Design Optimization of PVPP with Solar Trackers

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***Abstract*—The support structure of CPV and PV trackers and heliostats are one of the most important cost elements of a solar plant because they typically contribute of ~20% - ~30% to the total cost of the system. Consequently, it is important to reduce the cost of solar trackers or heliostats as much as possible to improve the economic viability of a solar plant. In this paper, a new method is presented for optimizing trackers with arbitrary design and geometry. It is based on linear optimization and implemented as a custom-built finite element library, developed by the author. The user can choose from a set of configurable tracker geometries, which is extensible by arbitrary tracker geometries defined using a text file, and let the software optimize the amount of steel required for the support structure. Stress and buckling (lateral and local) validations are performed in conformity to Eurocode EN 1993-1-1 - Design of steel structures. Wind load assumptions are taken from the wind tunnel studies of Peterka and Derickson and applied as non- uniform load distributions on the tracker surface. Additional national standards can be considered by setting appropriate safety factors for wind and dead load. In summary, this software represents a powerful tool for optimizing and performing a preliminary design of CSP and PV structures with the potential to reduce developing times significantly. The results of the performed investigation could be used to determine the specific weight of a tracker in kg/m² as a function of the wind speed and tracker area with respect of the tracker aspect ratio. Next steps of the optimization task are targeted towards optimization of arrangement of tracking structures on site terrain with minimal ground works and optimization of the concentration of the generated electrical power and driving power supply.**

Keywords—Heliostat; Wind load; Aspect ratio; Design; PV; CPV; Tracker; Optimization; Eurocode; CSP; FEM.

I. INTRODUCTION

In recent years, due to climate change and the global energy crisis the interest in renewable energy sources has been steadily increasing. Concentrated solar power systems, heliostats and solar trackers in general are continuously tracking the sun during the day in order to maximize the amount of collected energy. One of the most important cost factors of a solar tracker is the amount of material used for the support structure. In comparison to other cost factors the choice of geometry and design of the support structure offers significant potential for optimization.

For a shell or solid models the preferred design method is topological optimization. Nowadays, the preliminary design is made on the basis of simplified models using beams and/or trusses. After recognizing the main critical points detailed shell or solid models are made and investigated separately or embedded in the global structure. Using a simplified beam structure, linear programming is a way to achieve the best outcome in a given finite element model considering a list of boundary conditions and trying to minimize an objective function. In our case the objective function is to minimize the weight of a tracker. In this paper, we present a tool for carrying out a preliminary design of a solar tracker through such a linear optimization.

TABLE I. NOMENCLATURE

Parameter	Description
$v_m(z)$	mean wind velocity at a height z above terrain (m/s)
v_b	basic wind velocity is 10 minute mean wind velocity with an annual risk of being exceeded of 0.02 (m/s)
$v_p(z)$	peak wind velocity is 3 second gust wind speed at height z above terrain (m/s)
c_{prob}	probability factor for annual exceedence (–)
z	height above ground (m)
z_0	roughness length (m)
$z_{0,II}$	roughness length for ground category II (m)
r_a	tracker width to height aspect ratio (–)

II. OPTIMIZATION TOOL DESCRIPTION

The chart, describing the internal workflow of the software, is divided into three parts:

- Preprocessor: handling all input parameters
  - tracker geometry: width, height, ground clearance
  - safety factors for wind load and dead load
  - wind parameters: wind speed, wind load cases, field factor
  - material related data: steel grade
- Core: implementing the FEM analysis and the optimizations routines
- Postprocessor: result evaluation and stress visualizing

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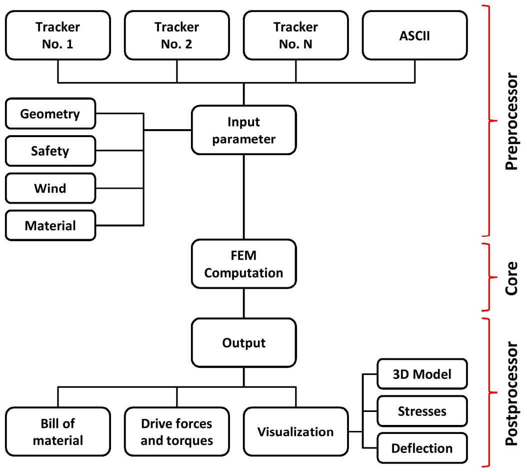

Fig. 1. Flowchart describing the internal work flow of the application.

