Synchronous Condensers with Flywheel for supporting power grid inertia: achievements and experience after first year of commercial operation

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Abstract

Synchronous condensers with directly coupled flywheel play a key role to maintain high voltage grid stability and power quality with the continuous increase of renewable sources and consequent shutting down of conventional power plants.

In response to dedicated commercial contracts to provide grid stability services with Italian Transmission System Operator, TERNA Rete Italia, Ansaldo Energia developed, manufactured, and installed 8 Synchronous Condensers with under vacuum flywheel (1750 MJ inertia each) for Synchronous Condenser plants realized in cooperation with ABB/Hitachi Power Grid.

At present day, five of these units are in commercial operation, depending on their execution stage, they are monitored on site or remotely by Ansaldo Energia personnel.

This article, after a brief description of flywheel design and of the experience gained during the erection, commissioning, and operation of these synchronous condensing plants presents the Synchronous Condenser plus Under Vacuum Flywheel solution made by Ansaldo Energia as a reliable and already available technology for the energy transition and beyond.

1. Evolving Electrical Grid and Synchronous Condensers, A Solution to Assure Power System Quality in Italy

The progressive phase out of conventional power plant using fossil fuel for power generation is gradually leading to a reduction of power grid inertia due to the consequently minor rotating masses connected to the power grids. In fact, the majority renewable energy is coming from source as solar or wind, whose generators have not big rotating masses, or no masses at all interacting with the grid, as for solar panels or power electronics. This new scenario provides huge challenges in power grids management due to the increasing complexity on voltage and frequency regulation and the decreasing of short circuit power [1][2].

For these reasons Italian Transmission System Operator, TERNA Rete Italia, established and continuously updates safety and development plans for the Italian high voltage grid, foreseeing installation of several synchronous condensing units in the Italian territory.

Ansaldo Energia supplied and commissioned two of the first wave of synchronous condensers part of this development plans more than five years ago [3] to support Sardinian grid.

It is noticed that first installed units did not foresee an additional flywheel, that was added in more recent bids following a specific approach related to Network contingencies.

With reduced inertia of the system, network contingencies can lead to extremely high rate of change of frequency (RoCoF) potentially exceeding the maximum allowable value of 2.5 Hz/s tolerated by power electronics [2] [4], hence the sizing criteria for the overall inertia constant of each synchronous condenser unit with flywheel is defined by the ratio between active power loss on the grid and maximum admissible RoCoF [2], similar definition can be found on pathfinder projects in UK [5], with inertia expressed in MJ or MW.seconds:

$$Inertia = H \times S_{rating}$$

$$H = \frac{\Delta P \, f_0}{2 S_{rating} RoCoF}$$

[1] Sardinia is an Italy island of Mediterranean Sea whose characteristic is to have a high renewable penetration level so it can be considered as a real testing area of future power grids.

Starting from the above requirements TERNA defined locations and standard requirements for synchronous condenser plus flywheel solutions to be installed in Italy.

It is to be noticed that the realized values of roughly 1750 MJ per power train provide an inertia value about 6% smaller than that of a AE94.3 gas turbine with the same air-cooled generator model.

TERNA furtherly fixed also challenging requirements for the maximum losses at no load and at rated load of the synchronous condensing plants [2].

The aim of Limiting the maximum losses is to make sustainable the synchronous condenser operation, because the overall absorbed power of a synchronous condensing plant is a cost for both the plant Owner and the Community.

After successful bids, Ansaldo is completing the commissioning of eight synchronous condensers plus flywheel units, distributed in seven plants.

2. From Conventional Generation to Synchronous Condensing Plants

Thanks to its experience with more than 1,300 units installed worldwide, Ansaldo Energia can provide a wide portfolio of proven and reliable generators equally suitable for both power generation and synchronous condensing applications. However, some modifications must be carried out to transform a synchronous generator into a synchronous condenser with flywheel.

On the generator itself the adaptation task is relatively easy: addition of a location or thrust bearing, key phasor, axial position probes and speed sensors.

Considering the experience gained from Ansaldo Energia in open cycle gas turbine powered plants, also the auxiliaries are a simple reshaping of existing reliable design (electrical BOP, mechanical BOP, starting system, closed circuit cooling water system, control and protection systems, firefighting system).

Although flywheels are not a new concept, it is on flywheel that the highest design efforts concentrate.

Ansaldo Energia is not new in designing and supplying flywheels: in the 1980s a short circuit generator with flywheel was supplied to ENEA Frascati as feeder for experiments on nuclear fusion, that flywheel had low inertia and no need of extreme losses reduction.

2.1 Flywheel Design

2.1.1 Design challenges

Inertia value, minimization of losses and good torsional behaviour are the key driver to design a modern, easy to use, reliable, and with low operational costs, flywheel.

Regarding the flywheel mechanical design, Ansaldo Energia choose to maximize the flywheel diameter, obviously within the limits of a safe rotor dynamics behaviour of the whole shaft line; this project choice has been preferred because at the increasing of flywheel diameter, at same inertia, a reduction in length and weight occurs, with a corresponding considerable reduction of bearing losses, forging cost, and civil works.

Regarding the flywheel fluid-dynamic design, a high flywheel diameter leads to a high tangential rotating speed, with consequent high windage/ventilation losses, and temperatures. A vacuum chamber is the solution to minimize such temperatures and losses. The lower the absolute pressure inside the vacuum chamber the lower are the windage losses.

To maintain the vacuum atmosphere within the inner shell of the flywheel, Ansaldo Energia, together with Criotec Impianti, started research and development activities for designing and manufacturing a vacuum rotating seal technology suitable for rotating shafts of roughly 400 mm diameter and 3,000 rpm speed.

These seals are insensible to operating vibrations and shaft axial thermal expansion as they have a large air gap filled by demineralized water which creates a liquid film to counteract the vacuum leakage.

The seals are described below in this article.

