Annual Energy Production (AEP) optimization for tidal power plants based on Evolutionary Algorithms - Swansea Bay Tidal Power Plant AEP optimization

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Abstract. In order to be able to predict the maximum Annual Energy Production (AEP) for tidal power plants, an advanced AEP optimization procedure is required for solving the optimization problem which consists of a high number of design variables and constraints. This efficient AEP optimization procedure requires an advanced optimization tool (EASY software) and an AEP calculation tool that can simulate all different operating modes of the units (bi-directional turbine, pump and sluicing mode). The EASY optimization software is a metamodel-assisted Evolutionary Algorithm (MAEA) that can be used in both single- and multi-objective optimization problems. The AEP calculation tool, developed by ANDRITZ HYDRO, in combination with EASY is used to maximize the tidal annual energy produced by optimizing the plant operation throughout the year. For the Swansea Bay Tidal Power Plant project, the AEP optimization along with the hydraulic design optimization and the model testing was used to evaluate all different hydraulic and operating concepts and define the optimal concept that led to a significant increase of the AEP value. This new concept of a triple regulated “bi-directional bulb pump turbine” for Swansea Bay Tidal Power Plant (16 units, nominal power above 320 MW) along with its AEP optimization scheme will be presented in detail in the paper. Furthermore, the use of an online AEP optimization during operation of the power plant, that will provide the optimal operating points to the control system, will be also presented.

1. Introduction
The optimization of the Annual Energy Production (AEP) for tidal power plants can be a challenging task; not only because an advanced optimization software is required, but also because the necessary components of the toolchain employed within the optimization procedure should enable the optimization loop to run robustly and in a time efficient way.

In this paper, the main components of the toolchain used for the AEP optimization for tidal power plants are presented. As shown in Figure 1, this tool chain consists essentially of an energy calculation tool, developed by ANDRITZ HYDRO, and an efficient optimization platform (herein the Evolutionary Algorithm System - EASY). The energy calculation software is able to model different operational modes of the turbine units, providing the reservoir level during operation of the tidal power plant and the energy produced in a specific time period.
For the initiation of the optimization loop, a set of user-defined parameters (design variables) is generated by EASY in order to obtain a set of new candidate solutions. In the AEP optimization application, the operational modes, the reservoir level path, the starting and stopping head of each mode and the speed (in case of a variable speed bulb unit), for each operating point through the year, consist the design variable set. For each one of these candidate solutions, the energy and the operation of the power plant for a specific time period is calculated. The optimization objective function refers to the maximization of the energy produced. The values of the objective function indicate the quality of each candidate solution and are subsequently used by EASY to generate the next generation of candidate solutions. In this way, the optimization searches for the optimal operational modes and optimal reservoir level path for the whole year that maximize the AEP. In addition to that, due to operational range constraints (generator power output, speed and cavitation limitations) and environmental restrictions, the optimal solutions are subject to a number of constraints that can be added in the optimization platform.

![Figure 1. The AEP Optimization Scheme based on the AEP calculation tool developed by ANDRITZ HYDRO and the EASY optimization tool. The optimization is based on the definition of the optimization design variables and constraints and provides the maximum AEP along with the optimal tidal plant operation throughout the year.](image)

In what follows, the AEP calculation tool, the optimization platform and the AEP optimization problem are presented and demonstrated in the Swansea Bay Tidal Power Plant optimization application.

2. AEP calculation tool - Modelling of the problem
   In order to set up an optimization loop for the AEP maximization of a tidal power plant, a fast, robust and reliable tool, that models the reservoir level by simulating all possible operational modes and calculates the energy produced, is necessary. This AEP calculation tool models 8 different operational modes over a tide period that can be selected by the optimization in order to increase the AEP. This operation is allowed by a triple regulated bi-directional bulb pump turbine unit that can turbine, pump and sluice water in both directions. ANDRITZ HYDRO developed this new concept of a “bi directional bulb pump turbine”, with variable speed, turnable runner blades and guide vanes that was applied in the Swansea Bay Tidal project in order to produce energy at incoming and outgoing tides, [1]. The triple regulated turbines allow very efficient power generation and the possibility of pumping, gives an additional energy increase, as it will be presented in Section 5.
   The various operational modes over a tide period, modelled by the AEP calculation tool, are presented in figure 2. During flood, starting from an optimal reservoir level, water is pumped (Pump Mode Reverse, PMR) through the turbine in opposite direction, emptying the reservoir until the
allowed level. Then idle time (Idle Mode, IM I) begins in order to build up a head for turbining in reverse direction (Turbine Mode Reverse, TMR). This mode ends with sluicing (Sluicing Mode, SM I) until sea and reservoir levels are equal. Then, during ebb, water is pumped again (Pump Mode, PM) through the turbine in normal direction filling up the reservoir until the allowed level. Subsequently, idle time (Idle Mode, IM II) begins in order to build up once again the adequate head for turbining (Turbine Mode, TM) in normal mode. This mode ends again with sluicing (Sluicing Mode, SM II) until sea and reservoir levels are equal again. During SM I and II, water can be sluiced through the sluicing gates and the units at the same time in order to increase and reduce the reservoir level, respectively, as much as possible. Another variant of sluicing is to start sluicing through the gates not at the end of TMR and TM, but in parallel with power generation, as in figure 2.

