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Maintenance and optimization of the TCV power supply

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ABSTRACT

The TCV tokamak is powered by a flywheel generator to supply the magnetic coils and the auxiliary heating systems. The generator has just undergone its fourth major overhaul to make it ready for the next ten years, after more than thirty years of almost trouble-free operation.

In the context of the energy crisis in Europe, we took advantage of the generator outage to evaluate the power consumption of the TCV power supply system and to implement some changes to increase the energy efficiency.

After a presentation of the operation history and a brief description of the operating mode, this article presents the work and the findings of the generator overhaul. Then, the changes implemented in the generator plant are discussed in terms of reducing the energy cost and improving the availability of the TCV experiment.

1. Introduction

TCV (Tokamak à Configuration Variable) is characterized by a unique magnetic coil system fed by 20 independent power supplies [1, 2], associated with an advanced control system [3] and a high degree of flexibility in its heating [4]. It offers unrivaled plasma shaping capability and an extensive range of accessible plasma parameters that are highly relevant to the physics of nuclear fusion by magnetic confinement [5].

TCV is powered during the plasma discharges by a flywheel generator (turbo-generator) to supply the coil converters and the auxiliary heating systems (4.5 MW/2 s ECRH + 2 MW/2 s NBH). Delivered in 1989 [6], the generator was designed to provide 120 MJ every 5 min. In 1998, a flywheel was coupled to the generator rotor to double the rotating inertia, thus doubling the deliverable energy [7]. At that time, the interval between the pulses was extended to 10 min, to accommodate both the extra time required to speed up the rotating masses and the increased losses due to the addition of the flywheel.

The turbo-generator is a synchronous machine derived from a commercial model for a steam turbine. It is distinguished mainly by the 120 Hz operating frequency, and a 4-pole rotor. However, the operating mode is quite different compared to the standard application. It is first used as a motor to accumulate kinetic energy in the rotating masses and then takes advantage of the reverse conversion of the mechanical energy into electricity to deliver high power during very short time. The drive system that is used to speed up the machine can provide a maximum of 2.2 MVA under reduced voltage (2.5 kV instead of 10 kV), whereas the generator is rated 220 MVA.

In the context of the energy crisis in Europe, we took advantage of the recent generator outage to evaluate its power consumption, which in the end is precisely the consumption of the TCV power supply system. Looking at the different types of generator losses, we quickly realized that the generator efficiency could be greatly improved by reducing the venting losses in particular, taking better account of the duty cycle between motor and generator modes. The margin for improvements stems from the fact that the air cooling is designed to remove the losses at rated power, i.e. in generator mode (220 MVA/10 kV), while the machine is operated in motor mode (2.2 MVA/2.5 kV) for almost 99 % of the time.

After a description of the generator history and the findings of its 4th major overhaul, we present and discuss here the result of the study undertaken in collaboration with General Electric Steam Turbine (GE) to reduce the energy consumption of the generator. Note that the power saved also enables the generator to be accelerated more rapidly, reducing the time to prepare a TCV plasma discharge.

2. Operation history

The generator was commissioned in 1990. The first years of operation were mainly dedicated to the commissioning of both the TCV power supply system and the TCV control system, so the first official plasma in TCV took place on the 26th of November 1992. The first generator overhaul was performed at the end of 1995, according to the manufacturer's guideline: an overhaul every 5 year, alternating minor and major overhauls.

During a minor overhaul, the rotor remains inside the generator. The

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Table 1
History of the generator overhauls.

Year	Activity	Main purpose
1990	Commissioning	
1995	Minor overhaul	Visual checks
1999	1st major overhaul	FW installation
2004	2nd major overhaul	Rotor balancing
2012	3rd major overhaul	Rotor balancing
2023	4th major overhaul	Rotor cleaning

main goals are to check the condition of the bearings and the cleanliness inside the machine. During a major overhaul, the rotor is removed from the generator, giving access to the magnetic core for checking. Inspection and balancing of the rotor has to be done on the manufacturer premises. As these operations are costly, the rotor is only transported in specific cases, for instance if the vibration characteristics have changed over time or if the rotor isolation has deteriorated.