Summarizing, the main technical challenges covered during the design of the flywheel rotor, casing, and auxiliaries are:

- Rotor dynamic
- Lateral Analysis
- Torsional Analysis
- Mechanical Integrity
- Overspeed Conditions
- Fatigue Analysis
- Flywheel Cooling
- Flywheel cooling system design
- Flywheel painting solution
- Emergency flywheel ventilation (in case on vacuum loss)
- Customized rotating vacuum sealing development
- Sealing designing and power losses verification
- Experimental tests of sealing operation
- Braking System
- Acoustic Emissions

The painting solution chosen for the flywheel was also an interesting challenge : to maximize thermal exchange and not to be detached by the high tangential speed (around Mach 1, in certain conditions) of the flywheel. Dedicated qualification procedures were implemented to select, with the aid of our reputable suppliers, the optimal surface treatments, paint type and painting cycle for the different parts of the flywheel rotor.

Painting shall be idoneous for high temperatures to consider the possibility of vacuum loss.

Painting applied to central part of the forging shall not lose adhesion at high tangential speeds that could lead to painting detachment with consequent both debris inside the vacuum chamber (critical for operation of vacuum pumps) and protection loss on the flywheel surfaces. That paint shall maximise heat transfer.

Painting in the seal areas shall be suitable to the continuous contact with sealing water to avoid rust appearance in one of the most critical sections of the flywheel forging.

Painting in the remaining sections of the flywheel can be the same applied on generator rotors.

After complex iterations based on several multiphysics simulations of mechanical and thermal coupled problems, made to optimize the diameter and the thermal conditions of the flywheel, the design activity focused on the rotor dynamics, by implementing a shaft line model (Figure 1) to calculate torsional (Figure 2) and lateral behaviour. Stress limits were verified to ensure the integrity of the whole shaft line (condenser rotor and flywheel) in the worst network contingencies, such as nearby faults on the EHV grid and out of phase synchronization at 120°.

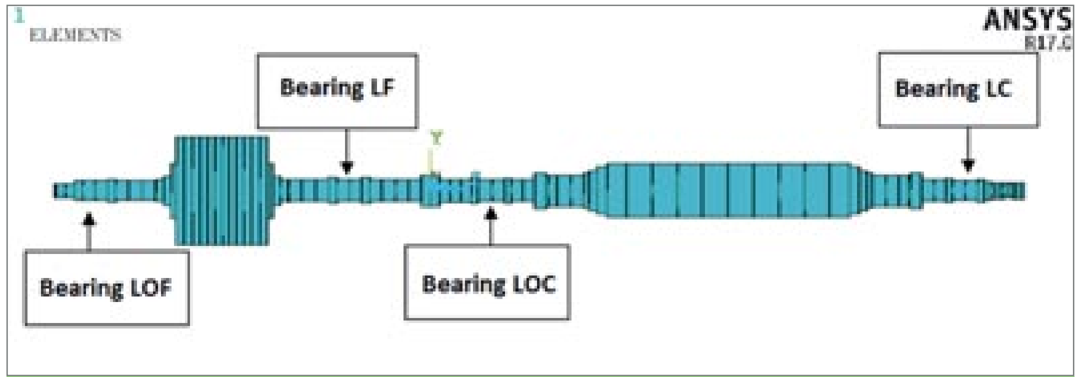

Figure 1 - Shaft line model. LC=collector side, LOC=opposite collector side, LF=braking side

