A 30 YEARS RELIABILITY SURVEY OF A GENERATOR FAMILY

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1. Abstract

This paper presents a reliability survey of 12 GE generators type 9H2, over a service period of about 30 years. These generators accumulated 350 unit-year, representing a large statistical population for survey.

2. Purpose

From these 12 units, 10 are currently being sold as per Government's structural changes of generation sites [1]. Furthermore, 4 years ago, the stations were reorganized. All these changes lead to the goal to preserve the history of this generator series.

The discussed generators are driven by GE E-class heavy-duty gas turbines (named also Frame 9E or series MS9001E). These packages were acquired in the late eighties and early nineties to be fast started and loaded during peak system loads, or to be used in baseload operation mode as required by system fast development.

The 50 Hz gas turbines type 9E and generators type 9H2 are comparable to 7E turbines and respectively 7H2 generators designed for 60 Hz. However, the 9H2 conclusions below are not necessarily applicable to 7H2 generators. The 60 Hz gas turbines have 20% higher speeds and consequently the 50 Hz Frame 9E has roughly 40% higher outputs than the corresponding MS7001E units[1] [2], [3]. More than 3000 E-class units have been installed around the world during the last 40 years [4].

The main historical data related to these 12 generators are concentrated in the attached table. For simplicity, they are named by a letter (site) and a digit (unit).

3. Features

All 12 generators type 9H2 are rated 11.5 kV, are hydrogen cooled and almost identical in their design and dimensions, but have slightly different ratings as a result of gas turbines design progress.

The first six generators, rated 133.75 MVA, were installed in units R1 and R2 (1989), Z1 and Z2 (1990), A1 and A2 (1991-1992). A subsequent four slightly larger generators – 137.5 MVA – were synchronized in R3 and R4 (1993), H3 and H4 (1994). The above-mentioned 10 generators have been specified according to ANSI C50 standards.

Another two generators, rated 148.5 MVA (a result of being specified according to IEC 34 standard for higher temperature rise[2]) were installed in units H5 and H6 (1996).

Armature winding insulation is epoxy-bonded-mica class F (Micapal), designed for class B temperature rise. Field insulation is class F, but for class B temperature rise.

[1] In general, gas turbines are speed-scaled versions of the same basic design, restricting the tangential speed at blade tips; for geometrically similar gas turbines, the airflow is proportional to the compressor inlet area.

[2] Class B armature winding temperature by RTD: 100°C by ANSI C50.15-1989 vs. 116°C by IEC 34-1:1989.

4. Operation

Initially all 12 industrial gas turbines burned distillated oil and operated in open cycle. Later on, six units were integrated in 3-shaft combined cycle power plants (each including 2 gas turbines and one steam turbine): R3 and R4 (1999), H3 and H4 (2002), H5 and H6 (2002). The other six units remained stand-alone.

Another modification occurred when eight units were converted to natural gas as primary fuel (H3, H4, H5 and H6 in 2009, R1, R2, R3 and R4 in 2010), while Z1, Z2, A1 and A2 gas turbines continued to be operated on distillated oil. These changes obviously influenced also the operation mode (service hours and number of starts) for economic reasons.

The machines operated during long time in two-shift mode[3], at about 100 starts/year in case of stand-alone units and about 200 starts/year for units belonging to combined-cycle plants. It is worth noting that according to standard ANSI C50.15:1989 for hydrogen cooled gas turbine driven generators (in effect at manufacturing date), the starting frequency to substantial load should not exceed 500 starts per year. The current standard IEEE C50.13 mention the number of start/stop cycles over the life of the unit.

In H5 rotor, typical signs of negative-sequence currents have been found in 2008, however not backed-up by any reported past event.

A couple of seal-oil in generator incidents have been recorded during the years (R4, H6), without direct consequences.

5. Maintenance

The planned maintenance frequency depended by many factors, and mainly by gas turbine inspection intervals. According to the original GE instructions, the generator minor outage should be done during turbine Hot Gas Path Inspection, in cyclic duty being every 9000-16000 fired hours (depending by different fuels) or 1200 starts. Similarly, the rotor-out major outage of the generator was performed during turbine major inspection, in cyclic duty being every 18000-32000 hours or 2400 starts. Later on, gas turbine maintenance was updated according to OEM's recommendations GEK 103566 and user's experience.

