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Analytical method for design and thermal evaluation of a long-term flywheel energy storage system

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***Abstract*—This paper presents a novel analytical method for electro-mechanical design of a high speed long-term flywheel energy storage system and thermal evaluation of possible operating modes of the system. Flywheel's composite shell rotor along with the motor/generator unit are assumed to be placed into a sealed vacuum chamber, which presents a challenge of heat transfer, produced by rotor losses. Developed method takes into account thermal radiation properties of the rotor and is realised using Mathcad software, which allows for quick investigation of any flywheel configuration. The method involves calculations for preliminary rotor sizing and determining achievable operation modes, while keeping the rotor under a specified temperature limit. Results of using this method for studying dependencies of thermal performance on initial system parameters are presented and conclusions are drawn. Based on the conducted study, recommendations on system design considerations are given.**

***Index Terms*—Flywheel energy storage, calculation method, electrical machine, thermal analysis, vacuum operation.**

I. Introduction

Flywheels as energy storage devices are gaining popularity nowadays, due to latest developments in composite materials, magnetic bearings, efficient high-speed electrical machines and high frequency power converters [1]. So far, flywheels have been most successful in uninterruptable power sources, due to their fast reaction to power grid disturbances, and in aerospace applications, because of high reliability and little to no maintenance [2]. Among other possible applications, there is a rising need for a storage device to compensate for irregular operation of renewable power sources, that inevitably creates problems with coordination between the power being generated and load demand [3].

As the spread of environmentally friendly energy generation based on wind and solar power, heavily depends on its efficiency and stability an enabling technology is needed to improve upon these important characteristics. Modern flywheel's superior power and energy densities, efficiency, reliability, long life-time and environmentally friendly nature make it a viable alternative for conventional energy storage means and an enabling compliment for renewable power generation.

However, common irregularities of wind and solar power often occur hourly and/or daily and require energy storage for hours. Many challenges arise from adopting a flywheel for long-term energy storage, as any idling losses are draining the stored energy, which can make a flywheel unusable for long-term operation. This issue is commonly addressed by placing the rotor of the flywheel into a sealed vacuum containment and implementing a magnetic bearing support to allow for a completely contactless operation and mitigate losses. [4]. Alternatively, the designed electrical motor could be equipped with an additional winding set capable of producing radial force to support the rotor [5, 6]. In this way, a magnetic bearing can be removed from one end of the shaft, and as a result, the shaft length is reduced. This furthermore leads to a higher critical speed of the machine [7]. However, these measures create a very harsh environment for rotor cooling, so that dissipating motor/generator losses, produced in the rotor, becomes a very difficult task [8].

Due to the mentioned reasons, design process of an electrical machine becomes important not only for reaching high overall system efficiency [9], but also for lowering thermal load on the rotor and allowing for better operating conditions. Hence, the main contribution of this work is the proposed analytical method for calculating and evaluating thermal properties of a vacuum operating electrical machine along with the design of the electro-mechanical part of a flywheel, capable of efficient long-term energy storage.

II. Proposed design method

The design of a motor/generator for a long-term flywheel is a very important issue, which strongly influences system performance, as the process of energy conversion from mechanical into electrical and vice versa happens in the electrical machine. The design process for vacuum rated operation and a sophisticated purpose of driving a flywheel should be based primarily on heat transfer conditions [10].

The discontinuous operation of the flywheel implies that a specific amount of energy produced by the rotor losses can be stored for a number of operating cycles, but then will require some time to be transferred to the stator by means of thermal radiation, as it is the only way of heat transfer in a contactless vacuum operation. All these complications require a new design method that would allow to size the machine according to the properties of the materials, system configuration and the needs of a specific application.

