

Analysis of a flywheel storage system for ultra-fast charging station of electric vehicles with regard to electric machine design and operational speed range

Abstract. This paper introduces design aspects of flywheel storage system used as energy buffer for ultra-fast charging station of electric vehicles. Calculations of nominal efficiency of surface permanent magnet machine, round-trip cycle and long term efficiency of flywheel system have been presented. Finite element analysis of the machine was carried out in order to obtain its characteristics and estimate performance of entire system. The results have shown approximate value of system efficiency and system weight in relation to various operational speeds as well as acceptable time for energy storage.

Streszczenie W artykule przedstawiono zagadnienia projektowania magazynu energii kinetycznej zastosowanego w ultra-szybkiej stacji ładowania baterii pojazdów elektrycznych. Analizowano sprawność znamionową maszyny z magnesami trwałymi umieszczonymi na powierzchni wirnika, sprawność pojedynczego cyklu ładowania oraz długookresowego gromadzenia energii. W celu określenia parametrów silnika posłużono się analizą elementów skończonych. Przedstawiono zagadnienia sprawności systemu i jego masy w zależności od zakresu zmian prędkości kątowej, jak również czas dla jakiego gromadzenie energii jest uzasadnione. (Analiza pracy magazynu energii kinetycznej dla ultraszybkiej stacji ładowania baterii pojazdów elektrycznych uwzględniająca projekt maszyny elektrycznej dla przyjętego zakresu zmian prędkości)

Keywords: Efficiency of Flywheel Storage System, Flywheel Energy Storage Systems (FESS), Energy Storage Systems, Surface Permanent Magnet machine (SPM)

Słowa kluczowe: Akumulatory energii kinetycznej, magazyny energii kinetycznej, silnik z magnesami trwałymi, sprawność magazynu energii kinetycznej

Introduction

As the share of renewable energy sources and open energy markets is growing, many companies put a lot of effort to develop electricity storage systems of various physical natures. The principle of flywheel storage is to transform electrical energy into kinetic one, accumulated in a rotating mass, where the stored energy is proportional to the rotating speed squared. Since high strength carbon fibre composites appeared, flywheel energy storage systems (FESS) have become more competitive to batteries. Lifetime and high power capabilities are their main advantages. The main drawback is relatively low stored energy per mass unit, i.e. the gravimetric energy density, making them suitable rather for applications where weight is not a matter of high importance. They have been used in some commercial applications such as uninterruptible power supplies [1] [2], grid frequency regulation [3] and heavy electric vehicles [4] [5]. Also a few automotive companies are making some effort to use FESS in hybrid vehicles as an alternative to batteries [6].

In our case we have investigated feasibility of a flywheel storage unit for ultrafast charging station of electric vehicles (EV). The main purpose of this unit is to ensure high charging power despite of power limitation of a standard 400 V low-voltage grid. The idea is to use the storage unit as a buffer in order to deliver high peak charging power and continuously draw small power from the grid. The energy can be released rapidly during car charging cycles and slowly restored between them.

Although several flywheel storage systems exist on the market, their energy capacities and powers vary one from

another. From this reason new system studies has been made. In this paper an attention has been paid to an electric machine and it was shown which parameters are especially important and how they affect the total system performance. An approximate energy storage efficiency of such system has been studied considering its duty ratio. The given efficiency of flywheel systems often refers to single charge-discharge (round-trip) cycle, which has not the same relevance as an operational storage system with variable idle times. Therefore an investigation of system efficiency has been done more widely. The system with permanent magnet machine has been chosen and justification of this choice will be given in further part of the paper.

In the beginning fundamental information about flywheel system is given and the influence of motor torque on stored energy is explained. It is shown, how motor torque affects utilization of energy stored in a flywheel and what torque value is necessary to obtain required power. Then main requirements for motor and basic assumptions are shown as well. An illustrative design of surface permanent magnet motor is presented, which is further used to estimate motor losses and other system parameters. The parameters are obtained from finite element analysis (FEA) and used to assess the field weakening properties of the machine. Furthermore charge-discharge efficiency of flywheel unit is calculated. At the end, the efficiency in function of idle time is presented. This illustrative system approach shows how singular properties of the machine are related with whole system and when a use of flywheel storage system is justified taking into consideration idle time and performance of electric machine.