Figure 2. The various operational modes over a tide period. Sluicing water through the gates (SM I and II) is presented in parallel with power generation (TMR and TM) in order to increase and reduce the reservoir level, respectively, as much as possible and increase the energy produced.

As it can be seen in figure 2, in a tidal power plant, wide variations of the reservoir level are usual. For this reason, through bathymetry studies, a relation between the volume of the reservoir \( V_{r,l} \) and its respective level \( h_{r,l} \) is obtained. In this way, the reservoir volume variation during the operation of the tidal power plant is predicted through time.

As it is presented in figure 1 and will be thoroughly explained in Section 4, the optimal reservoir level \( h_{r,l} \) and speed \( n_i \) for each time step \( t_i \) (i.e. for each operational point) are provided by the optimization, since they constitute the optimization design variables. Each tide cycle is divided into small intervals of time. For a time interval \( \Delta t = [t_1, t_2] \), e.g. during flood generation, the discharge through the \( N_t \) turbine units and the net head are given by

\[
Q = \frac{(V_{r,2} - V_{r,1})}{N_t(t_2 - t_1)}, \quad H_{net} = H_{gr} - kQ = |h_{r,1,2} - h_{r,1,1}| - kQ
\]  

(1)
where $h_{SL}$ stands for the sea level and $k$ for the loss coefficient for turbine intake and exit losses. The unit generator power output is given by

$$P = \rho g \eta_i \eta_M \eta_E h_{net} Q$$

(2)

where $\eta_i (H_{net}, Q, n)$, as a relation of $H_{net}$, $Q$ and $n$, represents the hydraulic efficiency that is calculated from the Hydraulic Efficiency Hill Chart, provided through the hydraulic model testing of the bulb unit. $\eta_M (n), \eta_E (n, P_M)$ stands for the mechanical and electrical efficiencies, as a relation of speed and turbine shaft power $P_M$. The total sluicing discharge through the $N_G$ sluicing gates, $Q_{SLG}$, and the turbines, $Q_{SLT}$, of the power plant is given by

$$Q_{SLG} = Q_{SL} = c_{d, G} A_G \left(2 g H_{gr} \right)^{1/2} N_G + c_{d, T} A_T \left(2 g H_{gr} \right)^{1/2} N_T$$

(3)

where $c_{d, G}, c_{d, T}$ correspond to the sluicing gate discharge coefficient and the discharge coefficient for sluicing through the turbines, respectively, and $A_G, A_T$ to the gated and turbine area, respectively. The energy produced based on the energy generated during turbining (TMR and TM) and the energy consumed during pumping (PMR and PM) in a time interval $\Delta t$ is given by

$$E_{produced} = E_{generated} - E_{consumed} = N_T \sum_{i=1}^{N_G} P_{TMR, TM} \Delta t - N_T \sum_{i=1}^{N_G} P_{PMR, PM} \Delta t$$

(4)

Figure 2 shows the reservoir level during only one tide cycle. In order to calculate the AEP, the optimization should be applied for a time period that covers one year of operation.

3. Optimization Platform

Nowadays, EAs are capable of handling complex, constrained, multi-objective problems by accommodating any analysis/evaluation software, without even requiring access to its source code. Another advantage of EAs is their ability to reach the global optimum without being trapped into local optima. Being the most known representative of global optimization methods, EAs are widely used to solve engineering optimization problems. In fact, the only prerequisite for carrying out an EA-based optimization is the availability of an appropriate evaluation software (considered as a black-box tool by the EA) and well-defined objective functions and design variables. In the AEP optimization application, the AEP calculation tool is the evaluation software. The objective functions, design variables and constraints of the AEP optimization will be presented in the Section 4.