Main advantage of the developed method is quick analytical evaluation of any flywheel configuration. The basic outline of the method is presented in Figure 1. This procedure can be used with any electrical machine type, as firstly it provides the

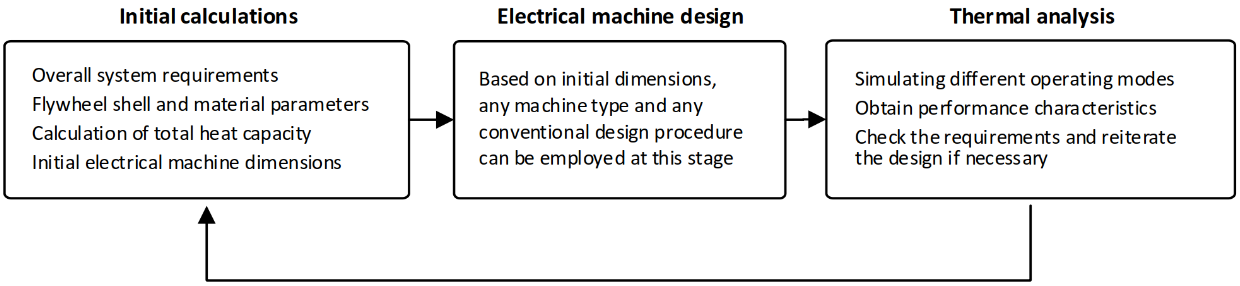

Fig. 1. Outline of the design procedure

initial parameters and dimensions for the electrical machine design and after the design is complete, the performance of the resulting flywheel system is analysed. Developed method covers most important aspects of the flywheel system in a single worksheet, which is very convenient as any parameter change influences can be instantly monitored in different parts of the design process. Thus, the proposed method is a very practical tool for studying thermal properties and system performance with different operating configurations. If the results of a specific configuration do not satisfy the requirements, the design can be reiterated from any point in search for an optimal configuration. Also it allows for an investigation of relationships between different parameters and their influences on each other. The diagram in Figure 2 presents in detail the workflow of the method, calculation sequences and relations.

Basic system requirements are making up the most important initial parameters for further calculations: total energy stored in the system, rotational speed range of the flywheel, energy conversion cycle (charge/discharge) time, corresponding machine power etc. Also, necessary material properties are defined, such as density, specific heat capacity, emissivity coefficient and maximum sustained temperature. Calculations performed further are divided into three main parts: flywheel system parameters calculation, design of electrical machine and thermal evaluation of the system.

A. *Flywheel system parameters calculation*

This first part of the design process is primarily based on [11] with regard to designing and producing composite flywheel shells. The assumptions about possible energy densities and properties of composite materials are made based on the aforementioned reference.

This part starts with definition of stored energy, rotational speed range and composite material selection. Based on those parameters, the required dimensions of the shell are calculated and the appropriate shaft size is defined. After the definition of thermal properties of materials, the flywheel shell and the shaft heat capacity is calculated, at this stage, without taking into account thermal properties of the machine. The results of this calculation will influence strongly the thermal inertia of the rotor and the time and energy it takes for the rotor to reach specified temperature limit. The higher values of total stored energy imply a bigger flywheel and thus a higher overall heat capacity.

B. *Design of the electrical machine*

The second part can be divided into two smaller parts, the first of which is a preliminary calculation of machine parameters and size. Initial parameters for this part, are the rotational speeds of the flywheel, charge/discharge time at rated power, corresponding machine power and the desired efficiency in the rotor. The first limitation imposed on the rotor size is the mechanical stress at high speeds. Based on the mechanical strengths of electrical silicon steels, the surface speed limit of laminated rotor is selected [12] and corresponding maximum radius at specified angular velocity is calculated. For the selected maximum radius, an optimal rotor length is calculated [13]. However, this part is not meant to provide exact rotor dimensions, but rather to provide reference values that can later be changed according to specific application needs.

Based on the selected rotor size, its volume and heat capacity are determined. When total heat capacity and temperature limits of the rotor are known, the resulting characteristics allow to determine the number of energy conversion cycles that can be performed before the rotor reaches its temperature limit. Corresponding operation time and energy being absorbed by the rotor can already give an insight into possible system performance and give an initial guess for required rotor size and efficiency.

The second part of the machine design involves the complete design of an electrical machine based on previously obtained parameters. Any machine type can be selected and any design method can be employed at this stage. However in this study a three-phase permanent magnet machine is designed, as it is considered one of the most efficient topologies for high-speed flywheels [14]. Calculation method is based on [13] and follows the outline presented in Chapter 7 of the same reference.