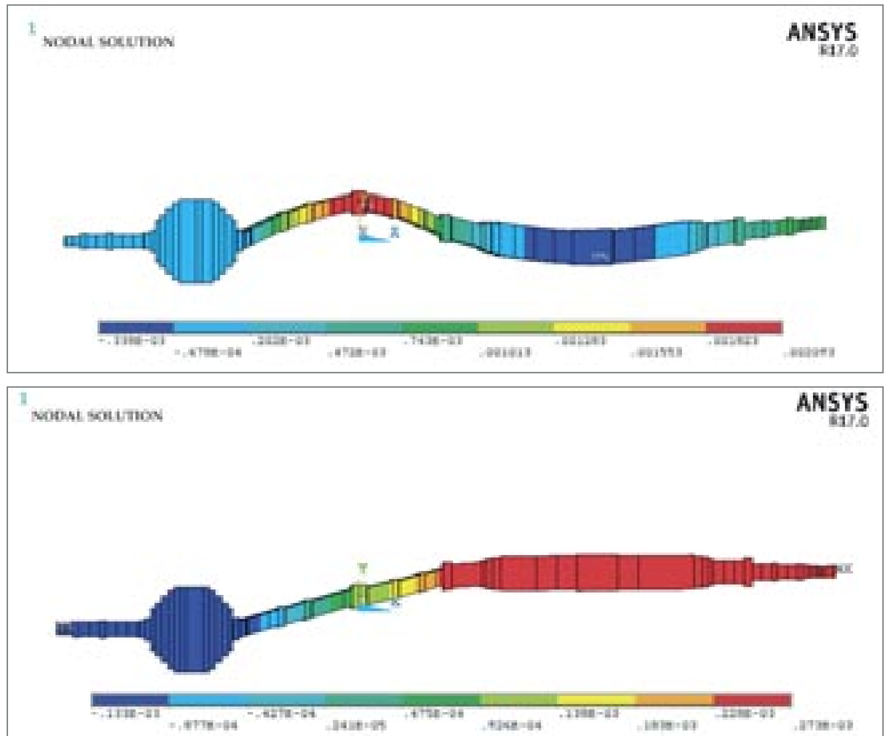

Figure 2 - First torsional mode verified by finite elements approach

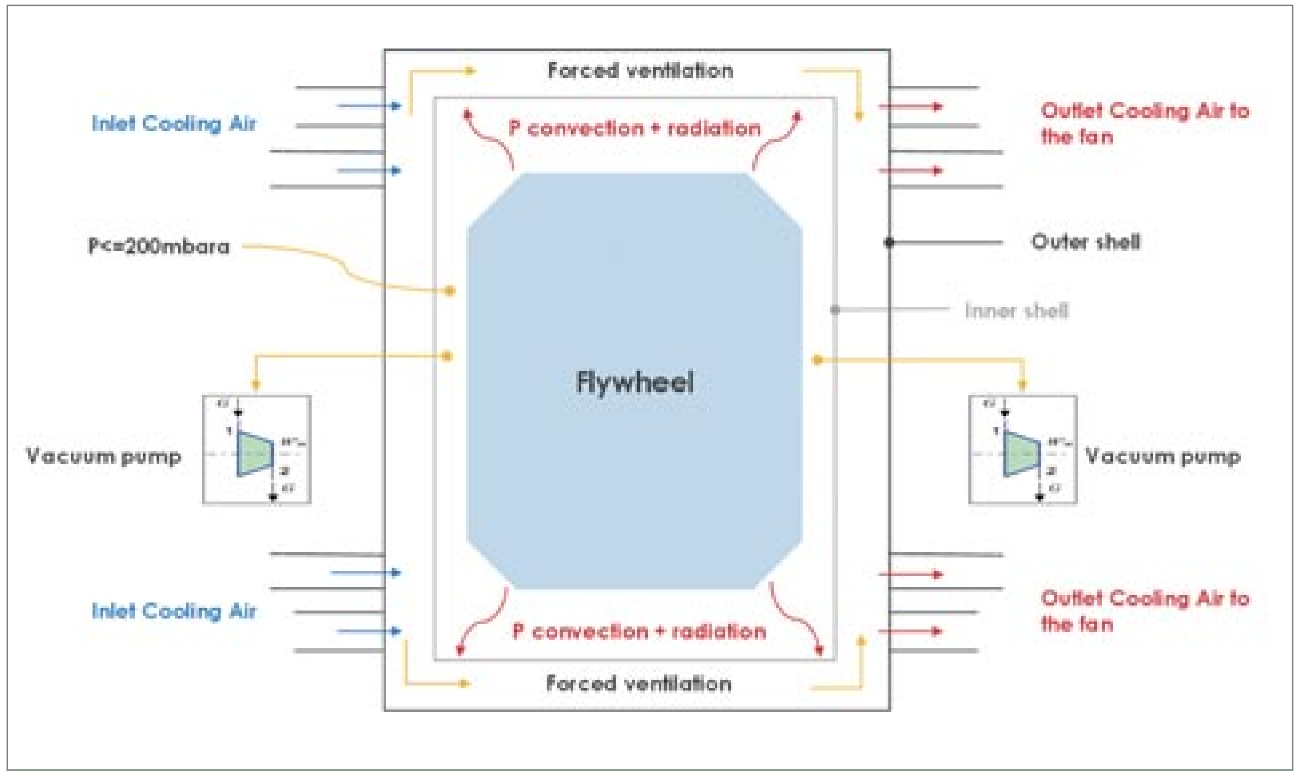

Figure 3 – Flywheel cooling scheme (under vacuum, with indicative absolute pressure)

The lateral stress verification has been mainly based on the modal analysis and dynamic response, respectively to avoid natural frequencies in prescribed ranges, and to simulate the vibration amplitudes considering an admissible residual unbalance. The obtained results have been within the admissible range foreseen in ISO 20816 standard.

Figure 3 shows the designed flywheel cooling scheme obtained after 3D thermo-fluid-dynamics modelling activities and analytical considerations. On Figure 3, it can be seen the vacuum chamber (inner shell), within where the vacuum pumps work. Since at low pressure, the convection effectiveness worsens due to the reduced air density, Ansaldo Energia designed an external forced ventilation to maintain the lowest possible inner shell temperature, thus contributing to the flywheel cooling both via convection and radiation. For the standard operating condition, Ansaldo Energia has calculated, by means of finite element models, the temperature distributions of the flywheel surface and the internal flywheel case environment, as shown as visible on Figure 5.

2.1.2 Vacuum rupture

In case of emergency, the vacuum atmosphere within the inner flywheel chamber can be broken for two reasons:

1. Any malfunction of the vacuum system or of the seals; in this case, if the operation remains safe , the unit will continue to operate thanks to the immediately switching on of the emergency fans up to the restoration of vacuum condition or sealing, having as a unique drawback a momentary increment of the power absorbed from the HV grid due to the increased windage losses resulting at the atmospheric pressure respect to the operation at low pressure

2. Any other situation that could lead to the complete stop of the unit and, depending on the kind of stop required, the unit could brake electrically with power recovery to the grid thanks to the static starter and then with the mechanical brake or with natural slowdown.

As written above at point 1., when the vacuum is broken, the emergency additional fans ensure the flywheel cooling. The emergency fans and the relative cooling path have been designed by Ansaldo Energia making a wide use of numerical and analytics thermos-fluid-dynamics calculation models as the one in the next Figure 6 reported.

The whole emergency set-up was successfully tested in the field.

To further optimize the emergency set-up, a mechanical brake helps reducing the run-down time by braking below a fixed speed (100 rpm in emergency conditions).

2 An operating condition can be considered as “safe” for the flywheel when the temperatures and mechanical vibrations not exceeding the maximum admissible values.