In the following subsections the main parts preprocessor, core and postprocessor are described in more detail.

A. Preprocessor

The preprocessor is the part of the software where the input parameter: safety factors, wind loads and geometry are specified. It is also the place where the user has to select a certain tracker from No. 1 to No. N. At this stage the tool has only one implemented default tracker which can be selected.

According to the country specific building code safety factors for dead and wind load have to be specified. The default values represent the safety factors in conformity to Eurocode EN 1990 - Basis of structural design [4]. It is also possible to set one of the safety factors to unity and to analyze the impact of the other one only.

For the structural design the relevant wind velocity is defined as a 3-second-gust speed at 10 m above ground, that is exceeded on average only once in 50 years. A wind profile according to terrain category II (area with low vegetation) is used to determine the wind speed at the height of the center of the tracker module area (1):

$$v_m(z) = 0.19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0.07} \cdot \ln\left(\frac{z}{z_0}\right) \cdot c_{prob} \cdot v_b \qquad (1)$$

The life time of the structure was considered to be 20 years according to Eurocode 1991-1-4 - General actions on structures - Wind actions [5].

The calculation of the wind forces and moments acting on the tracker are based on the wind tunnel testing of Peterka and Derickson [1]. The investigated heliostats are nearly square in shape and the influence of the aspect ratio is not known from the evaluated and documented in [1]. Therefore, an additional aspect ratio factor presented in the work of Pfahl [2] was considered in the calculation of the wind loading. In [1] the peak loads are determined by multiplying the mean wind speed with the non-dimensional drag force / moment peak coefficients. The conversion from gust to mean wind speed is accomplished using (2).

$$v_b(z) = \frac{v_p(z)}{\left[1 + 7 \cdot \ln\left(\frac{z}{z_0}\right)^{-1}\right]^{\frac{1}{2}}} \qquad (2)$$

The field factor allows considering the influence on wind loading if solar trackers are placed in an array. Depending on the field density, external fences and position of the tracker in the field a multiplying factor could be determined using the Generalized Blockage Area (GBA) method described from Peterka and Derickson in [1].

The weight of all modules is calculated from the tracker area and the specific module weight. For the tracker design the user has the possibility to choose from three different steel grades with the following yield stresses: 235 N/mm², 275 N/mm², 355 N/mm².

B. Core

The analysis is carried out in the finite element core developed by the author. The FEM library is verified trough a comparative calculation using Sofistik [8]. Stress and lateral buckling calculations, which are imbedded into the library, were proven trough an analytical approaches. The core is implemented as a C++ light-weight library, developed to suit the hardware and software capabilities of modern mobile devices and stand-alone desktop machines. The few implemented finite elements (truss, beams and multi freedom constraints) provide great versatility allowing performing structural analysis beyond the field of solar trackers.

Beside the stress and displacements calculations a lateral buckling analysis is performed for all members of the tracker according to EN 1993-1-1 - Design of steel structures [6]. Cross section classification according to Eurocode was used to avoid local buckling failure meaning that the class 4 cross sections were not considered. The core interface makes it possible to use not only cross section given in EN 10210 - Hot finished structural hollow sections [7] but also any kind of cross section library.

The effects of vibrations, acting perpendicular to the wind direction, induced by vortex shedding are not part of the FEM library.

C. Postprocessor

The graph tab is the place where all forces and moments acting on the tracker are visualized. These values can be used to dimension the tracker's elevation and azimuth drives.

The bill of material summarizes the amount of required steel and distinguishes between five different structural elements: purlins, purlin support beams, cross beams, torsion beam and the post. For every structural element the optimized cross section and the total weight are listed.