As a result of the thorough design, all machine parameters and dimensions are determined, along with the parameters needed for further thermal analysis such as efficiency, rotor losses, masses of active parts etc. After the machine design is complete, the heat capacity is recalculated to include the final machine dimensions and parameters. In the end of the second part, the thermal radiation properties are defined by computing the surface areas of the rotor A_r, introducing emissivity factors ε_r to corresponding materials and finally

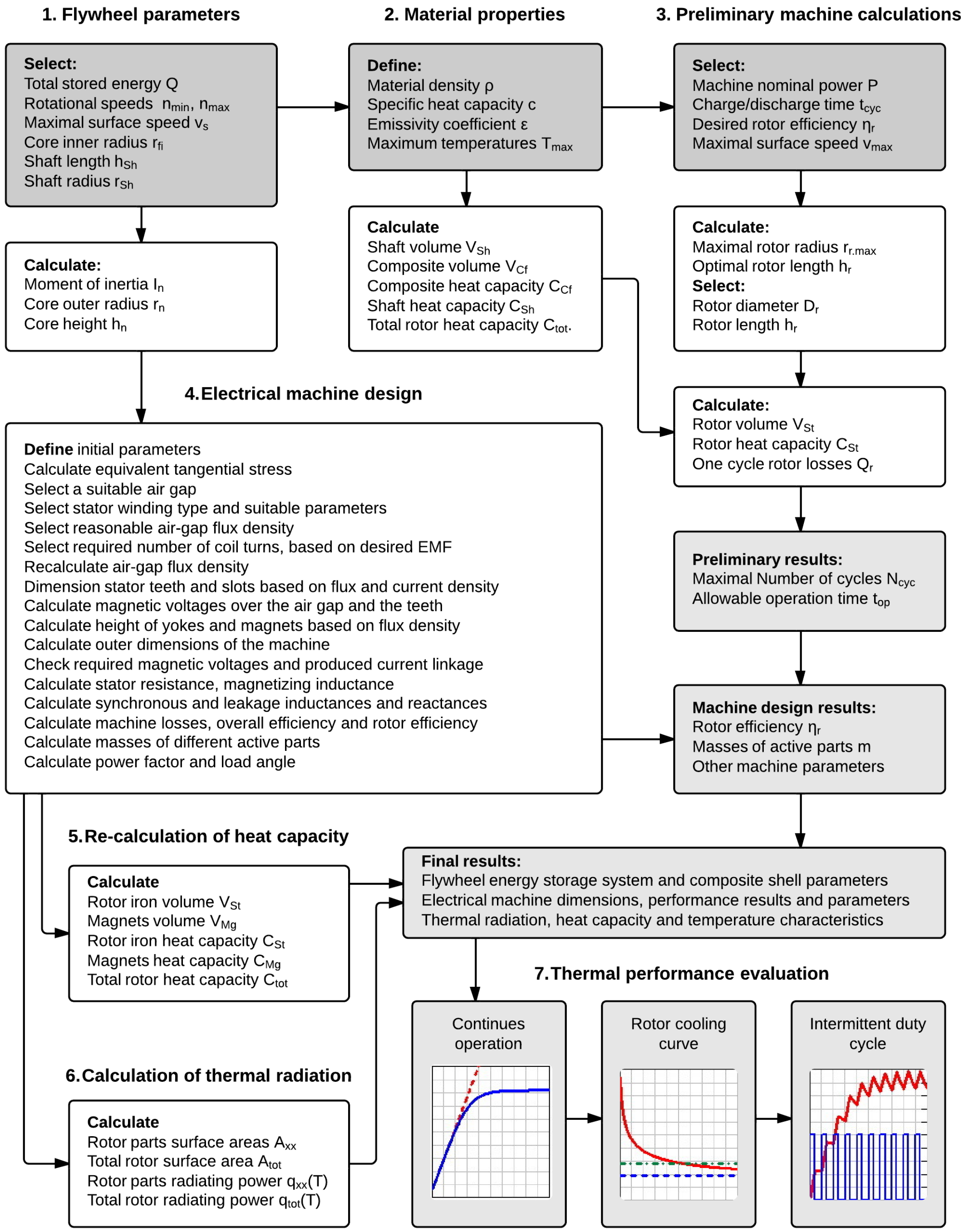

Fig. 2. Flywheel design method and calculations workflow

assembling an equation of total rotor radiating power Q_{rr}, as a function of rotor temperature T:

$$Q_{\mathrm{rr}}(T) = \varepsilon_r \sigma \left(T^4 - T_s^4\right) A_r \qquad (1)$$

where T_s is assumed stator temperature and σ is the Stefan-Boltzmann constant.