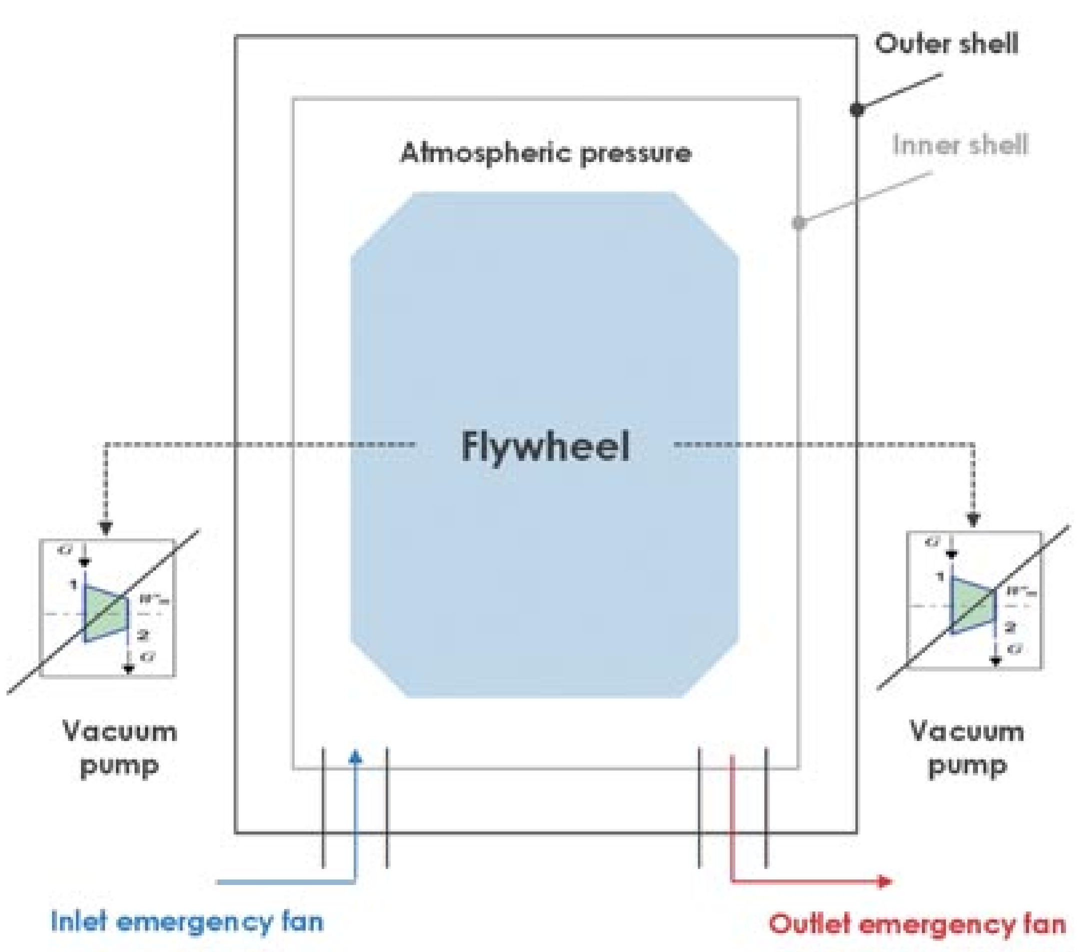

Figure 4 - Flywheel cooling scheme (without vacuum)

TEMPERATURE DISTRIBUTIONS

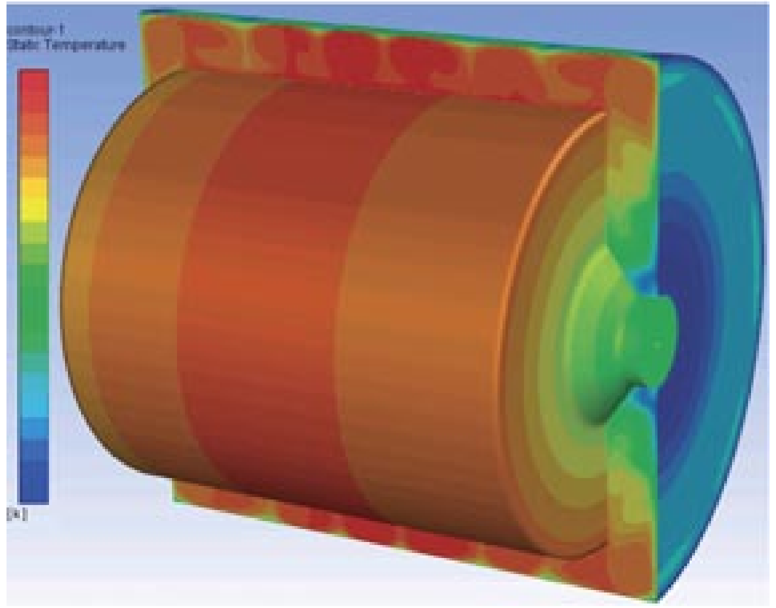

Figure 5 - Temperatures distribution of the flywheel surface within the under vacuum chamber

EMERGENCY COOLING AIR STREAMLINE

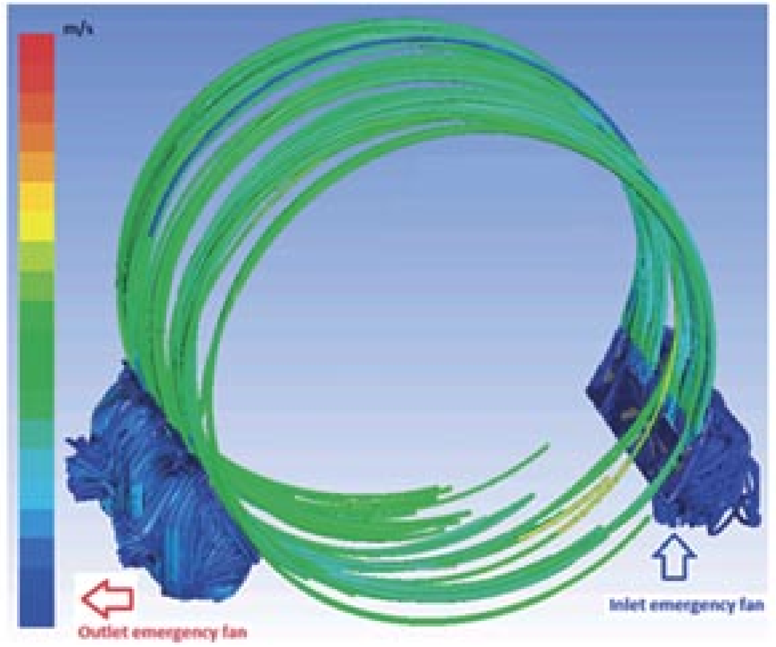

Figure 6 – Streamline within the flywheel and the inner shell

2.2 The Liquid Seals

On flanged and brake sides of flywheel shell module, there are installed two rotating seals within which a liquid ring is created to assure a correct pressure inside the shell.