Table 1 gives the history of the generator overhauls. The generator manufacturer recommends to carry out an overhaul every 5 years or 25′000 equivalent hours, counting 20 h for each start-up. This factor of 20 is intended to take into account the aging of the rotor winding due to both the fatigue caused by the centrifuge force and the thermal fatigue.

An overhaul is a major cost for a research institute having limited budget for the infrastructure maintenance. It amounts approximately to 1 % per year of the purchase price. SPC has thus tried to extend the time interval between two outages. During the 2nd and 3rd major overhauls, the rotor inspection in factory did not raise particular concern, leading us to define a new pragmatic rule for the maintenance plan: an overhaul after 10 years of operation or 10′000 effective operating hours, unless there is a clear indication that an earlier intervention is necessary.

Fig. 1 shows the evolution of the number of TCV plasma discharges performed since the previous overhaul. Fig. 2 shows instead the evolution of the operating hours. On both figures, one can observe that TCV operation becomes more and more effective. In 2022, the total number of plasmas discharges exceeded 5′000 over approximately 1′500 h of operation, in spite of the fact that TCV is operated only from 8 AM to 6 PM, from Tuesday to Friday. The 4th major overhaul took place 11 years after the 3rd, but there was no operation during the whole year 2014, due to the modification of the TCV vacuum vessel in view of the installation of the 2 neutral beam injectors (NBIs).

3. Operation mode

Fig. 3 shows the layout of the generator and the flywheel. As anticipated in the introduction, there is no pony motor to speed up the generator. It is driven by a static frequency converter (SFC), which has 3 set-point speeds, called n1, n2 and n3. The set-point n1 is the programmed speed at which the generator mode is triggered. It can be adjusted in the range from 3′260 rpm to 3′800 rpm, according to the energy required by the TCV plasma scenario. The machine runs at n2= 2′880 rpm between the pulses, in order to reduce the energy consumption. The speed can be lowered to n3= 1′620 rpm, to further reduce the energy consumption, when the time delay between two pulses is expected to be longer than usual.

Although the generator was built to perform a pulse every 5 min, it is in any case almost impossible to have two TCV plasma discharges in less than 10 min: first, because the physicists need time to configure the plasma discharges, and second, because the TCV internal walls are cleaned between the pulse applying 5 min of helium glow discharge. Despite this, the TCV pulse cadence has been drastically increased, since there is always a minimum of two scientific programs running in parallel (interleaved) to leave enough time to the physicists to prepare and program the plasma discharges, since 2014.

4. Generator overhaul

The rotor extraction out of the stator is the most spectacular task of the overhaul work, although it is not inherently difficult. Nevertheless, it requires approximately three weeks of preparation work, including among others the disassembly of both generator bearings and the collector brush gear, plus the complete disassembly and the removal of the flywheel and its bearings. See Fig. 4.

The rotor was then transported to the rotor factory in Birr (Switzerland). The main finding of the inspection was carbon dust contamination of the rotor winding. The insulation value was so low that it would probably not have been possible to postpone the overhaul for another year.

The root cause of the presence of carbon dust inside the generator is believed to be an excessive wear of the carbon brushes, due to the run-out of the slip rings and to the sharp edges of the collector grooves.

A careful cleaning of the rotor winding heads, after the removal of the retaining rings, enabled the insulation measurement to recover a standard value. In addition, the collector was entirely disassembled from the rotor shaft. The slip rings were re-machined to comply with the mechanical standards. Then, the insulation between the slip rings and the shaft was replaced, and finally the whole collector assembly (slip rings + cooling fan) was entirely repainted.

