Abstract— Kinetic energy storage systems (flywheels) offer a good solution to increase the stability of electric grid. The joint operation of these systems with renewable energy sources such as photovoltaic (PV) panels can help integration of these environmental friendly solutions to regular power grid.

An investigation is being pursued at Budapest University of Technology and Economics, Department of Electric Power Engineering for joint operation of flywheel energy storage (FES) systems and PV systems. The designs of these kinds of systems are complex problems which require new approach. Multidisciplinary Design Optimization (MDO) offers a good opportunity for solving the design issues. This article focuses on the initial steps of the MDO process for a switched reluctance machine (SRM) used in flywheel application.

I. INTRODUCTION

Multidisciplinary design optimization (MDO) first appeared at the aircraft industry at the 1990s. It is easy to understand that an aircraft should fulfill many different criteria and the design process involves many different disciplines of science and engineering. Often the requirements – coming from separate sides – are in opposition to each other, e.g. weight vs. structural strength. [1]

Since then “regular” systems started to become more and more complex and certain new aspects – like environmental issues and sustainability – raised new requirements towards engineering designs. In many cases regular (means linear) design methods cannot fulfill these objectives or fulfilling them involves lots of trial-error steps. This approach is not efficient enough in terms of time, resources, money. And so far we only talked about fulfilling requirements not creating truly optimal solutions to challenges. Regular method does not guarantee an optimal solution, especially if the system a new construction.

II. MDO APPROACH

A. The Goal of This Project

Kinetic energy storage systems (i.e. flywheel systems) offer a good possibility for bulk energy storage. These systems have many advantages: no toxic components, insensitive to the number of charge/discharge cycles, deep discharges, temperature resistant, easy charge level monitoring, high energy density, high allowable maximum output power [2].

An investigation is being pursued at Budapest University of Technology and Economics, Department of Electric Power Engineering for joint operation of flywheel energy storage (FES) systems and PV systems. The current aim of this work is to investigate the possibilities of using switched reluctance machines in these systems. Fig. 1. shows the components of the proposed system.

B. Multidisciplinary Design Optimization (MDO) [3][4][5]

Multidisciplinary design optimization is used to solve problems which involve many engineering disciplines. Instead of solving to the underlying equations separately, usually one after another, MDO solves them simultaneously. This results in a more complex problem which is difficult to handle by regular methods. On the other hand solving the equations together will result an absolutely optimal solution, not just a local optimum in the problem field.

Solving these kinds of problems is quite well supported by various softwares so if someone correctly formulates the problem it is only matter calculation time to get the optimal solution. The definition and formulation of the problem cannot be done automatically it requires the creative thinking of the designer. With a well known problem the MDO approach may not increase the quality of the solution compared to one done by an experienced designer [6], but with new systems the method offers the best possible system at first shoot. This paper will present the formulation of the given problem.

C. Definition of the Problem

Every MDO process starts with an exact problem definition. The problem statement must be as accurate as possible. In our case is:
“Maximize the power output of a flywheel energy storage system using SR motor/generator which is connected to a solar energy system at a certain power level.”

As we are going to see the statement gives a good foundation to formulate the problem. During the formulation of the problem one has to identify the design variables, the constraints and the objectives. After that the designer should choose an appropriate model.

The design variables are the parts of the model which the designer can control. Usually we have greater freedom of choosing their values.

The constraints are limitations which ensure that the final result can be realized. Constraints can be the laws physics or the maximum possible price of the unit. There are also parameters of the model which have only a small interval in which we can change its value, or the parameters are given for some kind reason, e.g. we want to use certain iron material with given saturation values.

The objectives are the values to be minimized or maximized. This can be for example weight, price, efficiency, speed, etc. Finally we will get an objective function and we have to find the local minimum or maximum of the objective function in the design space where every variable adds one dimension of freedom.

The separation of the all possible parameters of the problem into these categories is strongly relies on the experience of the designer.

Also it is useful to identify the disciplines involved in the current problem. Based on the regular requirements of flywheel systems, the following fields of engineering would be considered:
- electrical machine design (motor/generator)
- drive design (for the previous machine)
- power electronics (converters for solar systems)
- superconducting bearing design (for low loss superconducting magnetic bearing)
- cryogenics (for superconducting components)
- vacuum technology
- solar panel technology

Putting together the equations of these fields indeed can be a complex task, but the MDO approach will result an optimal solution.