The liquid seals chosen as the better solution in the flywheel system have been developed by Ansaldo Energia together with Criotec Impianti.

Criotec Impianti is an important player in the field of high vacuum and cryogenic applications, Partner of Ansaldo Energia and its subsidiaries also in the Nuclear Fusion technology sector.

Demineralized water level is the key to correct operation of liquid rings, the flywheel shell system with its auxiliaries takes care of cooling and recirculation of demineralized water, moreover a make-up system automatically adds demineralized water to compensate from evaporation or leaks.

Temperature, pressure, and flows are monitored for a safe, inexpensive, and correct operation of the flywheel.

The average values of absolute pressure measured on different units inside the inner shell remains between 25 and 35 mbar, hence minimizing the windage losses of the flywheel.

The sealing ring is maintained by the combination of shaft speed and water conditions (temperature and liquid ring thickness/level), the vacuum is naturally lost if one of the above mentioned variables goes out of a specific range, this means that, to avoid losing the plant, the flywheel can operate also without the vacuum with the fallout of increased losses, but also that in case of shut down the flywheel will slow down quicker due to increased windage losses after a certain speed reduction, as visible in Figure 11 liquid seals are deactivated below 2500 rpm.

It is to be noticed that originally the flywheel emergency operation in air at atmospheric pressure was thought to be applicable only during flywheel slowdown.

Thanks to the monitoring of temperatures and losses during tests on the field recreating emergency conditions, Ansaldo Energia can consider safe flywheel operation without vacuum as continuous in case malfunctions of the vacuum/sealing system for the time needed to restore normal condition and operation.

3. Factory Tests

All flywheel manufactured by Ansaldo Energia are subject to standard testing both at the premises of the Forger (chosen among our referenced suppliers for our turbine and generator forgings) and then in Ansaldo Energia before and after machining.

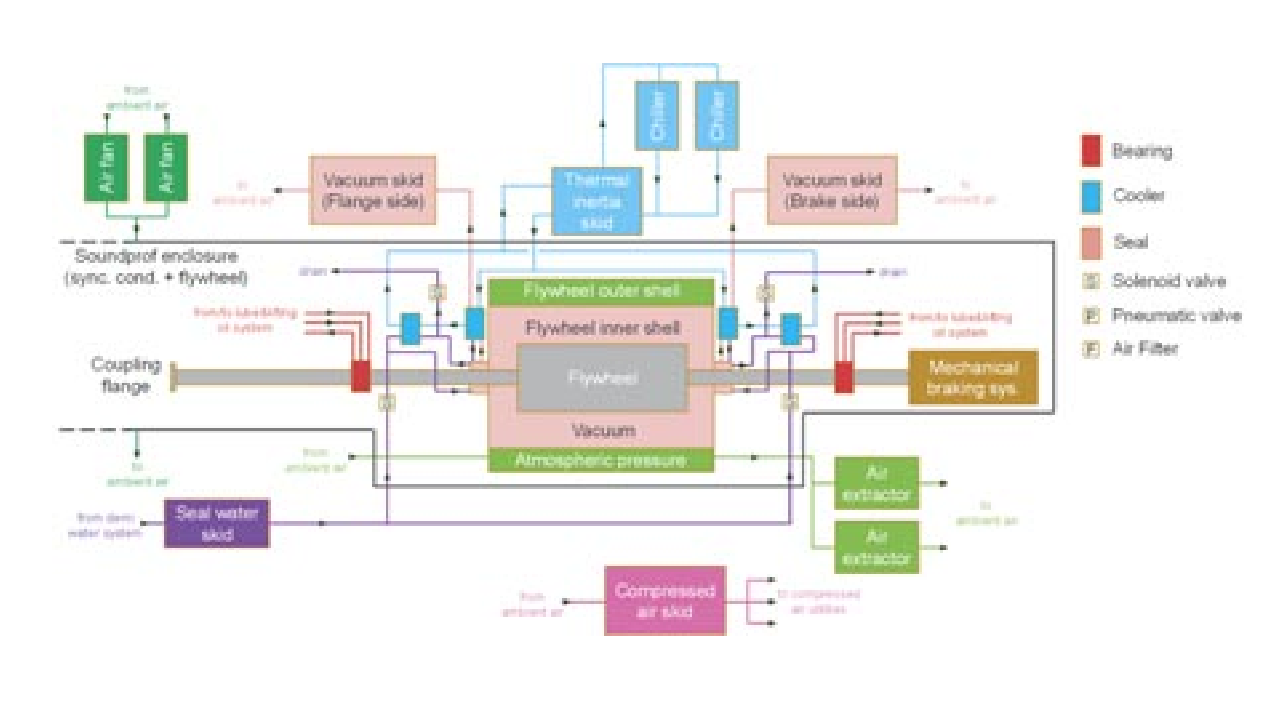

Figure 7 – Simplified P&ID of the flywheel system

All flywheels are balanced and overspeed tested in Ansaldo Energia factory in Genoa, Italy.

During overspeed and balancing tests it is possible to measure the ventilation losses as a difference between the prime DC motor power consumptions and the DC motor and bearing losses. Ventilation losses measured in open air can been reported at vacuum conditions by means of analytical way, giving an idea (no flywheel shell) of flywheel behaviour without vacuum.

On Figure 8 it is visible the flywheel during balancing (on the left), and, on the right, the detected temperature distribution is visible, captured by means of a thermographic camera. As predicted by calculations, the higher temperature is reached in proximity to the outer flywheel diameter due to the increasing of tangential velocity (around Mach 1) and consequently of the higher air friction losses.

It is to be noticed that moving from atmospheric pressure to under vacuum operation, windage losses will be ten time lower.

Roughness of the surface also give a relevant contribution to windage losses, as consequence it has been duly controlled during manufacture.

On some of the flywheels, Ansaldo Energia carried out type tests both for tuning of the auxiliaries and for checking the operation of the flywheel itself; the test bench, located in Ansaldo Energia factory, in Genoa, used to tests synchronous generators has been adopted for this activity.