This relationship states that for the most efficient rotor cooling, its temperature T along with the emissivity factor ε_r should be as high as possible (Fig. 3), so the selection of the flywheel materials should be made accordingly.

C. *Thermal evaluation of the resulting system*

The last part presents a summary of all relevant system parameters including mechanical, electrical and thermal characteristics, and allows a thermal performance evaluation of the flywheel system and based on them, reiterate the design from any point if necessary.

For the thermal analysis of resulting system, a first order differential equation is assembled, which includes continuous heating due to rotor losses of the electrical machine and

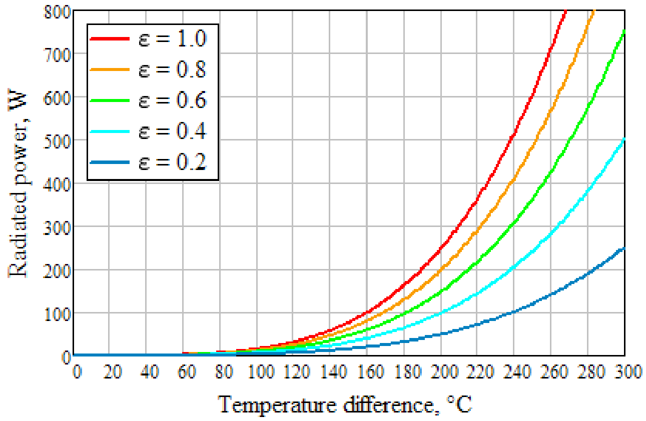

Fig. 3. Radiated power as a function of temperature difference

cooling by means of thermal radiation, which is dependent on the fourth power of the temperature according to Stefan-Boltzmann Law. Using this simple equation allows only for modelling continuous operation mode of the machine, or eliminating the losses part of the equation to model the cooling process while the machine is idling.

When continuous operation is impossible due to overheating, a dynamic model is required to evaluate characteristics of intermittent periodic duty. To model this operating mode, the differential equation includes rotor losses, as a function of time. When the machine is operating at full power, rotor losses are at their nominal value and are equal to zero during idling periods. The duty cycle of such operating mode is defined as a ratio of motor on-time to the overall on-off period.

Iteration of the duty cycle value allows to find the operating point which is closest to temperature limit, as it allows for the best system utilization. Also, the same equation can be adjusted to model other operating modes of the machine, or to simulate a system with temperature feedback.

As an example of the proposed method in use, a 10 kW h flywheel system with a 300 kW motor-generator was designed and investigated. The rotor structure shown in Figure 4 and system parameters shown in Table I were obtained.

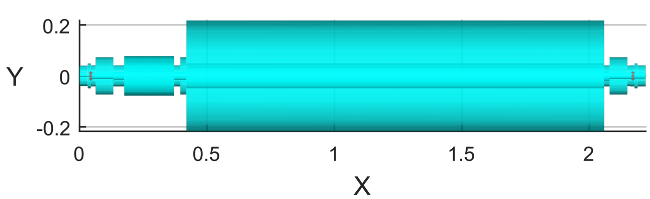

Fig. 4. Rotor structure including radial active magnetic bearings, motor-generator unit and composite flywheel shell.