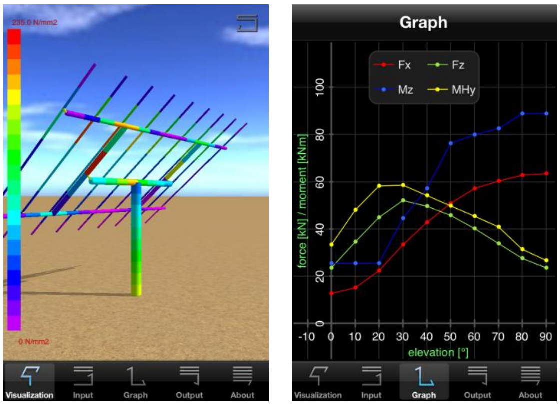

Fig. 2. FEM model (left), forces and moments acting on the tracker (right)

III. Definition of the Case Study

In the following, the geometry of the tracker, area size and the relation between single members was parameterized in a way which allows changing the entire geometry with the single change of the two variables: width and height. The latter are directly dependent on the area and on the tracker aspect ratio. Some parameters like tracker height above ground and the distance between the purlins are set to default values and not changed during the entire study.

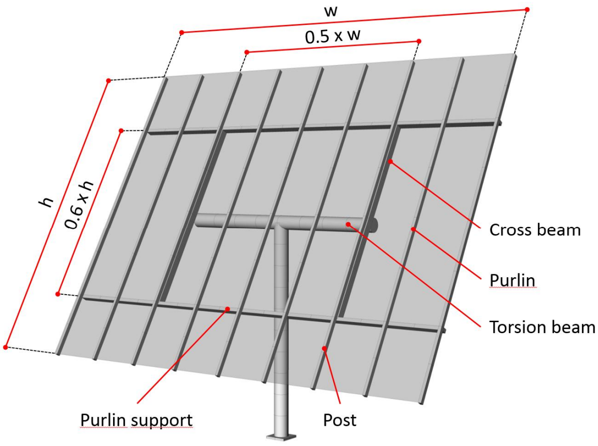

Fig. 3. Tracker parameterization

- Tracker height above ground: 0.50 m
- Maximum distance between purlins: ≤ 1.0 m

Fig. 6 shows the dependencies between the structural elements of the tracker. The length of the cross beam and the distance between the support beams were fixed to specific values based on a separate investigation not further mentioned here. The distance between the purlin support beams was fixed to 60 % of the height of the tracker and the cross beams to 50 % of its width.

For convenience and fast result evaluation the FEM library, discussed in the previous section, was compiled to a stand-alone desktop tool which was run with the following tracker parameters.

- aspect ratio [-]: 0.5, 1.0, 1.2, 1.5, 2.0
- area [m²]: 1, 5, 10, 15 to 150 in 5 m²
- wind speed [m/s]: 0, 5, 10, 15 to 100 in 5 m/s

Additionally, two operation modes were investigated: go to stow and stow position. Stow position is intended to be the one with the smallest impact due to the wind loading. For most trackers including the one used in this investigation elevation 0° is chosen to be the stow position. For each mode the analyzed elevations positions and wind directions are enumerated in the following:

- Go to stow
    - elevation [°] : 0 to 90 in 5°
    - wind direction [°] : 0 to 180 in 15°
- Stow position:
    - elevation [°] : 0°
    - wind direction [°] : 0 to 180 in 15°

Load combination and design code was set to EN 1990 - Basic of structural design [4] respectively EN 1993 - Design of steel structures [6]. The steel grade was fixed to S235 in conformity to EN 10210 [7].

IV. Results and Discussion

The results are evaluated separately for both operation modes. The weight of the tracker is plotted in contour charts for each aspect ratio. The blank area in the upper right corner is empty as respective trackers are not feasible due to exceeded allowable stresses or lateral buckling. In some cases, changing the steel grade of a single member can turn a previously unfeasible tracker into a feasible one.