Several actions were taken to mitigate the risk of contamination by carbon dust. The sealing of the brush gear covers has been improved, and a new filter assembly has been designed for the collector cooling air ducts. The replacement of the stator air filter has also been added to the maintenance plan. Moreover, the measurement of the rotor insulation is now included in the routine procedure for monitoring brush wear. Anyway, a visual observation of the brushes vibration during operation must occur regularly, since the collector is not provided yet with vibration sensors.

5. Generator power in motor mode

The energy drawn from the grid by the TCV plant can be split into two parts. On the one hand, there is the energy required to wind up the rotating masses to accumulate the energy that shall be delivered to the TCV power supplies. On the other hand, when the machine is running at constant speed, the energy delivered by the SFC compensates for the generator losses, which are presented on Fig. 5.

When operating in motor mode, the generator is fed under reduced

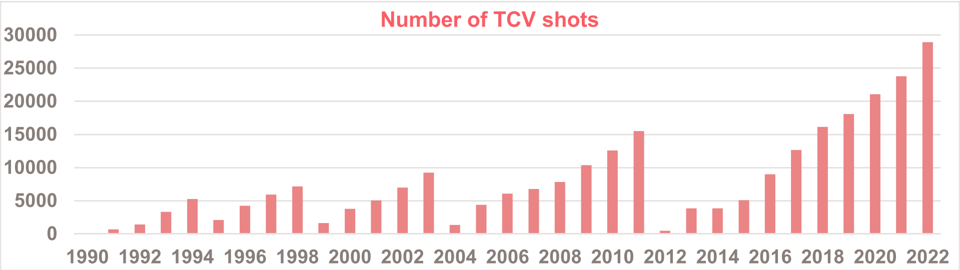

Fig. 1. Number of TCV plasma discharges (shots), from the last overhaul.

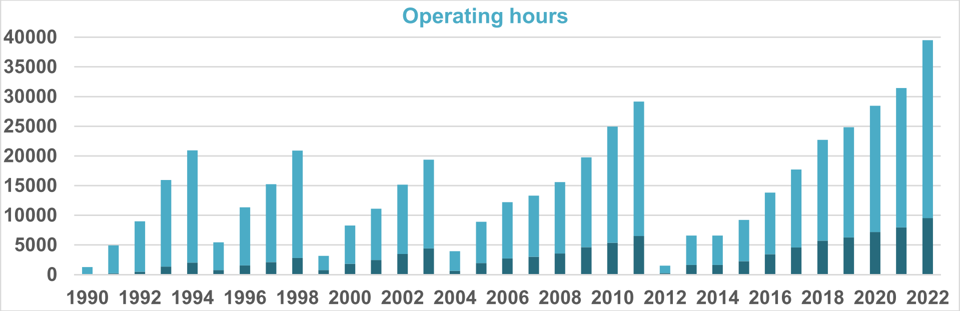

Fig. 2. Effective operating hours (dark blue) and equivalent hours, i.e. counting 20 h per start-up (light blue).

voltage. This simplifies the design of the motor drive, and dramatically reduces the magnetic losses. Moreover, as already mentioned, the ratings in motor mode are approx. 1/100th of the ratings in generator mode, so the copper losses in the windings are very low. The losses in motor mode are therefore dominated by the venting losses and the bearing losses.

The venting losses inside the generator can be divided into three parts: the fan losses, the losses due to the friction of the rotor body, and the losses due to gas friction in the rotor winding. The distribution of losses among these three parts cannot be established by measurement on site; only the total of the venting losses can be measured, by calorimetry on the generator air cooler. Nevertheless, the cooling fan of the generator was measured in factory, at the time of the series production, and is well characterized for several blade angles. The losses on the generator bearings were also measured by a calorimetric method during the factory acceptance tests. The surface friction losses of the flywheel and the losses of its bearing were measured as well before being delivered on site.