TABLE I
PARAMETERS OF FLYWHEEL SYSTEM

Parameter	Symbol	Value	Unit
Flywheel energy capacity	E	10	kW h
Machine nominal power	P	300	kW
Overall machine efficiency	η	96.1	%
Number of pole pairs	p	1	-
Max. rotational speed	n_{max}	30000	rpm
Min. rotational speed	n_{min}	15000	rpm
Rotor length	l_r	250	mm
Rotor outer diameter	D_r	159	mm
Rotor total mass	m	162.2	kg
Estimated rotor losses	$P_{r.loss}$	3336	W
Rotor efficiency	η_r	98.9	%
Rotor total heat capacity	C_r	558398	J/K
Rotor maximum temperature	$T_{r.max}$	250	°C
Assumed stator temperature	T_s	30	°C
Composite shell emissivity factor	ε	0.9	-
Duty cycle period	t	6	h

Figure 5 shows the result of the intermittent duty cycle modeling which has a maximum allowable duty cycle of 14.08 %, while not exceeding the specified temperature limit of the rotor. In this example the limit is set to 250 °C, which is considered to be one of the highest possible operating temperatures for a PMSM rotor [15].

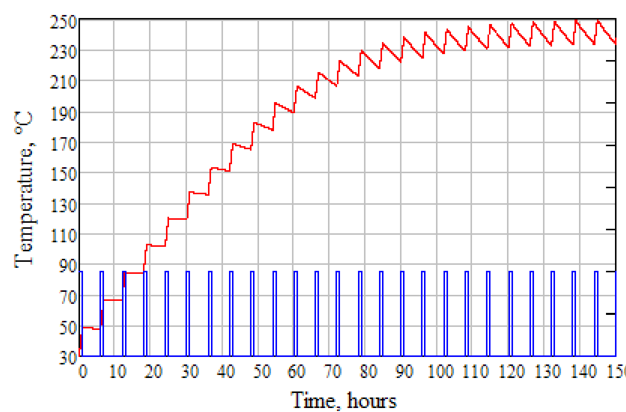

Fig. 5. Modeling result with the blue line representing the intermittent duty cycle of the machine and red line representing the rotor temperature

III. Thermal Performance Study

Based on the method presented above, a study was performed to investigate the relationships between initial parameters of the system, and its thermal performance. Maximum duty cycle, at which the system is not exceeding its temperature limit, was chosen as the main investigated feature for representing performance and system utilization. The first system parameter in question is the efficiency in the rotor.

Figure 6 shows possible duty cycles at the same maximum temperature of 200 °C for different values of rotor efficiency and different flywheel sizes.

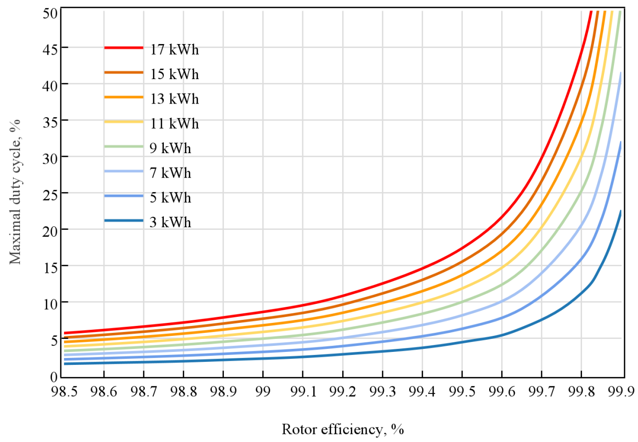

Fig. 6. Rotor losses influence on system performance

It can be clearly seen from the figure, that higher values of duty cycle for any flywheel size, can be achieved at higher efficiencies, as lower rotor losses allow the machine to operate longer without having to be stopped due to overheating. Also larger flywheels tend to have higher possible duty cycles, because of bigger surface areas of the shell which contributes to the intensity of radiated power.

In figure 7 a feature under evaluation is the maximum allowable rotor temperature for different flywheel sizes, while system utilization is measured by the highest possible duty cycle. The rotor efficiency is fixed at 98.9 %.