Fundamental parameters of a flywheel storage system

In a basic construction the flywheel and electric machine are mounted on a common shaft, suspended on contactless magnetic bearings (Fig. 1). All rotating components are placed in vacuum, so the mechanical friction and air drag are minimized. The flywheel system has an advantage of long lifetime, above 20...25 years, during which it may perform up to 300'000 cycles. Moreover, its performances do not degrade in time and do not depend on ambient temperature. On the other hand the main drawback of flywheel system is high idle losses. All these features make flywheel systems very suitable for application where high power and short storage time are expected.

The power of the system is determined by electric machine and the stored energy is strongly related with mechanical construction of flywheel. The key issues for energy capacity per mass unit are the flywheel's material and its geometry [7]. It is important to point out that limit of stored energy does not depend on maximal rotational speed until flywheel dimensions are not determined. In other word a flywheel can be designed for different operating speeds and stored energy may be kept unchanged. A change of maximal speed requires change of flywheel diameter in order to keep the mechanical stress on the same level. The moment of inertia is changed but the amount of kinetic energy remains the same [8].

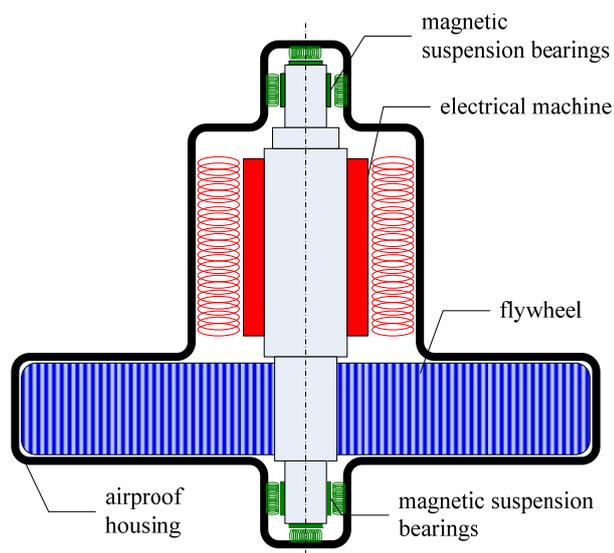


Fig. 1. Construction of a flywheel energy storage unit

The comparison of different flywheel materials is shown in [8] [9], according to which the best of them are composites of epoxy matrix and carbon fibres, which give the highest energy/mass ratio. Approximate energy density of this material is about 350 Wh/kg, but this is only theoretical limit obtained from maximal material strength referring only to flywheel itself. The effective energy density of the system is lower due to mass of additional components, safety margins in mechanical construction and only partial energy utilization. In fact, not all accumulated kinetic energy can be transformed back into electrical form and this is strongly related to electric machine. The first obvious reason is efficiency of conversion process. The second reason is a fact that only part of mechanical energy can be discharged if a limit of minimal discharge power is assumed. In order to determine how much kinetic energy can be extracted from a flywheel, a discharge process will be introduced and illustrated by a simple numeric example. While energy is being discharged from flywheel, the rotational speed decreases. In order to keep the constant

power, braking torque must increase proportionally to decreasing speed (Fig. 2.). Since maximal torque of the motor is limited, not all energy can be discharged with a given power restriction. That moment is visible on the graph as a minimal speed below which a discharging power is no longer constant. Discharge characteristics of two motors with different values of maximal torque were plotted in figure 2. As a result, the two flywheel systems operate in different speed range. The figure shows that the motor with double value of torque (Fig. 2b) is able to operate at half of minimal speed than the other one. This has consequence in utilization of accumulated energy. The discharged energy is described by following equation:

$$(1) \quad E_{dis} = \frac{J}{2} \cdot (\omega_{max}^2 - \omega_{min}^2)$$

where: E_{dis} – discharge energy, ω_{max} , ω_{min} – maximal and minimal rotational speed of the flywheel.

It can be noticed that for the first case (Fig. 2a) minimal rotational speed $\omega_{min} = 0.5 \cdot \omega_{max}$ and we can use 75% of stored energy. For the second case (Fig. 2b) $\omega_{min} = 0.25 \cdot \omega_{max}$ and the discharged energy is 94%. In conclusion higher torque of motor means the lower minimal operating speed and more energy which can be recuperated. On the other hand higher torque requires bigger motor and increase total weight of the system. A reasonable minimal speed point lays somewhere in a range $(0.5...0.75) \cdot \omega_{max}$, however, a final choice is a complex issue. A decision criterion may be defined as a minimal weight, cost and the best efficiency of the system or a different combination of them.