On the collector, the losses are from three factors: (a) mechanical friction between the brushes and the slip rings, (b) electric dissipation due to the current flow through the brushes and (c) venting losses due to the collector's own cooling fan. They were measured on site by calorimetry, at n2 only. The last power loss to mention is the power required by the main oil pump driven directly by the generator shaft. This power is well defined by the pump provider.

6. Reduction of the energy consumption

Rising electricity costs and fear of energy shortages have prompted us to find solutions for reducing the energy requirements for the TCV plant, especially since TCV may appear to the energy supplier as a heavy consumer which can easily be disconnected from the grid [8].

Generally speaking, the best way to save energy is to reduce the generator speed, since the venting losses rise as the cube of the speed. Although there is no margin for lowering the n2 setting, being just above the flywheel critical speed (2′700 rpm), it was possible to decrease the n1 set-point. It has thus been redefined, such as to have 120 MJ of extractable energy between n2 and n1, which is sufficient for all routine plasmas in TCV. Hence, the total kinetic inertia J being 9′600 kg*m^2, the n1 speed has been reduced from 3′400 rpm to 3′260 rpm.

Fig. 3. generator (red) and flywheel (black).

Fig. 6 shows various traces during a TCV standard shot (TCV #77,979) performed with n1 set to 3′260 rpm. The last two frames are the most relevant here. The mechanical power extracted from the rotating masses (P_{mec}, second frame from the bottom) is calculated with the rotating speed (third frame from the bottom) as only input, according to Eq. (1). Then, the extracted energy (last frame) is the integration of the mechanical power Eq. (2). One observes that the extracted energy was lower than 100 MJ for this shot, and the speed did not drop below 3′000 rpm. This means there was an energy reserve exceeding 20 MJ to be used e.g. for the auxiliary heating of the plasma.

$$E_{cin} = \frac{1}{2}J\omega^2;\ P_{mec} = -\frac{dE_{cin}}{dt} = -J\omega\frac{d\omega}{dt} \tag{1}$$

$$E_{extract} = \int P_{mec}\, dt \tag{2}$$

with E_{cin} = kinetic energy and ω = angular speed

The reduction of the venting losses has been studied by GE, in the framework of a specific contract. With the help of computational fluid dynamics (CFD) simulations, they proposed two modifications for the air cooling of the generator. First, the blade angle of the generator cooling fan (Fig. 7, left) could be reduced from 18° to 11° In this way, the air flow is reduced by approx. 50 %, and the power to drive the fan by 85 %, saving approx. 80 kW at n2. An estimation of the generator cooling in pessimistic conditions allowed us to validate this proposal.

CFD simulation models and detailed calculations are not presented here, as GE declined to provide information. Anyhow, the modification of the fan blade angle has been implemented during the overhaul, so that the results of the study have been verified. Intensive shot cycles (up to 8 shot per hours) confirmed that the generator cooling is not affected by this modification. The benefit in terms of power consumption is presented on Fig. 8. One can observe e.g. that the saving is of 130 kW at 3′400 rpm.

Fig. 4. Generator rotor (left) and stator (right).