In real-world applications with computationally demanding evaluation software and a great number of optimization design variables, the optimization time increases noticeably. In order to reduce the wall-clock time of EA-based optimizations, the most common technique is the extensive use of surrogate evaluation models (or metamodels), the so-called Metamodel-Assisted EAs (MAEAs) [2]. The metamodels are used to inexpensively approximately evaluate the objective function value(s), after being trained on previously-seen evaluated individuals. In this paper, artificial neural networks are used as metamodels. Metamodels can be incorporated into an EAs in different ways, depending on whether their training takes place during (on-line) or separately from the evolution (off-line). In this paper, Metamodel-Assisted EAs (MAEAs) with on-line trained metamodels are employed, [3]. According to the inexact pre-evaluation (IPE) approach, with the exception of a few starting generations, all population members are approximately evaluated using local metamodels trained on the fly. Then, a few of them, practically the most promising among them, as indicated by the metamodel, are re-evaluated on the exact model.
Although the AEP evaluation software is not time expensive, the application involves a great number of design variables and constraints. The high number of design variables deteriorates the efficiency of a conventional EA, since it requires more evaluations and increases the computational cost. As EAs are population-based search methods, one way to overcome this problem is parallelization by concurrently evaluating candidate solutions on different processors. Also, in MAEAs, the metamodels’ training time increases and the prediction accuracy decreases as the number of design variables increases. A way to tackle optimization problems with an excessive number of design variables is to decrease the problem dimension via dimension reduction techniques. This can be done via principal component analysis (PCA) techniques. In this paper, PCA is used in EAs by adding new evolution operators, the so-called PCA-driven ones, and PCA driven metamodels. The PCA-driven evolution operators have been proved [4] to improve the performance of the EA and the PCA-driven metamodels lead to much better performing MAEAs [5]. The Evolutionary Algorithm System - EASY optimization platform supported by MAEAs and the PCA technique is used in this paper for the AEP optimization application.

4. AEP Optimization Scheme

In figure 1, the AEP Optimization Scheme based on the AEP calculation tool and the EASY optimization platform is presented. For the definition of the AEP optimization problem, the objective functions, design variables and constraints of the optimization are presented as follows.

The optimization objective function $F_{\text{obj}}$ refers to the maximization of the annual energy produced, as defined in Equation (4). Apart from this, another optimization goal could be the maximization of the annual income, based on the different energy prices for the energy generated during turbining, $p_{\text{gen}}(t)$, and the energy consumed during pumping, $p_{\text{cons}}(t)$, that can be changing per time and affecting the optimal operational strategy.

$$F_{\text{obj}} = \max \ E_{\text{produced}}$$
$$F_{\text{obj}} = \max (E_{\text{generated}}(t)p_{\text{gen}}(t) - E_{\text{consumed}}(t)p_{\text{cons}}(t))$$

(5)

The goal of the AEP optimization is to define the optimal operational modes, optimal starting and stopping head $H_{OM_j}$ of each mode $j$ and optimal reservoir level path $h_{r,i,i}$ for each time step $t_i$ (i.e. for each operational point) for the whole year, that maximize the energy. In case of a speed regulated unit, the speed $n_i$ per operational point is an additional design variable. The number of operating units $N_{Ti}$ per operational point can be also part of the group of the design variables, concluding to an optimization platform with the following optimization design space:

$$h_{r,i,i}^{\text{min}} \leq h_{r,i,i} \leq h_{r,i,i}^{\text{max}}, \quad H_{OM_j}^{\text{min}} \leq H_{OM_j} \leq H_{OM_j}^{\text{max}}, \quad n_i^{\text{min}} \leq n_i \leq n_i^{\text{max}}, \quad N_{Ti}^{\text{min}} \leq N_{Ti} \leq N_{Ti}^{\text{max}}$$

(6)

where $h_{r,i,i}^{\text{min,max}}, H_{OM_j}^{\text{min,max}}, n_i^{\text{min,max}}$ and $N_{Ti}^{\text{min,max}}$ stand for the lower and upper limits of the reservoir level, starting and stopping head of each mode, speed and number of operating units for each operational point, respectively.