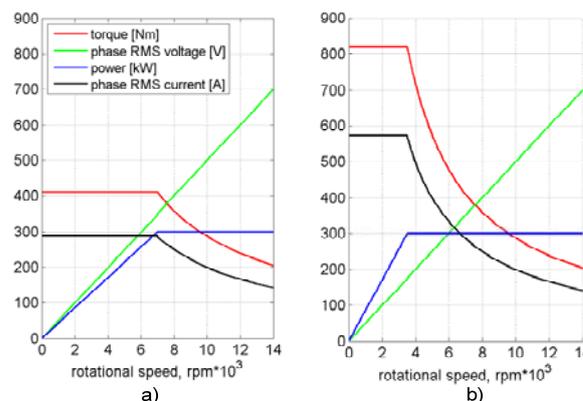


Fig. 2. Operating speed range of motors with different nominal torque and minimum speed - motor works without field weakening; a) 409 Nm and 7'000 rpm; b) 818 Nm and 3'500 rpm

Requirements on the electric machine

The flywheel storage system is quite special application for an electric machine. Besides typical requirements such as high efficiency and low weight possibly, the choice of machine should be made taking in consideration some special following requirements:

- **Relatively big air gap:** The contactless suspension of the flywheel causes higher shaft displacements than classic mechanical bearings, so this imposes a special requirement on the air gap. The gap must be big enough to prevent mechanical contact between rotor and stator in case of shaft displacement during rotation.
- **Tough rotor structure:** The rotational speed of flywheel is very high, and so are the centrifugal forces acting on the rotor, necessitating a tough construction.
- **Brushless construction:** In practise the high speed eliminates all brushed constructions, which cause additional friction losses and wear away very fast at high speeds.

- *Low standby (idle) losses:* When energy is stored in flywheel the motor rotates at maximal speed without any load. The losses caused by residual air drag and friction deteriorate system efficiency. Therefore these losses should be as low as possible when long stand-by time is required.
- *Field weakening:* This feature has two positive effects on the system. Firstly it can reduce required power of converter by improving its utilization in entire operating speed range (considering the case when constant power on the output is required e.g. charging station for the EV). The second advantage is significant reduction of eddy current losses in stator if magnetic flux excitation can be switched off or reduced at idle state.

Choice of the machine type

The choice of electric machine is not self-evident since any of present machine technology cannot fulfil all presented requirements. In this FESS investigation a surface permanent magnet machine (SPM) has been chosen. In first approach, the choice of this machine type has been done because the high air gap is easy to overcome by using strong permanent magnets (PM) and it does not cause significant parameter deterioration. The disadvantage is high idle power loss due to the presence of PM, which is a point of investigation in this paper. The reason of big air gap was due to a fact that mechanical details of flywheel and bearings system were not known beforehand, so conservative restriction of 5 mm air gap length was assumed. Because small air gap is necessary for good performance of induction and reluctance machines, both types were abandoned during the initial choice.

Overview of PM machine topologies concerning different magnet placements inside the rotor was presented by Chau [10]. The magnets's position in rotor influences strength of rotor construction and the difference in d - and q - inductances. The ratio between those inductances (saliency ratio) determines operating speed region above rated speed.

Internal permanent magnet machines (IPM) have better field weakening properties than machines with magnets on surface [11]. Despite of that, in this approach the variant with the magnets mounted on the surface has been chosen. The reason was simple rotor construction. Although the rotor with magnets glued to rotor surface using epoxy adhesives is weak by itself, an additional strengthening sleeve on magnets may be used to ensure high strength against centrifugal forces. The sleeve is usually made of high strength fibres and ensures withstanding high rotational speeds. Despite of poor field weakening properties of SPM machine, the assumption about the air gap size determines the choice of this machine type. It could be very difficult or even impossible to ensure required saliency ratio for IPM machine with such a big air gap. From this reason IPM type was abandoned in investigation and studies of surface permanent magnet machine have been done instead.

It should be pointed out that plenty of other PM machine modifications exist in FESS, such as ironless construction, slot-less stator, Halbach array of magnets [12], external rotor construction integrated with flywheel [13] [14] or construction with axial flux [15]. Although these machines show slightly different parameters, general conclusions from SPM machine studies are transferable to other types. Therefore the research on SPM machine shows which modifications of PM machine technology might be suitable to achieve desired system features. The examples of PM machine technology used in flywheel systems are presented by companies/institutions such as BeaconPower, Vycon, Boeing [16], ATZ [17], Williams F1 [14].