III. PROBLEM FORMULATION

A. System Parameters

Now we are going to show the results of the problem formulation for this actual case.

This system involves many parameters, e.g.:
- nominal input and output power
- maximum stored energy
- number stator and rotor poles
- rotation speed
- number of stator and rotor poles
- weight of the rotating mass
- material for iron part, windings, rotating mass
- airgap length
- cost

The actual possible parameters are not limited to these ones; only the most relevant were listed. The following section will show the separation of parameters into MDO categories.

B. Constraints

As a first step we start with the identification of the design constraints. The limitations are representing the either an early design decisions or experiences based on previous designs.

The input voltage is defined by the connected solar panel system. We made certain decisions for the planned system, such as the nominal output power and the maximum stored energy. We are going to use mono crystalline silicon solar panels. Average peak voltage for a 200 W panels is 30 V. Considering an average output of 100 W, the charge time is 10 minutes.

The base constraints of the planned experimental device are indicated in Table I.


<table>
<thead>
<tr>
<th>Parameter Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal output power</td>
<td>$P_{\text{out}}$</td>
<td>1</td>
</tr>
<tr>
<td>Maximum stored energy</td>
<td>$E_{\text{max}}$</td>
<td>50</td>
</tr>
<tr>
<td>Nominal output voltage (AC)</td>
<td>$V_{\text{nom}}$</td>
<td>230</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>$f$</td>
<td>50</td>
</tr>
<tr>
<td>Maximum input voltage (DC)</td>
<td>$V_{\text{in,peak}}$</td>
<td>30</td>
</tr>
<tr>
<td>Maximum input current (DC)</td>
<td>$I_{\text{in,peak}}$</td>
<td>7.5</td>
</tr>
</tbody>
</table>

To decrease to losses it is necessary to decrease the bearing friction and the air friction. The bearing friction can be lowered by application of magnetic, especially superconducting (SC) magnetic bearing. For this application only Type II SC materials are suitable (YBCO and BSSCO). For these materials requires it is enough to use liquid Nitrogen cooling (LN$_2$) and this gives us the necessary temperature for bearing which is 77 K.

The necessary vacuum level will be considered as design variable.

The maximum allowed rotation speed is depending on the material used for the rotating mass. Metallic material can only endure rotation speed of 10,000 rpm maximum. The application of the composite materials increased the possible
speed up to 90 000 rpm. Regular limit \(N_{\text{max}}\) for flywheels is 30 000 rpm so for our design we are going to use this limit.

Based on the maximum speed it is possible to determine certain parameters of the flywheel. With \(E_{\text{max}}\) and \(N_{\text{max}}\) it is possible to determine the necessary moment of inertia with the following equation:

\[
E_{\text{max}} = \frac{1}{2} \Theta \omega_{\text{max}}^2 ,
\]

where \(\Theta\) is the moment of inertia, the \(\omega_{\text{max}}^2\) can be calculated based on the \(N_{\text{max}}\) value.

Based on the maximum rotation speed the value for \(\Theta\) will be around 0.001 kg·m\(^2\).

Also cost will be considered as constraints in this case since we want to create an experimental unit. The reasonable price is hard to determine in this case, so our estimation will be 20 000 euros. Table II. indicates the newly establish constraints.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenics temperature</td>
<td>(T_{\text{cryo}})</td>
<td>77</td>
<td>K</td>
</tr>
<tr>
<td>Maximum rotation speed</td>
<td>(N_{\text{max}})</td>
<td>30 000</td>
<td>rpm</td>
</tr>
<tr>
<td>Cost</td>
<td>cost</td>
<td>20 000</td>
<td>€</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>(\Theta)</td>
<td>(10^3)</td>
<td>kg·m(^2)</td>
</tr>
</tbody>
</table>