Figure 8 – Flywheel during factory balancing in the pit with experimental thermography on the right

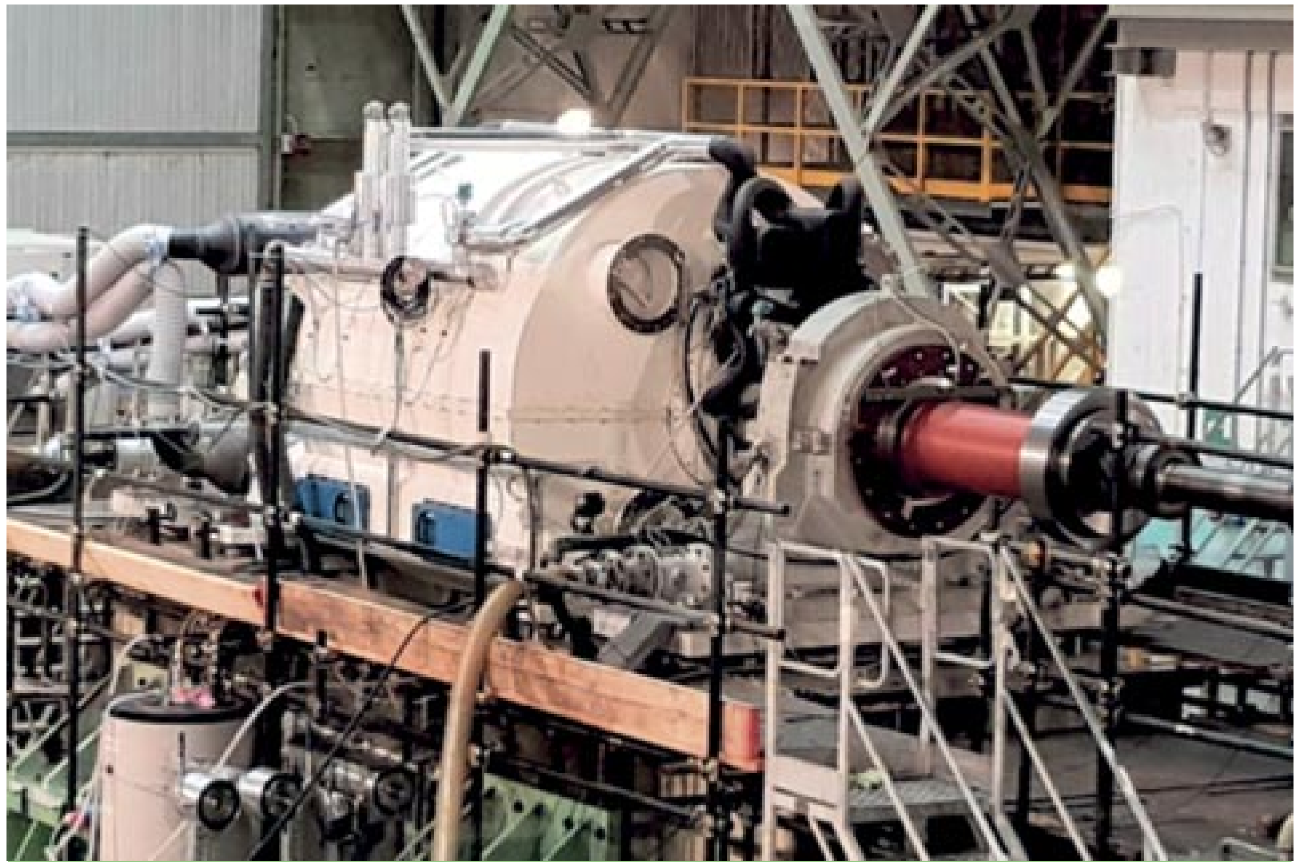
Figure 9 – complete flywheel system under test in Genoa, Italy

Tests were carried out mimicking what is carried out on synchronous generators (IEC60034-4-1, IEC60034-2, IEEE 115): a calibrated DC motor drives at full speed the flywheel to check shaft vibrations, and losses of bearings, liquid seals, and friction at different vacuum conditions.

Temperatures of the flywheel systems have been measured both with RTD's (where applicable) and pyrometers (for vacuum chamber).

Thanks to the factory tests, liquid seals were calibrated in operation, in factory.

A retardation test, inspired by those carried out on generators, confirmed the inertia of the flywheel, Factory tests confirmed the correct behaviour of the flywheel.

Overall behaviour of the flywheels together with the losses of the flywheel result within the expected values and the guaranteed limits.


Figure 10 – Site photos - Flywheel site assembly

Figure 10 – Site photos - Flywheel and Synchronous Condenser inside the weatherproof enclosure

