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Lessons Learned Based on SNL Experience in Reviews of SPA Controls Awardees

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ABSTRACT

This report summarizes the key contributions and lessons learned from SNL experience in technical reviews of Controls awardees in the DOE SPA program from 2013-2020. The purpose of this report is to provide observations and technical suggestions that are likely to be beneficial to the WEC industry as a whole. Over the course of the SPA FOA program, SNL has engaged in technical review for a total of 5 different Controls awardees. The awardees represent a diversity of WEC devices and the application of different control design approaches. The report begins with a summary of key performance metrics results reported by the 5 Controls awardees. This is followed by a summary of observations and lessons learned distilled from the technical reviews of the awardees. The report concludes with a list of general technical suggestions for future WEC controls projects.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
WEC	Wave Energy Converter
FOA	Funding Opportunity Announcement
SNL	Sandia National Laboratories
DOE	Department of Energy
WPTO	Water Power Technologies Office
SPA	System Performance Advancement
LCOE	Levelized Cost of Electricity
AEP	Annual Energy Production
JONSWAP	Joint North Sea Wave Project
RMS	root mean square
MPC	Model Predictive Control
PWR	power to weight ratio
PID	proportional integral derivative
PTO	power take off
LQR	linear quadratic regulator

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1. INTRODUCTION

Sandia National Laboratories' (SNL's) role in the DOE Water Power Technologies Office (WPTO) System Performance Advancement (SPA) FOA program has focused on performing technical reviews and providing technical guidance to DOE on the performance of SPA FOA awardees in two topic areas: Controls and Structures. This report focuses specifically on the experience SNL has gained from the technical reviews of SPA FOA Controls awardees. The report summarizes the key contributions and distills the lessons learned from these projects that are likely to be impactful to the WEC industry as a whole. Over the course of the SPA FOA program, SNL has engaged with a total of 5 different Controls awardees. The report begins with a summary of key performance metrics results reported by the 5 Controls awardees. This is followed by a summary of lessons learned from the awardees. The report concludes with a list of general suggestions for future WEC controls projects.

1.1. Summary of Key Performance Metrics Results from SPA Controls Awardees

1. Over the 5 SPA controls projects, the collective improvement achieved in Levelized Cost of Electricity (LCOE), measured in ¢/kW-hr, was an average 29.6% reduction in LCOE from each project's beginning baseline value. LCOE is one of the primary metrics by which awardees' performance is assessed.
2. Over the 5 SPA controls projects, the collective improvement achieved in Annual Energy Production (AEP), measured in MW-hr/year, was an average 83.6% increase in AEP over each project's beginning baseline value. AEP is one of the primary metrics by which awardees' performance is assessed.