Parameters of surface permanent magnet machine

In order to create a FEA model, the machine power was assumed as 300 kW and discharged energy on the system output as 25 kWh. The studies of flywheel mechanical construction were being made in parallel with machine investigation, so mechanical limitations of machine construction have not been defined precisely on the beginning. From this reason an approximate working speed was assumed from 7'000 rpm to 14'000 rpm in first approach. The power and speed assumptions gave approximately 409 Nm of required torque (Fig. 2a). In further part of the paper also other speed ranges have been investigated. A choice of operating speed has been made after some simple mechanical calculations in order to keep flywheel dimensions in reasonable limits. However this investigation is out of the scope of this paper.

The FEA was performed in order to obtain SPM machine parameters; the model is shown in figure 3 with the motor parameters summarized in table 1. The main task of the model is to estimate machine parameters in order to investigate flywheel system's parameters in the next step. There was no objective to find optimal design, because machine requirements were not precisely predefined. One pole pair design was chosen in order to minimize flux frequency and iron losses. Soft magnetic laminated steel with very low magnetic losses was used as stator material. The hysteresis and eddy current losses in iron parts were calculated in FEA, based on loss characteristic of a steel sheet. In table 1 we see that efficiency of machine is very high at rated speed, due to good properties of magnetic materials and relatively low flux density in iron. The losses in magnets are also low, due to big air gap and quite uniform field distribution on the magnet surface. All this parameters are at the cost of machine weight which was not so important for a stationary application.

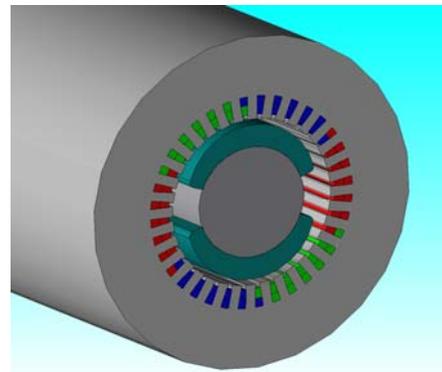


Fig. 3. 3D model of SPM machine

Table 1. Surface permanent magnet machine parameters

Parameter:	Value:	Unit:
Rated speed	14'000	rpm
Torque (avg.)	409.3	Nm
Estimated machine mass	229	Kg
Mechanical Power	600	kW
Phase EMF voltage (RMS)	723	V
Phase current (RMS)	287	A
PM flux (RMS)	0.475	Wb
Phase resistance	10.6	mΩ
Phase Inductance	0.41	mH
Copper losses	2.620	kW
Losses in magnets	0.240	kW
Iron losses	0.973	kW
Apparent power	622.5	kVA
cos(φ)	0.97	-
Efficiency	99.37	%
N° of pole pairs	1	-

Air gap	5	mm
Flux density in air gap (avg.)	0.63	T
Flux density in tooth	1.32	T
Flux density in back iron	1.28	T
Current density in windings	10.8	A/mm ²
Slot filling factor	50	%
Turns per phase	12	-
N° of slots	36	-

Operation in extended speed range

The extended speed region refers to operation above rated speed. This region also is called constant power speed range, but for PM machine it is rather difficult to say that power is constant in that range. The rated speed is defined as the speed at which the terminal voltage equals rated voltage with rated torque and rated current [11]. Operation above rated speed is important because it can reduce nominal power of converter and improve its utilization. The importance of this fact will be illustrated using a simple example. The machine torque is 409 Nm, imposed to the requirement of minimal power 300 kW at minimal speed of 7'000 rpm (Fig. 2a). It follows that rated mechanical power of machine is 600 kW at rated speed but only 300 kW of continuous power is required in entire speed range (table 1). This also causes that converter must be designed for higher power because of both nominal current and voltage. In conclusion power converter must have twice the power rating of the required discharge power and never operates at rated point; neither does the electric machine. The speed range where machine operates at constant power (Fig. 2), should not be confused with constant power speed region above nominal speed as previously defined. In figure 2 the machine works without field weakening in the range below rated speed, which simply is constant torque speed range according to the definition [11] [18]. Moreover, the torque is not fully utilized at whole speed range in this special case and that is why the torque is not constant. Study of operation mode for this particular machine design will be investigated below based on Soong's work [11].