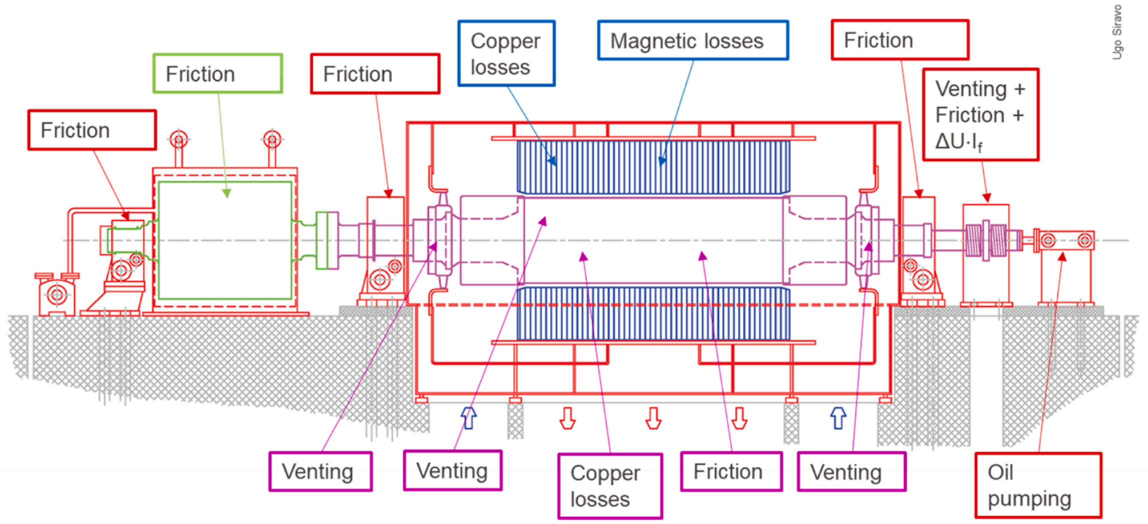

Fig. 5. Overview of the generator shaft line, with indications of the losses compensated by the generator drive.

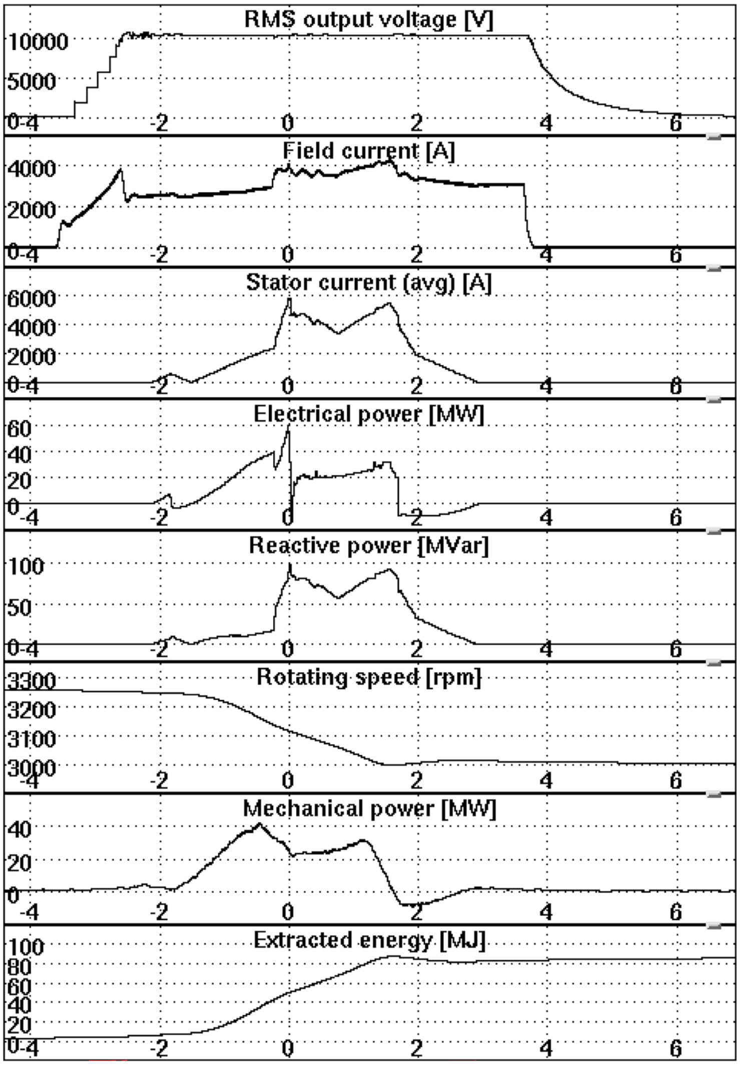

Fig. 6. Data vs time [s] of a TCV standard shot.