2. SUMMARY OF LESSONS LEARNED FROM SNL EXPERIENCE IN REVIEWS OF SPA CONTROLS AWARDEES

2.1. Control Observations

1. The JONSWAP stochastic wave model is often used for estimating sea states in WEC simulations. One of the unique developments regarding this model came out of an early SPA controls awardee and is documented in [1]. The innovation was the development of a finite dimensional approximation of the JONSWAP stochastic wave model for the incoming sea state. The identified power spectra have been demonstrated to have <1% RMS error in estimation of sea state when compared to JONSWAP power spectra.
2. Robustness of the control designs with respect to key control parameters or model parameters should be part of the analysis of control performance, perhaps even part of the component metrics to be considered (see Appendix A). Tests may show satisfactory performance of the developed control designs, but robustness to these parameters needs to be part of the performance evaluation. Without these robustness considerations, the control design may not be very repeatable or scalable to further testing.
3. There were many inconsistencies and omissions in the descriptions of implementation details such as digital implementation (e.g., sampling time), hardware selection, needed filtering to combat noise issues, real-time software implementation, sensors utilized for feedback control, and characterization of control command signals sent to the actuator(s). See suggestion no. 5 under general suggestions below for future guidance on this issue.
4. Model Predictive Control (MPC) was a control design methodology that nearly every controls awardee implemented. Further, MPC was consistently the best performing control design. MPC has several advantages. MPC is based on an iterative, finite time horizon optimization of a plant model. The optimization computes a cost minimizing control strategy for that finite time horizon in the future. Then it re-computes the optimization at each subsequent time instance. While the current time instance of the controller is optimized, MPC can still anticipate future events with the model-based aspect of the control. Typically, the model is an empirically derived linear model based on system identification techniques applied to experimentally obtained data. In the case of nonlinear MPC, a nonlinear model is used to approximate the system being controlled. Several projects used the nonlinear variant of MPC with reliable results. MPC has a distinct advantage over the linear quadratic regulator (LQR) that has long been the standard linear optimal control technique. The LQR method optimizes the control over a fixed time horizon whereas MPC optimizes in a receding time horizon, i.e., the prediction horizon keeps being shifted forward in time. MPC computes a new solution often whereas LQR uses the single (optimal) solution for the entire time horizon. Therefore, MPC allows real-time optimization against hard constraints. See [2] for further details of MPC as applied to WEC controls. The primary drawback to MPC is that it can be difficult to implement in a real-time hardware environment due to the computational complexities in solving the optimization problem at each time instance. Further, the decision to use a linear or a nonlinear model in MPC applied to WEC devices is not obvious. This will depend on the particular device and how wave models (if used at all) are chosen. Therefore, some transparency in how MPC is applied would really help future projects in their control designs. However, some of these details in implementing

MPC may be considered proprietary and therefore not available to future awardees. Some common ground on non-proprietary aspects of MPC design should be agreed upon and made available to the WEC industry. See suggestion no. 6 under general suggestions below for further guidance on MPC.

2.2. General Observations

1. Some of the SPA performance metrics were either too difficult to determine (e.g., LCOE in early stage research projects) or were not especially relevant (e.g., power to weight ratio (PWR) for moored devices if the mooring must be included as part of the device weight) to the WEC devices under testing.
2. Many of the models developed for analysis and simulation of control designs were novel and especially useful in evaluating multiple control designs. These models should be noted for their utility in control design and referenced for use by future projects in the WEC industry. See suggestion no. 7 for further insight on this issue.
3. The issue of feedforward vs. feedback was part of the control designs in several of the projects. In feedforward control, the control variable adjustment is not error-based as in feedback control. Instead it is based on knowledge about the system being controlled in the form of a mathematical model of the system and/or knowledge based on measurements of the disturbances to the system. In the case of WEC, feedforward control generally requires accurate wave modeling and/or the use of sensors to look ahead at the incoming waves and apply this information in the WEC device controls. Feedback can be as simple as proportional feedback (proportional integral derivative or PID in some cases) of sensor data that is not necessarily looking ahead at incoming waves. Sometimes, especially in MPC, models are employed in feedback control. The nature of feedback lessens the accuracy needed in these models compared to feedforward, but the issue remains: feedforward vs. feedback. From reviewing the awardees' control designs, the answer depends on the environment the WEC device is to be deployed. For rivers, it was shown that look-ahead sensors are not necessary since the current is rather predictable and uni-directional. For ocean environments featuring omni-directional waves that are not nearly as predictable, the answer is both, provided that the costs are reasonable, and the telemetry is reliable. For some of the awardees, the cost and time to implement these sensors (typically, acoustic or optical) was too much. Further, the telemetry needed (some kind of wireless communications) is not always reliable, which defeats the purpose of using these sensors. Thus, most of these projects ended up not using feedforward sensors. For the awardees that did use feedforward sensors, control results were improved compared to not deploying these sensors. However, the improved results may not justify the cost and effort to deploy. See suggestion no. 8 for further suggestions on this issue.

2.3. General Suggestions

1. One of the key issues impacting the WEC industry is a lack of apples to apples comparison studies between causal and noncausal controllers. With sensitivity analysis employed for various conditions and parameters, these studies could help the WEC

industry identify tipping points at which performance may favor one approach over the other.