### C. Design Variables

For design variable we have plenty possibilities to choose. Table III. indicates the possible design variables and the possible ranges for these ones.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stator poles</td>
<td>(N_p)</td>
<td>4..12</td>
<td>-</td>
</tr>
<tr>
<td>Number of stator poles</td>
<td>(N_{\text{st}})</td>
<td>4..12</td>
<td>-</td>
</tr>
<tr>
<td>Airgap length</td>
<td>(g)</td>
<td>0..20</td>
<td>mm</td>
</tr>
<tr>
<td>Length of the machine</td>
<td>(l)</td>
<td>50..400</td>
<td>mm</td>
</tr>
<tr>
<td>Pole height stator</td>
<td>(h_{\text{st}})</td>
<td>20..100</td>
<td>mm</td>
</tr>
<tr>
<td>Pole width stator</td>
<td>(w_{\text{st}})</td>
<td>20..100</td>
<td>mm</td>
</tr>
<tr>
<td>Pole height rotor</td>
<td>(h_{\text{rot}})</td>
<td>20..100</td>
<td>mm</td>
</tr>
<tr>
<td>Pole width rotor</td>
<td>(w_{\text{rot}})</td>
<td>20..100</td>
<td>mm</td>
</tr>
<tr>
<td>Vacuum level</td>
<td>(p_{\text{vac}})</td>
<td>(10^{-2}..10^{-4})</td>
<td>Pa</td>
</tr>
</tbody>
</table>

The variables listed here are only some relevant parameters, if we want to list all of them, it would be several tens of even close to one hundred. It is only the matter experience which ones are considered as relevant.

Even with this selection the variety of the design variable is so large that the actual solution of the problem would require large amount of computational time so it is necessary the decrease the number variables (dimensions) which we are going to use during optimization process. Later, during the design, many of the variables will be transferred into constraint, leaving only 4-6 variables which we are able to optimize. This narrowing down process may require several steps, but it is necessary to create a good model.

Also there are certain parameters which are hard to define in numbers, such as the control algorithms for the MPPT (Maximum Power Point Tracking) system or converters. An extensive literature search is necessary to quantify the operation of these algorithms at our case.

### D. Objectives

It would be possible to choose many different objectives, such as efficiency, cost, energy density (per volume or per mass), standby loss.

This actual study aims an experimental prototype so cost will be a constraint and we are not going to deal energy density. Our main goal is to maximize the efficiency and to minimize the standby loss. Table IV. is indicating the main objectives.

In this case calculating the efficiency is not same as calculating the efficiency of electrical machine. The energy fed into system may stored for an undefined time and after that the energy is taken out, so to get efficiency we have to consider \(E_{\text{out}} / E_{\text{in}}\) ratio. Since the time difference between charge and discharge action is unpredictable, the best way is the handle the storage losses separately by the means of the standby loss, which indicates the percent of stored energy lost in every hour when the unit is in standby mode (no charge / no discharge).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>(\eta)</td>
<td>%</td>
</tr>
<tr>
<td>Standby loss</td>
<td>loss</td>
<td>% / hour</td>
</tr>
</tbody>
</table>

With the separation of this two parameters it is possible to handle the losses coming from the machine side which are mainly the losses of the electro-magnetic conversion and the losses coming from the system side which are mainly the losses of the flywheel system (air- and bearing-friction) and the idle losses of the motor/generator.

### E. Software Support

At this point of the work we realized that it would be useful to involve more assistance into the design process. For this stage of new system/product development a suitable support is the Invention Machine Goldfire. This software is designed to support innovation process. The part we use for this project is the “New System Design” module’s “Model & Improve System” part. The purpose of this module is to help in the better understanding of the cooperation of the system’s components. Fig. 3. shows the first device model created in Goldfire Innovator.

![Fig. 3. Device Model from Goldfire Innovator.](image)

### IV. SIMULATION WORK

#### A. Softwares

As we mentioned earlier there are many softwares which can support the MDO process. One of these softwares is the
Comsol Multiphysics which is finite element method (FEM) software. This software is capable of handling the equations of different physical disciplines parallel to each other. We are conducting a parallel process where the possibility of using this software for new product design is being investigated.

B. FEM Results

Preliminary results of Comsol FEM simulations were already presented in [3]. We were able to determine certain electromagnetic parameters of a SRM, such as magnetic field distribution, electromagnetic torque, phase-inductance and over behaviour. These parameters can be used for drive design. Using Comsol and Matlab together it can be possible to simulate machine and drive together. The simulation work continues and now we are working on parallel thermal-electromagnetic simulation. As a first step we are focusing on the thermal transient behaviour of the machine.

V. SUMMARY

In this paper the Multidisciplinary Design Optimization (MDO) formulation of Switched Reluctance Machine Flywheel was presented. This is the first step of the design process which result a brand flywheel construction. Based on these results it is possible to continue with the detailed formulation of the problem. According to the MDO method we expect that we will be able to come up with an optimal design of this new system.

REFERENCES