The idea of field weakening in a PM machine is to control current in such a manner that a part of stator current produces a magnetic flux in opposition to flux produced by PMs. This can be made by controlling the current vector in dq reference frame, rotating together with the rotor. For an assessment of extended speed range it is convenient to use circle diagrams, which show possible current vector location in dq -frame, subjected to certain limits. The first limitation is rated current of machine and the second one is nominal voltage of the converter or the machine. They can be expressed as follows:

$$(2) \quad I_d^2 + I_q^2 \leq I_n^2$$

$$(3) \quad U_d^2 + U_q^2 \leq U_n^2$$

where: I_d, I_q – currents in dq frame, I_n – nominal current, U_d, U_q – voltages in dq frame, U_n – nominal voltage.

The voltage limitation should be expressed as a function of d and q component of current vector, therefore the simplified PM machine equations in steady state with neglected resistance are used, which are:

$$(4) \quad \begin{cases} U_d = -\omega L I_q \\ U_q = \omega L I_d + \Psi_m \omega \\ T = \frac{3}{2} p \Psi_m I_q \end{cases}$$

where: L – machine's inductance, Ψ_m – permanent magnet flux, p – N° of pole pairs, ω – electrical rotation frequency.

By substituting U_d and U_q into Eq. (3), the mathematical equation of circle can be obtained:

$$(5) \quad I_d^2 + \left(I_q + \frac{\Psi_m}{L} \right)^2 \leq \left(\frac{U_n}{\omega L} \right)^2$$

The radius of voltage circle decreases with increasing speed (Eq. 5). The current space vector can be placed only inside the common area of both voltage and current circles (Fig. 4). When the speed is higher than rated, the current vector cannot be set to obtain nominal torque because of limited position inside voltage and current circle on dq plane. Physically it means that d -axis component of current vector must be used to compensate PM flux as well as induced back-EMF [12]. In consequence the q -axis component is reduced as well as produced torque. The torque of SPM machine only depends on q -component; therefore it is represented by a straight line in figure 4.

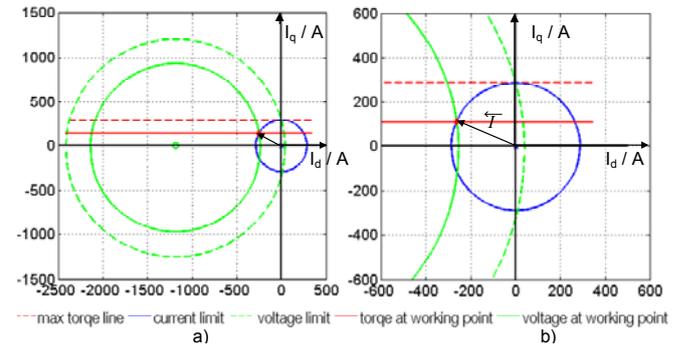


Fig. 4. Field weakening performance of SPM: a) circle diagram; b) a zoomed fragment

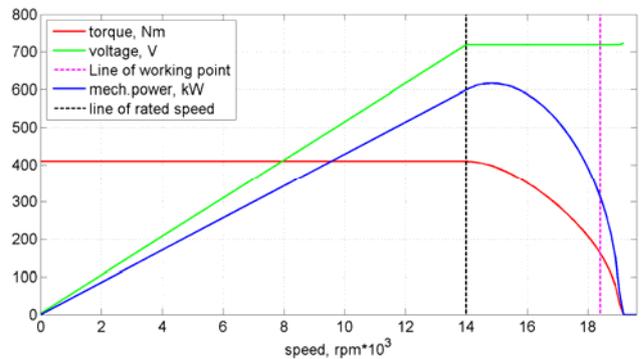


Fig. 5. Field weakening performance of SPM, voltage torque and power in function of speed

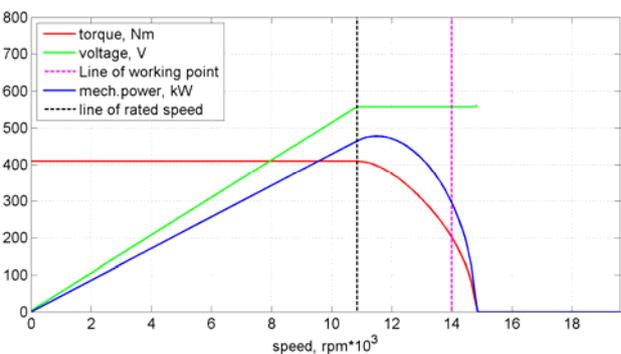


Fig. 6. Use of extended speed region: voltage, torque and power in function of speed (reduced rated voltage and speed)