A. *Operation mode: Go to Stow*

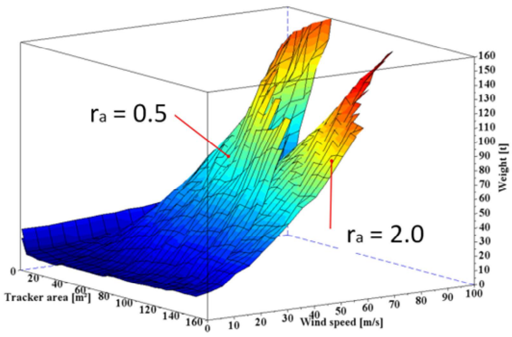

Fig. 4. Operation mode: Go to Stow

It can be observed that the wind loads vary significantly with the aspect ratio of the tracker. Trackers with a large aspect ratio are lighter than trackers with smaller one at fixed area and wind speed. It should be underlined, that this investigation considers only the amount of steel used.

B. Operation mode: Stow

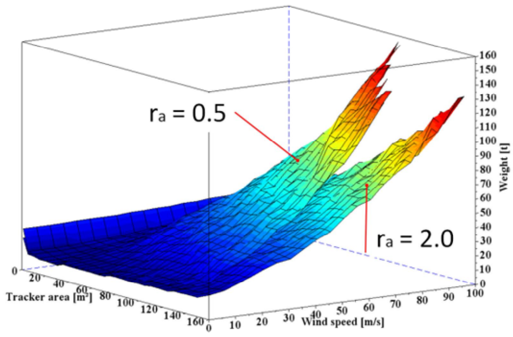

Fig. 5. Operation mode: Stow

The figures show the specific mass of the tracker in kg/m² as a function of wind speed and tracker area for selected aspect ratio.

V. PERESPECTIVES FOR NEXT STEPS OF PVPP OPTIMIZATION

The target of optimization of positioning of trackers on the site terrain is aimed to reduce ground works and simultaneously to identify changes in airflow around the structures.

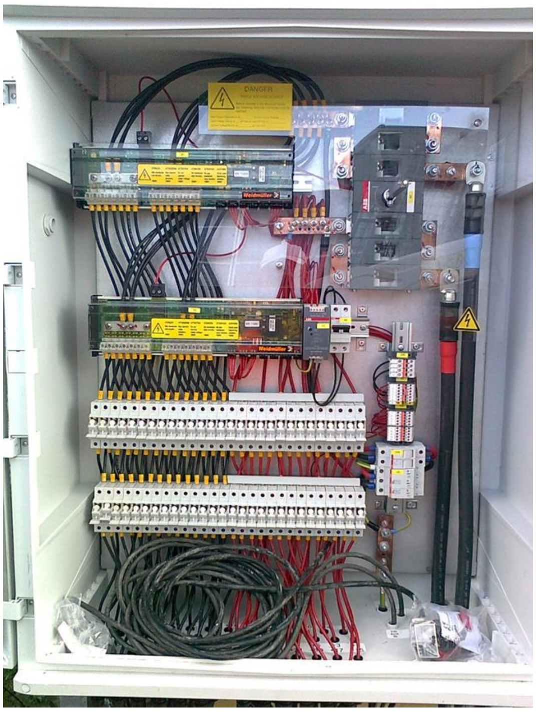

Fig. 6. Experimental junction box and string monitoring

Target: optimal design towards expenses for design and construction of PVPP with trackers on terrain with minimal ground works and optimal power centralizing and power distribution for the tracking system drives.

Aspects of optimization of electrical part:

- Optimal grouping of the strings (Currently study is performed for optimization tool for location of string grouping boxes and string monitoring. String monitoring software for fault location, performance analysis and maintenance support is under development.)
- Optimization of power supply for trackers drive mechanisms.

VI. CONCLUSION AND OUTLOOK

Results of public available wind tunnel tests have been combined with an FEM library and a set of PV tracker to create a software tool that allows quick and user friendly preliminary design and optimization of the investigated structure. For a final design additional wind tunnel testing should be performed in order to reduce the amount of steel for the support structure even more. Seismic analysis and the effect of temperature load have to be considering in an extended detail design. Techno-economical approach will require additional investigations of optical quality, deflection and costs to determine the lowest cost of energy (LCOE). Our intention is to create a data base of heliostats, CPV and PV trackers that will allow end users to choose an economic system for their site under considering the local environmental conditions and country codes.

The optimal design of mechanical, electrical and civil part of PVPPs will improve the cost reduction of energy produced. The study presented aims to support the sustainable development of completive renewable energy power generation plants.

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