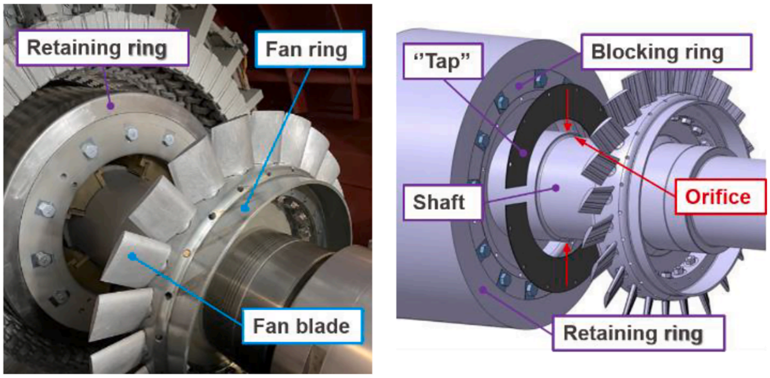

Fig. 7. Cooling fan (left) and rotor orifice (right).

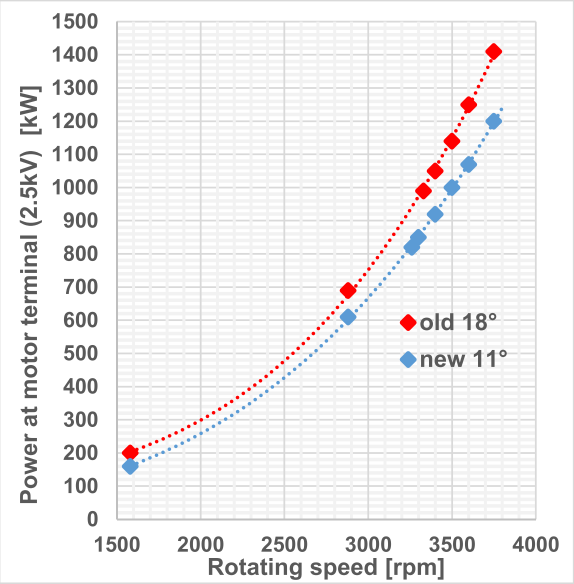

Fig. 8. Power measurement at generator terminal.

The second proposal is even more promising, saving an additional 100 kW at n2, thanks to the installation of an orifice at both ends of the rotor winding. This orifice will throttle the gas flow into the hollow winding conductors, thereby reducing the windage losses. Its mechanical design is not trivial, due to the high rotating speed. Its installation is also a concern. SPC has thus studied many options. The selected solution consists of fixing on the rotor end a light plate made in two parts to close the surface below the blocking ring in which the cooling air enters into the rotor. The orifice will be created between the taping plate and the rotor shaft, as depicted on Fig. 7 (right). This solution is still requiring the approval by the generator manufacturer (GE). It is therefore not decided yet if this proposal will be implemented or not.

Fig. 9 shows the value of the various generator losses in motor mode, running at the n1 speed, before and after the overhaul. The combination of the two measures taken (modification of the fan blades angle and reduction of the n1 set-point) saves over 20 % of power, at n1.

7. Benefit for the TCV operation

The reduction of the power losses allows the generator to accelerate faster, when it is driven by the SFC. Considering that the n1 set-point has also been decreased, the time to speed up the generator from n2 to n1 has been reduced by 1 min, from approx. 3.5 to 2.5 min.