In figures 4 and figure 5 the characteristics of chosen machine design are presented according to the previous simplification. The current space vector is shown when machine is operating with 300 kW power at 18'400 rpm. The machine is capable of exceeding rated speed by 30 % with required power, but it cannot work at this speed because we had previously assumed that maximal mechanically limited speed is 14'000 rpm. On the other hand the extended speed region can be shifted down by the reduction of rated speed and suitable control method. The change of machine construction is not necessary, because the rated speed is a preliminary assumption and is below the machine design limit. Obviously rated voltage and rated power will be lower too, but this fact does not matter if machine can still produce required power above the rated speed, which was artificially shifted. The characteristics at new rated speed are shown in figure 6. The rated speed was reduced to 11'900 rpm and nominal voltage to 560 V, so the power at new rated operation point is 483 kW instead of 600 kW. Furthermore the machine is still capable of delivering required 300 kW at the maximum speed of 14'000 rpm. The downscaling of power converter is clearly visible. Nevertheless an operation above rated speed requires that the current in *d*-axis must be supplied instantaneously to keep the voltage on allowable level. Therefore, the idle losses will be higher by amount of copper losses produced in the windings by this current. In this case the current in *d*-axis must be 255 A what adds 689 W of losses at idle state.

Efficiency of a flywheel storage system

As it was mentioned before, the efficiency of the machine does not directly translate into efficiency of energy storage. To obtain storage efficiency of the system, we have to calculate energy coming in and out, as well as take in consideration all losses in function of time. The calculation of efficiency for charge, discharge and round-trip cycle of flywheel storage unit was made as follows:

$$(6) \quad \eta_{ch} = \frac{E_{stored}}{E_{in_ch}} = \frac{E_{stored}}{E_{stored} + E_{losses_ch}} \cdot 100\%$$

$$(7) \quad \eta_{dis} = \frac{E_{out_dis}}{E_{stored}} = \frac{E_{stored} - E_{losses_dis}}{E_{stored}} \cdot 100\%$$

$$(8) \quad \eta_{in-out} = \frac{E_{out_dis}}{E_{in_ch}} = \frac{E_{stored} - E_{losses_dis}}{E_{stored} + E_{losses_ch}} \cdot 100\%$$

where: E_{stored} energy accumulated in flywheel as kinetic energy, E_{losses_ch} , E_{losses_dis} charging and discharging energy losses, E_{in_ch} , E_{out_dis} input and output energy of each process.

To calculate energy losses we have to integrate the power losses with respect to time according to equation:

$$(9) \quad E_{losses} = \int_0^t P_{losses}(\omega(t)) \cdot dt$$

where: P_{losses} - power losses of the machine.

Firstly losses characteristic in function of speed should be found, then a change of speed in function of time.

It was assumed that there are no mechanical losses and the speed change is described by dynamic equation as follows:

$$(10) \quad \frac{d\omega}{dt} = \frac{1}{J} T_m(\omega)$$

where: T_m - machine torque applied to the shaft of flywheel, J - flywheel's moment of inertia.

Using integration by substitution method, a formula for energy losses with respect to speed can be obtained:

$$(11) \quad E_{losses} = \int_{\omega_{min}}^{\omega_{max}} P_{losses}(\omega) \cdot \frac{J}{T_m(\omega)} \cdot d\omega$$

The discharge losses in function of speed are shown in figure 7. They were obtained based on internal resistance of machine's windings and losses characteristics of soft magnetic steel sheets, which were used to build the stator. The eddy current losses on magnet's surface were not taken in consideration, as well as additional ones like losses in converter, magnetic bearing system, air friction and evacuation. In order to calculate cycle efficiency, the stored energy in flywheel was assumed as $E_{stored} = 25$ kWh. The discharging time was 5 min and charging time 2.5 h. This corresponds to mechanical power of 300 kW on shaft during discharge and 10 kW during recharge. Speed range is 7'000 rpm...14'000 rpm. For the assumed power and speed range, the charging and discharging torque were calculated in function of speed. The charging and discharging torques are substituted to equation (11). Then equation (6) ... equation (8) were applied. Calculated efficiencies are presented in table 2. It should be emphasized that power of the machine during charging and generated power during discharging are not equal. Figure 6 shows only discharge losses; however other similar characteristic was used in charging cycle calculation.

