.8 / 39.6
Cooling air warm/ cold	66 / 32	34	46.3 / 19.8 51.9 / 21.8	26.5 / 30.1

Excitation current 1174.9 A on G1 and 1195.4 A on G2
Water flow on old generators 73-74 l/s (Protocol od 8.10.1971.), 550 l/s (2001.),
Air flow 67, 4 m^3/s (1971 y.), 55 m^3/s (2001 y.)
Water flow on revitalised generator 1: 48.2 l /s, Air flow 46.1 m^3/s
Water flow on revitalised generator 2: 35 l/s, Air flow 47.7 m^3/s

Table III: The excitation current, voltage and power

	Old Generator *	Rev. generators	
		Design	Test**
Excitation current for no-load (A)	677	581.1	575
Short circuit excitation current (A)	589	654	636
Excitation current for rated load (A)	1172	1082	1046
Rated load excitation voltage (V)	248	207	192.2
Maximum load exc. current at 105% Un and 110 MVA (A)	-	1200	1195
Excitation power for rated load (kW)	250.34 (75°C) 264.8 (95°C)	224 (95°C)	201 (95°C)

* - The old generator - measured value, ** - Protocol of 8 October 1971

Losses in the generator's combined bearing during contracting are based only on the friction losses of the sliding surfaces. Therefore, the table gives total losses with and without losses in the bearings.

Table V shows that losses, excluding losses in bearings, of refurbished generators compared to the old generators are lower by 480.94 kW, and when the losses of the bearing are calculated then the total losses are lower by about 380 kW.

Expressed in percentages, without bearing losses, losses are by 32.49% lower, and when losses in bearings are taken into account, the total losses are lower by 20.77%. It should be kept in mind that the temperature rise of the stator and the rotor winding is smaller in relation to the old

Table IV: Resistances, reactances and time constants

Characteristic data	Old gen.	Designed	Measured
Static winding resistance at 20°C (mΩ)	6.3	5.05	5.05
The resistance of the field winding at 20° C (mΩ)	142.2	142.2	142.2
Short-circuit ratio	1.2	0.972	0.978 (0.964)
Synchronous directional reactance (%)	90.22	110	110.6
Transient directional reactance (%)	29.7	32.2	28.06
Sub-transient directional reactance (%)	16.1	19.2	19.47
Sub-transient quadrature reactance (%)	-	19.98	21.7
Inverse reactance (%)	-	19.58	20.54
Zero reactance (%)	-	16.7	13.76
Leakage reactance (%)	-	11	10.24
Transient longitudinal time constant at short circuit (s)	-	2.08	1.3
Sub-transient longitudinal time constant at short circuit (s)	-	0.07	0.042
Time constant of armature winding (s)	-	0.26	0.283
Capacity of stator winding per phase (μF)	-	0.913	0.9635 (1.001)
Voltage wave deviation factor from ideal sinusoid (%)	-	1.81*	09225
Total deviation factor of voltage wave shape (%)	-	0.53*	0.3251

* - Deviation factor of voltage waveform from the ideal sine wave according to NEMA MG 5.1 is up to 10%
- Total deviation factor according to IEC 60034 is 5%

Table V: Losses and efficiency (for rated power and rated power factor 0.9)

	Old generators	New generators
	Measures in 2001	Measures in 2015
Rated Power (MVA)	90	100
Iron losses (kW)	400	185.6
Losses in copper of armature winding (kW)	267.7 (95°C)	266.8 (95°C)
Stray load losses in copper and iron (kW)	201.2***	111.25 (95°C)
Losses in field winding and brushes (kW)	267.2* (95°C)	203.1** (95°C)
Ventilation losses (kW)	344.4	232.9
Bearing friction losses (kW)	350.6[i]	451.2[ii]
Total losses for rated operation without bearinglosses (kW)	1480.5 (95°C)	999.56 (95°C)
Total losses for rated operation with bearinglosses (kW)	1831.1 (95°C)	1450.8 (95°C)
Efficiency for rated operation without bearinglosses (%)	98.205 (95°C)	98.90
Efficiency for rated operation without bearinglosses (%)	97.789 (95°C)	98.414 (95°C)