Moreover, internal procedures have been established for generator major outages (based on VGB recommendations R167), according to equivalent operating hours or maximum 12-year intervals. Some exceptions can be seen in the attached table, resulting from system / budgetary constraints, or serious findings requiring to prepare and thus to postpone significant maintenance.

As a result, every generator passed during the years two major (rotor-out) outages and several minor outages. One unsuccessful attempt was made at Z1 in 2013 to complete robotic inspection with rotor-in (because the airgap baffle).

6. Rotor issues

6.1. One rotor common problem was *creepage block migration* in slots, partially blocking the cooling vents by misalignment and inducing thermal sensitivity and abnormal vibrations. This issue appeared in 6 generators as soon as after 1400-1800 starts or 10-13 operation years; being strongly influenced by the number of starts, it is mainly related to units working in combined-cycle and normally solved by rotor full rewind

[3] Two-shifting is defined as starting up and shutting down a plant daily to meet the load demand.

only. (Obviously a full rewind permits to address also other issues). Some rotors required full rewinding (A2) after just 1400 starts. Other rotors have been completely rewound after greater number of starts as 2000-2700 (H5 and H6). In R3 the rotor was replaced in April 2020, 14 years and 2500 starts after a previous full rewind, because thermal sensitivity inducing vibrations. There are also machines that haven't been rewound because present just incipient signs of blocked cooling passages (R2, R4 after more than 1800-2100 starts) or seem to be in acceptable condition (R1, Z1 after 2100-2300 starts).

6.2. Another rotor issue was *terminal stud leaves* (main lead or "gooseneck") cracked or broken copper. This problem was mainly related to the number of starts (two-shift operation) and fatigue failures of copper connectors on terminal stud assemblies. It may lead to excitation open-circuit and inadvertent unit trip by loss-of-field protection. According to TIL 1161-3, this problem can appear as soon as after 100 start / stop cycles; in our case it occurred in 4 of the discussed machines as soon as after 1100-1500 starts or 5-7 service years (H4, R4) - in H4 the problem led to a forced outage. The only solution was replacing the terminal stud, actually meaning a partial rewind. Cracked leaves were found in 2003 at A2 after 1100 starts, repaired a couple of years later by a full rewind. During 2012 outage of H3, this issue (after a total of 3300 starts and overall 18 service years) led to rotor replacement by a new spare one.

6.3. *Dislocated turn insulation* in the end winding (TIL 1308) was found in several machines like H6 in 2016 (2200 starts and 11 years after the previous full rewind). May lead to shorted turns, thermal sensitivity and vibrations. Can be only addressed during a partial or complete rewinding work.

6.4. Damaged +/- *collector lead insulation* was detected in 3 machines, e.g. H3 in 2007 after 2300 starts and 12 years; it can cause rotor ground fault or in some severe causes it can be related to hydrogen leaks. A rotor ground fault occurred in 2015 at Z2 after 2600 starts and 25 operation years (the rotor replaced by the one dismantled from H3).

6.5. *Shorted coils* in 2007 at A1 after 1500 starts (15 operation years) following copper deformation. *Shorted turns* in 2020 in R3 after 2500 starts (14 years) from previous full rewind, because damaged interturn insulation.

6.6. Other recorded event was broken *pole-to-pole connector* in 2007 because copper fatigue failure (in R3, solved by a full rewind after 2800 starts and 14 years, following additional findings).

6.7. *Rotor rewind summary*: During the years, 5 complete and 2 partial rotor rewinds have been performed. Most rewinding works have been done in our power plants, using existing copper and without performing high speed tests. In other 3 cases, the faulty rotor was replaced by spare and repaired in contractor's factory.

7. Stator issues

7.1. A common issue, most probably also related to two-shift operation and consequent vibrations (and perhaps also to some oil in generator incidents) was *loose slot wedges*, as soon as after 13-14 years or 1400-1500 starts, as late as after 21 years and 4200 starts. The solution was partial or full rewedge, upgrading the stator wedge system from the original "Camel Back" wedge system to a "Piggy Back" (inclined plane) style installed with top ripple springs. This system uses a wedge with under-side taper and corresponding slide to allow positive downward pressure on the bars during assembly in the slot, and has proven to be more effective as the wedges remain tight and prevent stator bar slot movement.

7.2. Other infrequent stator issue was *greasing / loose loop ties* found in the end winding area, for example in H3 after 18 years or 3300 starts. Dusting and greasing is the result of loose ties, blocks, and oil contamination. All loose ties have been removed and replaced, or retighten / repaired.