Table 2. Efficiency of a single cycle:

Discharge, η_{dis}	Charge, η_{ch}	Round-trip, η_{in-out}
99.3 %	93.2 %;	92.6 %

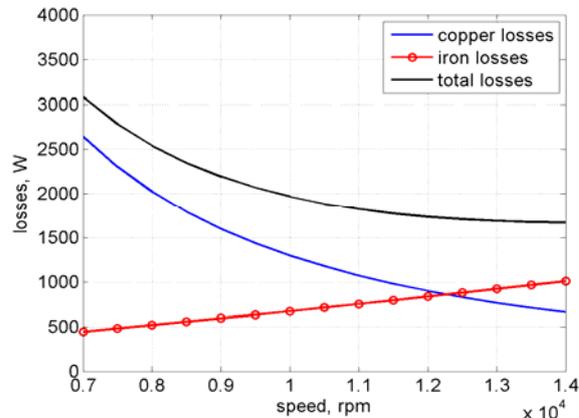


Fig. 7. Losses in machine during discharging, torque was controlled in order to obtain constant mechanical power 300 kW at entire speed range

We can notice that in-out efficiency of singular flywheel cycle is lower than machine's nominal efficiency because losses are not constant at entire speed range. Also the long duration of energy accumulation decreases efficiency of a charging cycle. The round-trip efficiency is quite high because it refers to singular charge-discharge cycle and additional losses were not included. The calculation assumptions cause, that electrical power will not be constant. Average value of charging power on machine terminals will be higher than 10 kW and the discharge one will be lower than 300 kW.

Study of different operating speed range was introduced in figure 8 and figure 9. In figure 8 an efficiency map is shown with efficiency variation for different maximal speeds

and relative minimal speeds. Figure 9 shows weight variation of flywheel system in function of the same parameters. The additional assumptions in this case were made as follows: the energy density of the flywheel is 60 Wh/kg, charge and discharge intervals are constant, the required rated torque of machine for different speeds was obtained by changing the machine's length, the machine's diameter was kept constant and the centrifugal force was not considered as a limiting factor. Also the amount of energy in use was kept constant. Only iron losses in stator and copper losses in windings were taken into account for each case.

The results show that the operation in narrow speed range and low maximal speed give better round-trip efficiencies. On the other hand, figure 9 shows that in these points the weight of system increases very rapidly. The reason is pure utilization of energy which had been discussed earlier. This leads to oversize of flywheel in order to keep the required amount of stored energy. We see that the choice of minimal speed is a trade-off between efficiency and weight. It should be mentioned that the maximum speed is not determined by the machine's design, but by mechanical design of flywheel for given capacity.

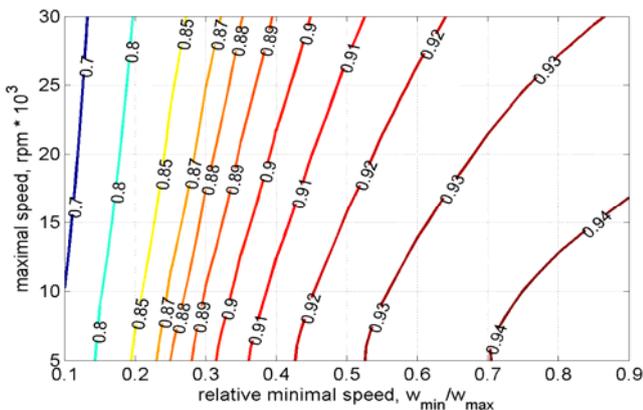


Fig. 8. Round-trip cycle efficiency map for different operation ranges of flywheel

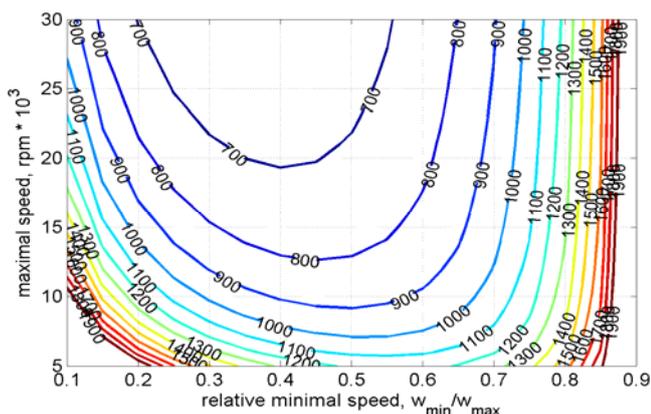


Fig. 9. Cumulated mass map of flywheel and machine for various speed operation ranges, values are expressed in [kg].