The optimization is also subject to a number of constraints. Constraints of the operational range, such as maximum generator power output $P_{\text{max}}^{\text{max}}$, maximum speed $n_{\text{max}}^{\text{max}}$ and maximum runner blade angle $\beta_{\text{max}}$, along with minimum cavitation limitations $\sigma_i^{\text{min}}$ are some of the constraints that can be applied in the AEP optimization. Due to possible environmental limitations, the lower and upper allowed reservoir level is also taken into account, resulting to the following constraints:
\[ P_i \leq P_{\text{max}}, \quad n_i \leq n_{\text{max}}, \quad \beta_i \leq \beta_{\text{max}}, \quad \sigma_i \geq \sigma_{i,\text{min}}, \]
\[ h_{r,l,\text{min}} \geq h_{r,l,\text{min}\text{constr}}, \quad h_{r,l,\text{max}} \leq h_{r,l,\text{max}\text{constr}}. \]  

(7)

The minimum allowed cavitation values are defined through hydraulic model testing and provided in a Cavitation Constraint Hill Chart.

5. AEP Optimization Case Study - The Swansea tidal project

5.1. Background

The Swansea Bay tidal power plant is being developed by Tidal Lagoon Swansea Bay PLC (TLSB) and will be located in the Severn Estuary on the west side of UK. The Severn Estuary holds the second highest tidal range in the world by featuring an average tidal range of 8.5m during spring tides. Figure 3 shows the dam, the west-south location of the powerhouse along with the maritime park for various recreational and educational purposes. Swansea Bay tidal power plant is the first of six planned tidal power plants in UK and it will be the first tidal power plant in the world which will have a nominal power above 320 MW, providing clean, renewable, and predictable energy for over 155,000 houses. In the year 2015, after a competition set by TLSB, ANDRITZ HYDRO was nominated as supplier.

During the competition, ANDRITZ HYDRO developed a new concept for a “bi directional bulb pump turbine” unit with variable speed, turnable runner blades and guide vanes that can turbine, pump and sluice water in both directions in an efficient way, [1]. Good performance for turbining and pumping modes in both directions was confirmed on the hydraulic test rig. Figure 3 illustrates also the arrangement of the turbine-generator-unit in a cross sectional view.

In reference to Sihwa tidal power plant in South Korea, [6], which is currently the world’s largest operating tidal plant equipped also by ANDRITZ HYDRO, two phases of hydraulic model testing were planned during the competition for Swansea Bay. Firstly, the feasibility of the project was investigated by evaluating all possible operational concepts through hydraulic model testing, assisted by Computational Fluid Dynamics (CFD) analysis and AEP optimization. In the second phase, improvements were applied on the well-chosen concept in order to ensure the maximum AEP.

5.2. Swansea Bay AEP Optimization problem

The Swansea Bay tidal power plant will be equipped with 16 bulb-type turbine-generator units, each having an installed capacity of 20 MW, and 8 sluicing gates with a gated surface of 14.5m x 13.5m each. Year 2003 is selected as the representative reference year for the AEP optimization. Figure 4 shows, between others, a time series that represents the tide variation in the early hours of January 2003. The reservoir volume in relation to the reservoir level is also available based on bathymetry studies in the estuary. Through hydraulic model testing of the bulb unit, Efficiency and Cavitation Constraint Hill Charts are available for each operating mode (PMR, PM, TMR, TM) resulting to 8 Hill Charts in total, for which the optimization searches for the optimal operational points that respect the cavitation constraint.

The objective function of the Swansea Bay AEP optimization refers to the maximization of the annual energy produced for year 2003. The goal of the AEP optimization is to define the optimal operational strategy (operational modes) along with the optimal starting and stopping heads for each mode throughout the year, as defined in Section 4. At the same time, the optimal reservoir level path and optimal speed needs to be defined, thus reaching a total of almost 200 design variables per tide cycle. All operating points are subject to the following constraints: generator power output \( P \leq 20 \) MW, speed \( n \leq 73 \) rpm and cavitation limitations, as explained in Section 4. Additionally, due to environmental limitations in Swansea Bay, the lower and upper reservoir level for each tide cycle is restricted to the lower and upper sea level of the corresponding tide cycle. This means that pumping for each tide cycle is allowed until the aforementioned sea level, imitating nature in this way (mitigation pumping).
The optimization problem was studied using a MAEA (PCA) with $\mu=10$ parents and $\lambda = 50$ offspring. The IPE phase started after 200 exactly evaluated individuals were stored in the DB. The $\lambda_e = 6$ most promising individuals according to the metamodel prediction, among the 50 offspring, were then evaluated using the AEP calculation tool. During the initial (non IPE) generations, 50 concurrent evaluations were sent to 50 different CPUs. As soon as the IPE phase started, the computational burden was reduced to 6 concurrent evaluations, thus freeing valuable resources.