7.3. *Stator rewedge summary*: Most machines (10 out of 12, excepting Z1and Z2) underwent rewedge, at an extent according to actual condition obtained by wedge tightness tests and internal / OEM acceptance criteria. In 6 machines a full rewedge was performed, and in other 4 partial rewedge. It is interesting to note that according to the OEM, “Camel Back” style wedges should be tested with a curl gauge, not wedge tapper.

8. Other Issues

8.1. One issue was *bushing damages*, which occurred in A1 after 13 years and 1300 starts, in H4 after 17 years and 2900 starts.

8.2. Some of these generators experienced *increased vibrations*. In some cases, the vibrations may be attributed to rotor thermal sensitivity resulting from closed cooling vents (R3), or misalignment / unbalance conditions (H6). Other vibration problems needed prolonged investigations in order to find root cause and solutions (H4, R4). This may be an interdisciplinary challenge, sometimes difficult and tedious to solve. Anyhow, such vibration issues appeared mostly in units operating in combined cycle, likely to be also related to the two-shift operation mode (many start / stop cycles).

8.3. The generators are equipped with *static excitation* (hybrid thyristor and silicon diode bridge, fed by a power potential transformer connected directly to the generator output leads). The voltage regulator is based on solid-state analogue electronic cards, originally furnished and still in operation.

9. Monitoring and Testing

During every outage we perform visual inspections of stator and rotor (borescope in case the rotor is not dismantled), electric diagnostic tests like insulation resistance, polarization index, offline tangent delta and partial discharge measurements up to phase voltage. In case of major outages we add ELCID test for stator laminations insulation, stator wedge tightness condition, RSO for turn-to-turn shorts, etc.

During full rewind opportunity, suitable NDT metallurgic inspections are performed on rotor forging, like dovetail load surface using eddy current technique and the rest of slot using magnetic particle technique (TIL 1292).

After 2005, flux probes were installed at rotor-out opportunities in most generators (the exceptions are R1, Z1, Z2). R2 and H4 rotors, which haven’t never been fully rewound, are living with 2-4 shorts for many years. No evidence has been found that shorted turns affect thermal sensitivity or vibrations. From the rotors which underwent rewind, despite having similar operation history, some are experiencing 1 turn-to-turn short (A2, H6, R3) and others are free of shorts (A1, H3, H5, R4).

No online stator winding partial discharge monitoring (PD) was installed. The truth is stator winding insulation was never a problem with these machines.

In some generators Electromagnetic Signature Analysis (EMI) tests were performed, without significant findings (H3 in 2011, Z1 in 2011, R4 in 2014).

10. Critical Spare parts

Following the above experience gained, a spare rotor suitable for all 12 generators was purchased in 2010, after a validation interchangeability study performed by the OEM. This spare rotor replaced the H3 one in 2012. The rotor dismantled from H3, despite having cracked stud leaves, was installed in 2015 at Z2 (which experienced a ground fault and forced outage). The rotor dismantled from Z2 was rewound abroad during 2016 and stored as the spare rotor for these machines. It replaced R3 in April 2020, while the rotor from R3 was sent to OM for rewinding (performed in 2021), intended to be mounted after that in Z1.

Regarding stator spare parts, 6 top bars and 6 bottom bars (10% of total installed bars) are kept in storage for winding emergencies, luckily never used. The stator has 60 slots. In addition, a complete set of wedges and ancillary materials is stored for contingency of loose wedge issues found during major outages.

11. Conclusions

All discussed generators are as old as 35 years from manufacturing, in operation for 25-31 years (average 29). They accumulated 2700-5400 start/stop cycles (average 4100).

With proper maintenance, the 9H2 generators are still reliable, mainly a result of their design simplicity. The most common failure modes are mainly related to the two-shift operation mode: terminal stud failures and insulation migration in rotors, vibrations and loose wedges in stators. The significant influence of generator operation is well documented in literature, e.g. [2] mentions that cycling regime may increase the forced outage rates up to 5 times.

Most stators (10 out of 12) experienced during the years a partial or full rewedge. The rewedge has been performed after an operation service of 1400-4200 starts (average 2600) or 13-21 years (average 16).

Most rotors (10 out of 12) underwent during the years significant maintenance, like a partial or full rewinding or a replacement to spare rotor. This has been performed after 1100-5400 starts (average 2400) or 5-28 years (average 14).