The overall time saved during an operating day would allow performing 2 or 3 more shots. Nevertheless, the time to prepare a TCV plasma discharge does not depend only on the time to wind up the

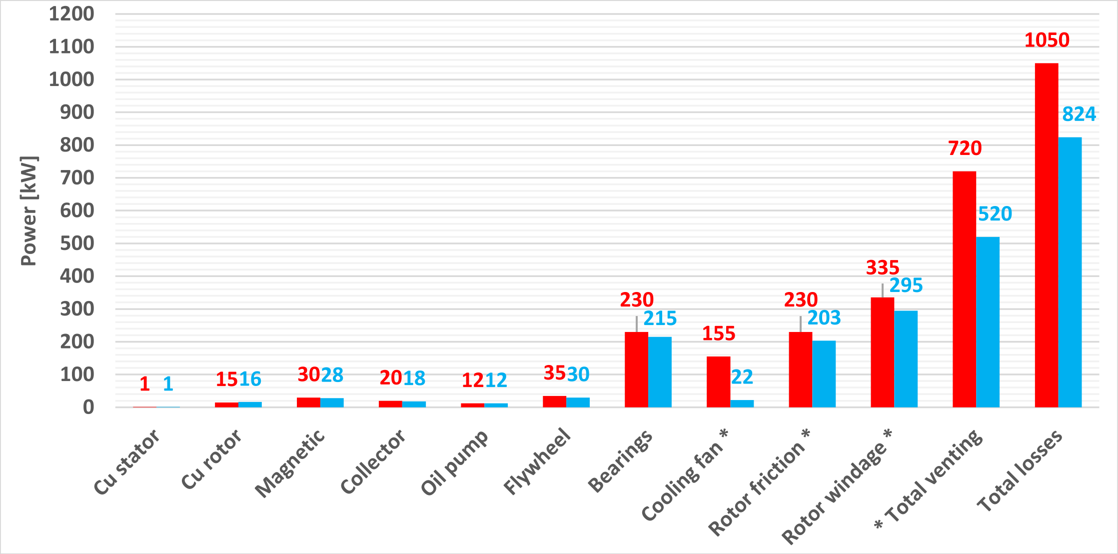

Fig. 9. Power losses at n1 = 3′400 rpm with 18° fan blades (red) and at n1 = 3′260 rpm with 11° fan blades (blue).

flywheel generator. It also depends on the time to prepare the control system, the data acquisition and the physics instrumentation (“diagnostics”) as well. In these conditions, the time saved during the ramp-up of the generator speed has not yet allowed to reduce the interval between two shots, up to now.

8. Efficiency of the flywheel generator

The energy efficiency of the flywheel generator could be defined as the ratio of the extracted energy over the energy consumed between two pulses. The reduction of the power losses obviously increases the efficiency, but the efficiency is affected more by the time running from one pulse to the next. Moreover, to have a better efficiency, the generator pulse must be triggered as soon as the generator has reached n1. In other words, the efficiency depends more on the course of the operation than on the power losses, so its value is not so relevant.

Anyway, the reduction of the power losses, and the decrease of the n1 set-point as well, will indeed reduce the TCV operating cost. With the new operating conditions, the electricity bill will be reduced by approximately 16 %. Knowing the annual consumption of the TCV power supply system may exceed 1′000 MWh according to the number of operating hours, this is a significant achievement.

9. Conclusion

We took advantage of the 4th major overhaul of the TCV flywheel generator to improve its efficiency, by reducing the venting losses. A first step consisting of the modification of the generator cooling fan has been implemented. At the same time, the generator running speed has also been decreased. A second step consisting of the installation of an orifice fixed at both ends of the rotor is still under evaluation.

This work was carried out in the context of the global energy crisis with the risk of electricity rationing in Switzerland. As a first result, the energy need for the TCV power supply system has been reduced by approx. 16 %, which will mitigate the increase of the electricity cost.

The new operating conditions of the generator flywheel allows in addition saving time in the TCV shot cycle, so that it would be possible to accommodate up to 3 more shots within an operating day.

CRediT authorship contribution statement

U. Siravo: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **J. Dubray:** Writing – review & editing. **H. Elaian:** Investigation, Writing – review & editing. **D. Fasel:** Writing – review & editing. **D. Velasco:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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