Figure 10 – Site photos - Close view of Synchronous Condenser plant

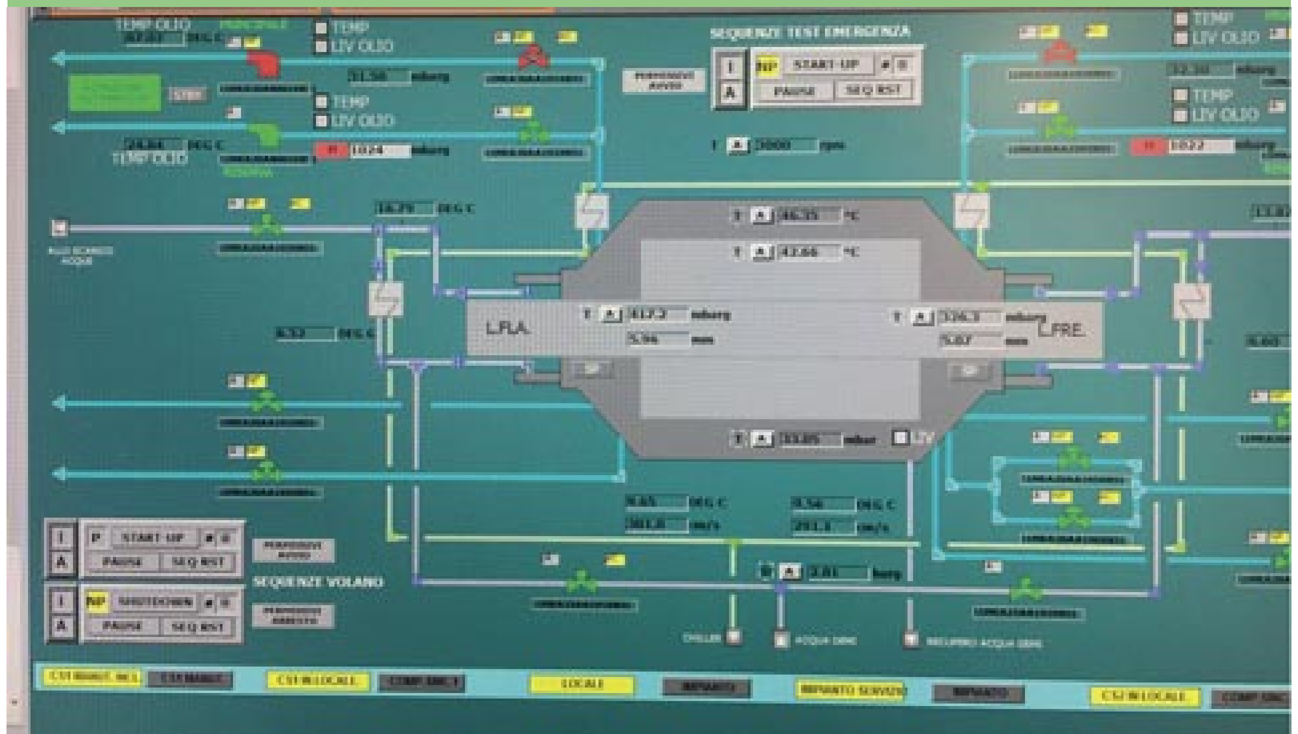

Figure 10 – Site photos - DCS screenshot (absolute internal pressure of the flywheel is 33.05 mbar)

4. Operational Experience

The first synchronous condensing plant in commercial operation was Matera at the end of 2020.

Matera, as all other projects for TERNA, is an outdoor facility.

There are two synchronous condensers in Matera, each one with its flywheel for an overall inertia of more than 3.5 GVAs. Relevant achievements for Italian HV grid have been deeply described for CIGRE session 2020 [2].

In 2021 three further plants went in commercial operation: Garigliano in October, Foggia in November, and Candia in December.

These three plants have one synchronous condenser plus flywheel each (more than 1.75 GVAs each).

With courtesy of TERNA several tests have been executed in these sites to define the actual operative logic and optimize the design of the auxiliaries/plant with great attention to availability, safety, and easy remote operation of the system.

The experience gained have been implemented in the various projects ongoing for TERNA and it is now in the state-of-the-art flywheel system proposed by Ansaldo Energia:

1. **Chilled water skid:** demineralized water is maintained at right temperature thanks to this skid, however in installations close to power electronics or with severe harmonics a traditional electric chiller is prone to unwanted shutdown with consequent loss of vacuum even in presence of a thermal inertia. In general, electronics should be minimized in this kind of plants (including also VSD on motors) or it must be resistant to strong harmonics. Mechanical chillers should be the preferred solution.
2. **Vacuum pumps shall be duly protected,** incoming air shall be filtered: this is a critical item in case of vacuum loss and then vacuum restoration without shutting down the synchronous condenser with manned intervention. Without proper filtering oil or water droplets could disrupt correct operation of vacuum pumps hence not reaching the required vacuum in the inner shell.
3. **Transition from vacuum operation to emergency operation in free air and continuous operation in free air:** dedicated noise study to minimize noise.
4. **Shaft vibration:** trip logics shall differ to those used in gas fired power plants, due to the involved masses, a different logic, more