It is expected that a new series of rotor rewinds and stator rewedge will be necessary in the near future, despite the number of starts decreased somewhat.

The attached table concentrates the main historical data of the discussed generators.

12. References

[1] Israel Electric site www.iec.co.il, Financial Reports
[2] S. Can Gülen, *Gas Turbines for Electric Power Generation*, Cambridge University Press, 2019, p. 33
[3] J. C. Rucigay, A. J. Orsino, *MS9001E A New 100 MW Gas Turbine*, ASME, 1981
[4] *Powering the World*, GE brochure GEA32045E, 2016
[5] EPRI Report 1008351, *Effects of Flexible Operation on Turbines and Generators*, 2004

HISTORICAL DATA TABLE

Unit name	R1	R2	Z1	Z2	A1	A2	R3	R4	H3	H4	H5	H6	
Gen MVA	133.75	133.75	133.75	133.75	133.75	133.75	137.5	137.5	137.5	137.5	148.5	148.5	Generator data
Mfg year	1986	1986	1989	1989	1990	1990	1991	1991	1991	1992	1994	1994	
First sync	Nov 1989	Oct 1989	Dec 1990	Dec 1990	Dec 1991	Feb 1992	May 1993	May 1993	Nov 1994	Nov 1994	Jan 1996	Feb 1996	
Standard	ANSI	ANSI	ANSI	ANSI	ANSI	ANSI	ANSI	ANSI	ANSI	ANSI	IEC	IEC	
Starts	606	500	1352	1121	1295	1135	1576	1525	2258	1107	2186	2008	From sync till incl. 1st MO*
Years	5.7	4.7	12.9	10.7	12.8	11.2	7.7	7.5	12.4	5.2	10.4	9.6	
1st MO*	1995	1994	Dec 2003	Sep 2001	Oct 2004	May 2003	Feb 2001	Nov 2000	May 2007	Feb 2000	2006	Sep 2005	
Rotor findings						Terminal leaves		Terminal leaves	Collector lead	Terminal leaves		Creepage migration	
Rotor solutions						Defer to next MO*		Partial rewind	Repair	Partial rewind		Complete rewind	
Other issues					Bushing damage			Oil ingress				Oil ingress	
Other solutions					Bushing replace								
Flux probe												Install	
Starts	1446	1267	968	1439	252	253	1271	2136	1089	1805	490	2195	After 1st MO* till incl. 2nd MO*
Years	13.5	11.8	9.2	13.7	2.5	2.5	6.2	10.5	5.1	11.7	2.3	11.2	
2nd MO*	Jan 2009	May 2006	Mar 2013	Jun 2015	Apr 2007	Nov 2005	May 2007	May 2011	Jun 2012	Nov 2011	Nov 2008	Nov 2016	
Rotor findings		Creepage migration		Collector lead	Shorted turns/coils	Creepage migration	Pole crossover	Creepage migration	Terminal leaves		Creepage migration	Dislocated insulation	
Rotor solutions		Rewind recomm		Replace by H3	Complete rewind	Complete rewind	Complete rewind		Replace by new		Complete rewind	Rewind recomm	
Stator findings	Loose wedges	Loose wedges			Loose wedges	Loose wedges	Loose wedges	Loose wedges	Loose wedges	Loose wedges	Loose wedges	Loose wedges	
Stator solutions	Full rewedge	Partial rewedge			Partial rewedge	Full rewedge	Partial rewedge	Full rewedge	Full rewedge	Full rewedge	Partial rewedge	Full rewedge	
Other issues			Robot unsuccess							Bushing damage			
Other solutions			Boroscope inspection							Bushing replace			
Flux probe		Install			Install	Install	Install	Install	Install	Install	Install		
Starts	1301	1587	837	192	1435	1340	2518	2001	1888	1433	2513	850	After 2nd MO*
Years	12.2	14.8	8.0	5.7	13.9	15.3	13.8	9.8	8.7	9.3	12.3	4.3	
Date							Apr 2020						
Other issues							Increased vibrations	Increased vibrations		Increased vibrations		Increased vibrations	
Other solutions							Replace by repaired					Alignment	
Total starts	3400	3400	3200	2800	3000	2700	5400	5700	5200	4300	5200	5100	
Total years	31	31	30	30	29	29	28	28	26	26	25	25	

*MO generator Major Outage
Outage performed by IECo
OEM outage services provider
Alternative outage services provider
Data until December 2020