2. One of the key conclusions detailed in [5] and [7] is that for most applications and device topologies wave prediction provides very little value added. Three factors make it difficult to reach definitive conclusions. One factor is the lack of apples to apples comparison studies available to the WEC industry between causal and noncausal control designs (see [6] for examples). The second factor is that different types of devices may benefit from wave prediction more than other types. Narrowband WEC devices are more likely to benefit from wave prediction than more general broadband WEC devices. The third factor is the lack of cost/benefit analysis to provide firm economic numbers as to the cost of wave prediction implementation for a range of WEC devices.
3. The integration of the controls design into the power take off (PTO) development effort was endorsed by most of the awardees. Further, recent controls algorithms (see [6] for examples) suggest this approach is more likely than a separated controls/PTO development effort to result in an optimal controller design.
4. As WEC devices become more efficient and cost effective, the electric power grid considerations should be part of the technology development effort. This would include an analysis (if not a full demonstration) of the power electronics required (e.g., inverters) to connect the WEC devices to the grid. This may also include the types of grids for which the devices are best suited (e.g., microgrids, remote power grids, island-based grids).
5. For control designs, more than one design should be developed and tested (in addition to the baseline control design). This allows the project teams to be open to the prospect that their primary candidate control design may not be the best suited for their device.
6. The project teams should consider the alterations necessary for their chosen control design to be applicable to other WEC devices that were not part of their project effort. This would allow the WEC industry to benefit from the developed control designs even if other WEC devices are adopted instead.
7. Because of the environmental restrictions, alternatives to standard hydraulic fluids should be considered. Specifically, seawater (for ocean-based devices) needs further study.
8. A common reporting suggestion should be adopted for all projects in the descriptions of implementation details for their control designs. This could be a matrix or enumeration of key details including digital implementation (e.g., sampling time), hardware selection, necessary filtering to combat noise issues, real-time software implementation, sensors utilized for feedback control, and characterization of control command signals sent to the actuator(s). This would help in future deployments of the control designs and/or WEC devices used in the project.
9. Model Predictive Control (MPC) has become the preferred control design technique adopted by the majority of awardees in the SPA I and II controls projects. Though there are commercially available software toolkits for MPC design (e.g., MATLAB), there are many variations in the implementation of MPC (especially the optimization algorithm). Most of these variations are due to differences in the WEC devices being deployed. However, the rationale for these variations can certainly be communicated by awardees

in their required documentation without disclosing proprietary details of the final design. This would enable DOE/SNL to compile a short lessons-learned tutorial on MPC design that should be of value to the WEC industry. Currently, the level of transparency in the design documentation provided by some of the awardees makes it difficult to produce such a document.

10. Several controls awardees employed novel modeling techniques in their control designs. Some of the models were for simulations to guide the control design process and validate results from testing. Other models (such as in MPC) were used on-line, embedded into the control system software. The development of these models and their usage was not always reported in sufficient detail to enable their use in future WEC control designs. Therefore, some consistent guidelines on required information for modeling should be considered. For instance, if the models used were previously known and available in the literature, these references should be well documented (both the theory behind the models and their usage in the WEC industry). For techniques adopted from other fields (e.g., fluid mechanics, wind energy), this should also be referenced with documentation of any modifications made to these models provided by the design team. Finally, for models developed from experimental data (system identification or statistically derived models) or first principles (physics-based, electromechanical), the steps in the derivation should be well documented with descriptions of the characteristics of the final models detailed. These characteristics could include (but are not limited to): linear vs. nonlinear, dimensionality, estimates of uncertainty in the parameters, indicators of where noise can enter the model (sensor noise, process noise), reduced-order modeling, and data requirements (in the case of empirically derived models). This information can be captured in a spreadsheet or as an appendix to the final report.