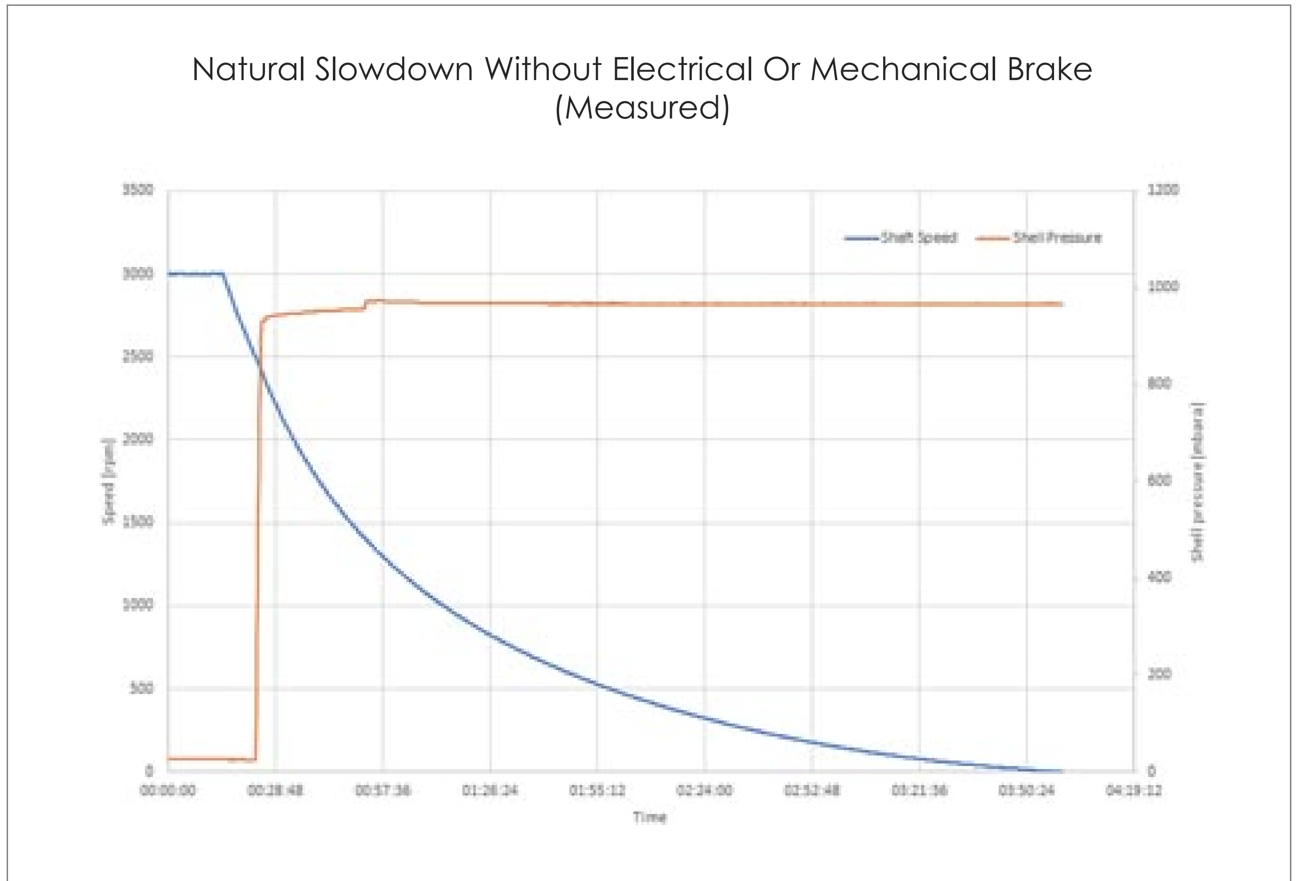

Figure 11 – Natural slowdown of the flywheel without electrical or mechanical brake

stringent, has been implemented to fully protect the shaft line.

5. **Tuning of plant DCS logics:** the timely activation and deactivation of valves, pumps, breakers is crucial for a correct start-up and run of the synchronous condensing unit. Improper timing could increase start-up time or decrease the start-up reliability of the unit.

All these plants are equipped with a Torsional Stress Monitoring System based on strain gauges on the shaft with redundant telemetry. This system act mainly as a monitor but also as a protection, after an initial tuning of the system, up to now no intervention of this protection has been registered.

These plants are remotely operated by TERNA and remotely monitored by Ansaldo Energia, thanks to the ten-year LTSA contract between TERNA and Ansaldo Energia.

Three further plants are under erection.

4.1 The Future of Liquid Seals

Liquid seals give several advantages in terms of losses minimization but, with actual design require both complex auxiliaries and low diameter of the shaft in the sealing area.

After more than 400 starts and 45000 operative hours gained on the five units in operation alternative sealing solutions with higher rotor diameters in the sealing zones are under evaluation in order to improve the overall availability.

5. Remote Monitoring and Diagnostic

The synchronous condensing plant realized for TERNA are remotely monitored by Ansaldo Energia Integrated Plant Support, IPS.

Based on a selected group of parameters of the machines such as temperatures, bearing vibrations, speed, voltage and reactive power values and of the complete plant (to have an overview of what is happening around the condenser) Ansaldo Energia IPS covers 24 hours/ 7 days customer requests, in order to provide technical recommendation within fast and standardized reaction time and to contribute to the preventive maintenance measures.

Giving the experience in design, manufacture, and assembly of synchronous machines the most common warnings notified to Customer Support team are related to problems on the measuring chain: a loosen connector, white noise on some acquisitions, and so on. In case of anomalous behavior of the machine and related plant (both detected by the Ansaldo Energia expert system or identified by IPS operator during daily checks or reported by customer) a dedicate Ticket will be opened and communicated to the customer to track all the information until the solution of the problem.

6. Conclusions

The progressive phase out of conventional power plant for power generation is gradually leading to a reduction of grid inertia and short circuit power. This scenario provides huge challenges in management of power grids and can disrupt the efforts for zero emission power generation sector.

A reliable and state of the art solution is the strategic location in HV grid nodes of synchronous condensing plants based on standard, reliable, two pole air cooled turbogenerators (full speed machines, 3000 rpm at 50Hz and 3600 rpm at 60 Hz) coupled with under vacuum and high inertia flywheels, to maximise effects on power quality while at the same time minimize investment and power consumption costs for the plant Owner.

To be cost effective the design of a full speed flywheel shall maximise rotor diameter and be enclosed in a vacuum chamber that allows both for losses minimization (measured absolute pressure inside flywheel shell below 35 mbar for liquid seals) and safe shaft diameter design.

Further the applied water-based sealing effect can be deactivated on needs, quickening plant shutdown and not limiting flywheel safe operation in case of vacuum system malfunction.

With the accumulated know-how in the energy sector, the experience and lessons learned during the execution of synchronous condensing plant projects for Italian Transmission system operator TERNA, Ansaldo Energia can provide state of the art synchronous condensers and flywheels with proven design and robustness for modern and future needs to stabilize HV grids.

7. Acknowledgement

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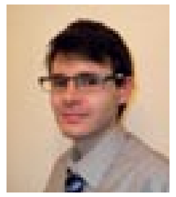
9. About The Authors

Roberto Biondi is a motivated electrical engineer having a major passion on generators and electric motors designing activities. Born near Livorno in Italy in 1984, and grew up in Grosseto southern Tuscany, he studied electrical engineering at the University of Pisa where he got the Master degree in 2011 and the PhD in 2016. Since 2012, he's employed in Ansaldo Energia as electromagnetic designer with the main goal to support company on the designing activities of large electrical machines used as turbogenerators in power plants



Mauro Priano is an electrical engineer that strongly feel electricity as the true engine for a modern world. Born (1981) and grown up in Piedmont region in Italy, he studied electrical engineering at the University of Genoa where he got the Master degree in 2006. His experience in Ansaldo Energia started that same year in the generator electromagnetic and functional design department. He is currently head of Functional Design and Tendering Department for Generators in Ansaldo Energia. ■