At the cost of 15000 AEP evaluations, the optimal operation along with the optimal reservoir level and speed for each operational point was defined by the optimization, resulting in an AEP optimal solution of 540GWh. The optimal reservoir level is presented in figure 4 for 9 tide cycles during the early hours of January 2003. In the same figure, it can be noticed that the reservoir level is restricted to the corresponding sea level of each tide cycle (mitigation pumping), fulfilling the environmental constraints. As it can be seen in figure 5, the optimal operational modes for the Swansea Bay case selected by the optimization are the PMR, PM, TMR, TM, SMI, SMII, IMI and IMII, as explained in detail in Section 2, figure 2. The generator power output that is being produced through turbining operation (TMR and TM) and the power consumed through pumping operation (PMR and PM), signed as negative, can be seen in figure 5. In addition to that, the optimal head difference between sea and reservoir level (gross head) along the operation is presented also in figure 5.

Both sluicing mode variants, i.e. starting gate sluicing operation at the end of TMR and TM or in parallel, were evaluated. Sluicing through the gates in parallel with power generation increased the AEP by almost 2% in comparison to gate sluicing operation only at the end of TMR and TM. In this way, for example by the end of flood operation, a higher reservoir level is reached, that leads to lower head and less power consumed during pumping, which concludes to an increased AEP.

At the early stage of investigations, it was proven that without pumping, the project would not have been feasible. The contribution of mitigation pumping in the AEP is significant by increasing the AEP by 10%. Pumping operation contributes to build higher heads needed for the turbining operation, which outperforms the energy that is consumed during pumping. The full potential of pumping (full pumping) in Swansea Bay can be achieved when neglecting the reservoir limitations due to the environmental constraints. In this case, pumping contributes to an increase of 15% in total in comparison to no-pumping. In figure 6, the optimal reservoir level and the generator power for mitigation and full pumping case scenario in comparison to the no-pumping case is presented.

The AEP optimization indicates at the same time the operational points, where the units should be operating through the year in order to reach the optimum AEP value. Any deviation from the optimal operation would conclude to deviations from the predicted AEP value. For this reason the AEP optimization can be also used during operation of the power plant in order to assure the optimal
operation. An online optimization, based on tide forecast that is available some days before, can provide in advance the optimal operational points (optimal speed, guide vane angle, runner blade angle) to the control system. In figure 7, the optimal speed, guide vane angle and runner blade angle that are proposed by the optimization during PMR, PM, TMR and TM, are presented through time for one of the highest tides of year 2003.

![Figure 4](image.png)

**Figure 4.** The optimal reservoir level along with the tide variation during the early hours of January 2003, corresponding to an AEP optimal solution of 540GWh.

**6. Conclusion**

This paper presented an Annual Energy Production (AEP) optimization tool for tidal power plants based on Evolutionary Algorithms that is able to maximize the AEP by optimizing the plant operation throughout the year. The selection of the optimal operating modes in sequence, between pumping, turbining and sluicing in both directions, in addition to the definition of the optimal reservoir level path for the whole year are the results of the optimization. The AEP optimization was applied on the Swansea Bay Tidal Power Plant, which along with hydraulic design development and model testing, led to a significant increase of the AEP value, of more than 50%. The application of the AEP optimization directly at the tidal power plant in order to provide the optimal operational points to the control system, according to tide prognosis, is a further advantage.
Figure 5. The optimal operational modes based on turbining, pumping and sluicing through the gates in parallel with power generation were used in order to maximize the AEP. The optimal generator power output along with the optimal gross head through 3 tide cycles is presented. Power consumed through pumping operation is signed as negative.

Figure 6. The optimal reservoir level and the generator power output for the without pumping, mitigation pumping (10% increase in AEP) and full pumping (15% increase in AEP) case scenario.
Figure 7. The optimal speed, guide vane angle and runner blade angle along with the gross head proposed by the optimization, during PMR, PM, TMR and TM, during one of the highest tides of year 2003.

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