* Excitation losses are converted to reference temperature 95°C from excitation current 1195 A, winding resistance 0.1854 (95°C) = 264.8 kW + brush losses 2.4 kW = 267.2 kW (Losses in Excitation system is not included).
** Excitation losses are converted to reference temperature 95°C from excitation current 1047 A, winding resistance 0.1854 (95°C) = 201 kW + brush losses 2.1 kW = 203.1 kW (Losses in Excitation system is not included).
*** Stray loa losses are determined from measured load losses at rated load 468.9 kW - I2R = 201.2 kW
[i] P_{UKB} = 220000 kp (generator rotor weight) / (220000 kp + 11100 kp (turbine rotor weight) + 150000 kp (axial water force)) × P_{TB} = 0.58 × 409.44 kW = 236.36 kW, P_{UGB} = 59.43 kW, PLGB = 59.43 kW
[ii] P_{UKB} = 2236.38 kN (generator rotor weight) / (2236.38 kN + 265 kN (turbine rotor weight) + 1050 kN (axle water force)) × P_{TB} = 0.63 × 480.158 kW = 302.38 kW, P_{UGB} = 74.387 kW, P_{LGB} = 74.387 kW = 2236.38 kN (generator rotor weight) / (2236.38 kN)

generators, and the actual losses in the copper armature winding are additionally smaller by about 6% and in the copper of the field winding by about 8%.

6. CONCLUSION

From all results of calculated and measured values, it can be concluded that all generator characteristics have been improved: losses, efficiency, temperature rise, reactances, noise, vibration, voltage wave form. Appropriate matching of calculated and measured values is evident, which confirms the accuracy of the applied algorithms. Some of the measured parameters are even better than the design, indicating that the production and erection of the generators are well done.

Total losses, without losses in bearings, on refurbished generators, despite increased power, are lower than the old generators at 480.9 kW (at the same reference temperature of 95°C). It should be kept in mind that the winding of the stator and the rotor is smaller in relation to the old generators, and the actual losses in the copper of armature winding are additionally smaller by about 6% and in the copper of the field winding by 8%. The efficiency of refurbished generators in relation to the old ones, with no losses in bearings, is higher by 0.695% and with losses in bearings by 0.625%.

The quality of the electricity that is expressed, among other things, through the wave shape of the generator voltage is significantly better than is required in the technical regulation, but is better than the old generators. This last claim is based on the changed winding diagram in which the winding pitch from the previous 16 has been reduced to 15 slots. The generator pole pitch expressed by the number of slots is 16,125. Only this measure significantly reduced the share of higher harmonics in voltage waveform.

The temperature rise of refurbished generators, despite of the increase in power by 10 MVA and the maximum continuous output by 21 MVA, compared with the temperature rise of the previous generators are smaller. Temperature rises are lower; stator winding for about 15 K, stator core for about 13 K, rotor winding for about 20 K.

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BIOGRAPHY

Zoran Milojković was born on November 12, 1950. He graduated in 1973 and got his master degree in 1978, both from the Faculty of Electrical Engineering and Computing from the University of Zagreb. He worked in several companies in the former Yugoslavia before he was employed at the KONČAR-Institute of Electrical Engineering in 1977. Since 1986, he had worked in KONČAR - Generators and Motors Inc., in various positions such as: Generator Designer, Project Manager, Head of Electromagnetic Design Department, and Head of Technical Department. Now, he works as a Senior Design Advisor for the design of medium and large hydro-generators. He was a member of the International CIGRÉ in Paris from 2004 to 2015 and through Company KONČAR - Generators and Motors Inc., he was a member of the Electrical Engineering Society of Zagreb from 1992 until 2015. He has been a member of the study committee A1 - HRO CIGRÉ Rotating Machines since 1999 so far and a member of the Croatian Standards Institute from 2001 until now.