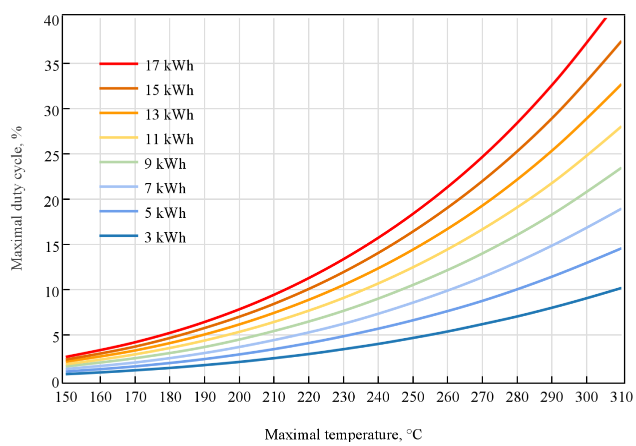

Fig. 7. Maximum rotor temperature influence on system performance

As the power of thermal radiation is dependant on the fourth power of temperature, its influence on system performance is very noticeable. The stated fact should influence the process of choosing rotor materials for different parts, such as permanent magnets and the composite materials which can be especially sensitive to high temperatures. Also it should be noted, that the net radiation of the stator/rotor system is dependent on the temperature difference, so an efficient solution for stator cooling needs to be addressed as well as increasing rotor's thermal limits.

Another important variable to note is the cycle length of the intermittent duty cycle and its influence on the rotor temperature, which is shown in figure 8.

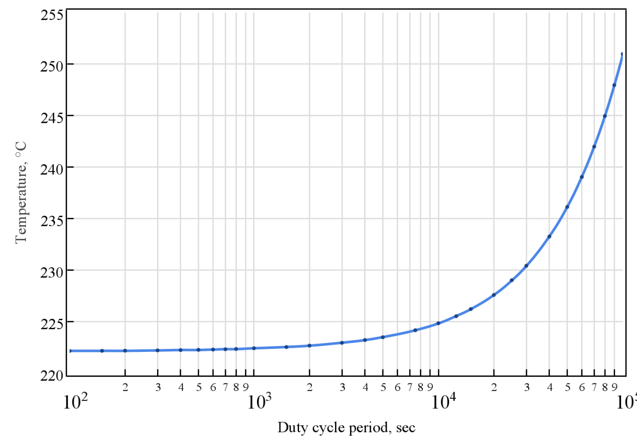

Fig. 8. Cycle length influence on system performance; actual value of the duty cycle is kept at the same level while temperature dependency on the cycle length is investigated

For maximum allowable duty cycle near the temperature limit, the period of on/off times plays an important role, as longer cooling times contribution lowers extremely fast with temperature decrease. So the most efficient operating duty cycle should be switched quicker and with shorter cooling times to allow operation as close to the temperature limit as possible. Although this feature should be mostly defined by the flywheel's application area, its influence is still worth mentioning.

IV. Conclusion

Overall, presented method of designing and evaluating the flywheel system from the thermal point of view, allows for a quick temperature analysis, which gives valuable insight on system performance and initial parameters for electrical machine design. For bigger flywheels, the thermal capacity of the rotor plays an important role in system performance, as just the absorption of the losses by the rotor allows for a number of energy conversion cycles, before the system reaches temperature limit. For relatively small systems with low heat capacity, efficiency in the rotor and thermal radiation power at maximum temperature become more important factors, as the operating point should be close to the temperature limit for maximum system utilization.

Important parameters that strongly influence system's capabilities, such as rotor efficiency, temperature limit and duty cycle period were investigated to give a reference for the design process. Losses in the rotor should be addressed by choosing an appropriate machine type [16] and a sophisticated design method. Moreover, this fact influences the inverter design, as its efficiency might be decreased deliberately for a better harmonic content in the electrical machine.

The demand for a high temperature operation requires research on properties of different materials involved into rotor construction and consideration of the ones withstanding higher thermal load. After a specific structure is selected and investigated using the analytical method, a more accurate FEM analysis is recommended, which can take into consideration non-uniform temperature distribution and other factors that present a challenge for analytical evaluation [17]. It will allow for better prediction and anticipation of temperature changes in different operating modes of the system.

Also, a recommendation to reach a point of better system utilization, while maintaining its reliability and life expectancy is implementing a wireless temperature sensor into the rotor structure. It presents a viable way of controlling temperature and driving the flywheel in the most optimal way, without estimating its temperature.

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