Storage time versus efficiency

Despite of good round-trip efficiency, the drawback of flywheel is relatively high loss during idle state. In order to show how the efficiency deteriorates, we must take these losses into account. The most significant additional losses at idle state apart from machine losses are caused by air drag on the surface of the flywheel and the losses in magnetic bearings. The magnetic bearing losses were roughly estimated as 500 W by the provider and air drag

losses as 400 W by preliminary calculations. Finally 1 kW of total idle losses was assumed in conservative approach. The idle losses of the machine equal 1 kW at maximum speed (Fig. 7), which are mostly iron losses, almost the same at idle and load states due to small armature reaction. The assumption had been made that idle losses are compensated from the grid at idle (stand-by) state, so they can be added to charging losses. The new equation for efficiency is as follows:

$$(12) \quad \eta_{in-out} = \frac{E - E_{losses_dis}}{E + E_{losses_ch} + E_{losses_idle}} \cdot 100\%$$

Figure 10 shows that efficiency decreases rapidly during the first hours of stand-by time. The first point of characteristic at zero time is input-output efficiency (round-trip), same as presented in table 2. This value of efficiency has decreased from 92.6 % to about 85 % by additional losses. The reason of such big deterioration is long time (95 min) of round-trip cycle, resulting in ~3.2 kWh of losses. If the cycle were 10 min, it would be only ~0.3 kWh. We can see then, that short round-trip cycle (high charge and discharge power) will ensure better efficiency. A more detailed example of idle losses, considering different system components, can be found in [17]. For the system with 3 kW power and 5 kWh of stored energy, the losses at idle state are predicted as 136 W. It gives 2.7 % loss of initial energy in first hour; in comparison, our system has 8 % losses. According to figure 10, the reasonable time of storage should not be longer than 1 hour in order to obtain efficiency above 80 % for this simple assumption.

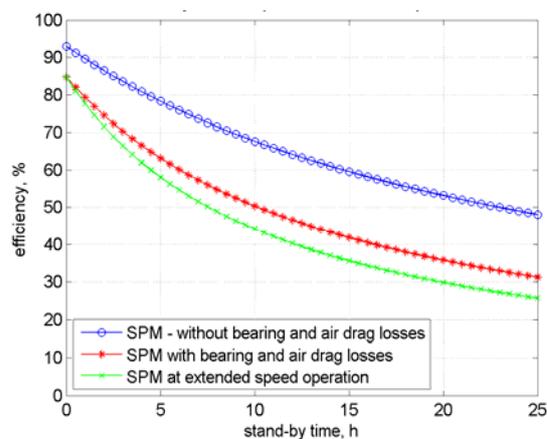


Fig. 10. Storage efficiency in function of idle time for different cases

Conclusions

In this paper the surface permanent magnet machine was proposed as an illustrative example in order to assess performance of a flywheel storage system. The choice of this machine type was determined by big air gap, the size of which was assumed due to unknown tolerances of bearing systems and additional safety margin. Meanwhile the SPM machine has being investigated; the parallel studies of mechanical construction have shown that the air gap size can be reduced to 1.0 mm ... 1.5 mm. This means that actual size of the machine can be reduced keeping the same machine parameters. Also other machine types might be used and could demonstrate good performance. The FEA showed that the big air gap size was not an obstacle to obtain good machine performance. The size of air gap has a positive effect on machine design by reduction of power losses in magnets. The investigation of field weakening revealed that machine is capable of working above rated

speed what may be used to reduce power converter ratings at the cost of higher idle losses. The comparison of results between round-trip cycle efficiency and long-term system efficiency has showed that idle losses are very important, especially when long stand-by time is required. The results lead to conclusion that SPM machine is suitable for flywheel systems where stand-by time is shorter than one hour. In this case machine ensures acceptable efficiency and also field weakening operation can be justified. However if charging and discharging times are long and idle losses high, even round-trip cycle may show low efficiency. From this reason the high power operations with short stand-by time are more preferable. The studies clearly show that for long time storage more effort must be done in reduction of stand-by losses. The ironless or slot-less construction of stator have potential to improve that issue.

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