Mario Brčić was born on 16/10/1978. He graduated at the Faculty of Electrical Engineering and Computing at the University of Zagreb in 2002. After finishing his studies, he has started work at KONČAR – Generator and Motors Inc. In 2002, he started working as an Electrical design Engineer. From 2008 to 2014, he worked as Head of Electrical design Department for Large Generators and from 2014 to 2016 as a Technical Director. He is currently working as Head of Electrical design Department. He has been a regular member of the study committee A1 - Rotary machines of the International CIGRÉ in Paris since 2014 until now. He was the Secretary of the Study Committee A1 - Rotary Machines HRO CIGRÉ from 2008 to 2014. Since 2014, he has been the Chairman of the study committee A1 - HRO CIGRÉ.

Ivan Brizar was born on April 11, 1960. He graduated from the Faculty of Electrical Engineering of the University of Sarajevo in 1985. Immediately after graduation, he was employed by the RO Hidroelektrane na Neretvi, RJ HE Rama, where he worked at the following positions: Electrical Equipment Referent, Engineer and Plant Engineer and Leading Electrical Engineer. Since 1992, he has been an employee of the JP “Elektroprivreda Hrvatske zajednice Herceg Bosne” d.d. Mostar, Department for Production of Electrical Energy, HPP Rama, at the following positions: Chief Technical Officer HE Rama, Head of Electric Power Plant of HPP Rama; currently as a Project Manager of Refurbishment of HPP Rama in UID Proizvodnja električne energije, Mostar.

Ante Marušić was born on November 16, 1968. He graduated from the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb in 1993. From 1994 to 1998, he was employed in the Ministry of Interior of Bosnia and Herzegovina, Herzegovina-Neretva Canton, Police Administration Rama. Since 1998, he has been employed by JP “Elektroprivreda Hrvatske zajednice Herceg Bosne” d.d. Mostar, Department for Production of

Electrical Energy, HPP Rama. Over the time, his positions included: Engineer of equipment and plants at HPP Rama, Chief Technical Officer HPP Rama and Project Manager of Mechanical Engineering Repairs at HPP Rama, last being his current one.

Ivan Papak was born on March 01, 1982. He graduated from the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture in Split, University of Split in 2009. Since 2009, he has been employed by the JP „Elektroprivreda Hrvatske Zajednice Herceg Bosne“ d.d. Mostar, Department for Production of Electrical Energy, HPP Rama. His positions included: Independent electrical engineer and Head of department, latter being the current position. He is also a member of the team for the revitalisation of HPP Rama.

Vinko Tomas was born on August 25, 1952. He graduated from the high school “Rade Končar” in Zagreb in 1976. After completing his studies, he started working at KONČAR, and now as a project manager at KONČAR – Power Plant and Electric Traction Engineering Inc. Zagreb, Croatia. He has worked on offering, contracting and realization of many new or refurbishment projects of old hydro and thermal power plants, and most important of them include: BEKHME DAM HPP, Iraq 6 x 295 MVA, UGLJEVIK TPP, Bosnia and Herzegovina 1 x 353 MVA, VELEBIT RHPP, Croatia 2 x 155 MVA, RAMA HPP, Bosnia and Herzegovina 2 x 100 MVA (MCR 111 MVA), DOBLAR 2 HPP,Slovenia 1 x 50 MVA, DOBLAR 1 HPP, Slovenia 3 x 16 MVA, PERUČA HPP, Croatia 2 x 34 MVA, ĐALE HPP, Croatia 2 x 24 MVA, PLAVE 2 HPP, Slovenia 1 x 23MVA, PLAVE 1 HPP, Slovenia 2 x 11 MVA, ULZAHPP, Albania 4 x 7.5 MVA, SHKOPETI HPP, Albania 2 x 15 MVA.