11. The use of sensors in controller implementations is another area where improved documentation could help the WEC industry. The information that future awardees should provide include: (a.) the type of sensors deployed (general category and specific sensor device), (b.) the quantity being measured, (c.) the means by which the measurement signal is acquired by the controller (direct electrical connection, wireless telemetry, etc.), (d.) the resolution and accuracy of the measurement signal, (e.) noise ratings of the sensor (either provided by the manufacturer or empirically obtained), (f.) cost (if research grade or proprietary, this can be estimated or omitted), (g.) ease of integration into controller implementation (this is a qualitative description, but if major headaches were encountered this should be noted), (h.) for projects that implemented a feedforward controls component using some type of look-ahead sensor, a brief discussion on the value of this approach vs. feedback only, and finally, (i.) a discussion of whether the sensor delivered on its expectations or would a cheaper sensor have sufficed or should it be eliminated altogether. This information can be captured in an appendix devoted to discussion of sensors deployed in the project. The information could be entered into a provided template in spreadsheet format or it could be entered as text into a Word document with subsections labeled as to (a.) – (i.) above. Non-proprietary notes on specific sensors should be added to the "Notes, Considerations & Suggestions" sections of sensors on the WEC Instrumentation & Sensor Database [4].

12. Several controls performance metrics of interest are described in Appendix A. These may be useful for individual projects in quantifying their performance improvement over

the course of a project. These metrics are not meant to replace the primary SPA metrics. Rather, they are more specifically used to help quantify and refine controller performance.

13. Techno-economic models can be used in sensitivity studies to determine the tradeoffs involved in developing an economically optimal WEC design. The claim is that MPC is an excellent tool for exploring these tradeoffs.
14. Real-time control hardware has advanced to a point where commercially available platforms are already up to the speed needed to implement complex nonlinear MPC algorithms. These speeds can span from ten times slower than real time to ten times faster than real time. For controls implementation, the cRio platform (National Instruments product) was used by several awardees and is capable of supporting the real-time processors that have the necessary horsepower.

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APPENDIX A. COMMENTS ON CONTROLS METRICS

Optimal Cost Criteria as a controls metric:

Since many types of control design techniques involve some aspect of optimal control or optimization (as in model predictive control), this provides an obvious measure of comparison between different control systems. However, one needs to be sure that this is a comparison of "apples to apples." That is, there are many cost criteria in use, and even though the criteria may be structurally the same, the exact weighting of the tracking errors and control effort can vary. There are several ways of handling this. One can re-evaluate different controllers using a standard cost criterion. Another method is to look at the sensitivity of the cost criterion to specific parameters of interest and compare (on a normalized basis) how well the different controllers reduce this sensitivity. With model predictive control becoming more common in the WEC control literature, the ability to evaluate and compare controller performance on the basis of an optimal cost criterion should become more standard in the near future.

Sensitivity as a controls metric:

Model uncertainty includes uncertainty in the parameters used for the design of the controller as well as unmodeled dynamics. Parameter uncertainty is generally easier to calculate than uncertainty associated with unmodeled dynamics (e.g. higher order dynamics), and therefore it is much more commonly used in sensitivity analysis of control systems. Parameter uncertainty can be evaluated analytically or empirically. To evaluate parameter uncertainty analytically, one needs a model containing the parameter(s) of interest. Generally, this will be a linear model. Then one can take the partial derivative of the transfer function (open or closed loop) with respect to the parameter of interest. In the empirical case, a numerical simulation of the system containing the parameter(s) of interest is carried out with a tabulation of how the response varies with variations in the parameter(s) of interest. For instance, one may vary the parameter by multiples of the standard deviation of the parameter and use Monte Carlo sampling (as in MATLAB) to evaluate how the controller response varies relative to the parameter variation.

Failure rates as they pertain to control systems:

Failure rates for control systems do not have generally accepted definitions, therefore one doesn't normally use failure rates as a metric of interest in evaluating controller performance. However, if this is of specific interest for a particular application, there are several ways to define failure rates. There is the failure rate of the control system itself. This would be how often (e.g., per month or per year) that the control system is unavailable or breaks down. There are also the failure rates of individual components of the control system which may or may not lead to the failure of the entire control system. These components can include sensors, processors, electrical logic circuits, motors, etc. If one has a baseline failure rate profile for a baseline controller or open loop controller, then one can evaluate how well a new controller design improves failure rates relative to the baseline design. The biggest issue in using failure rates as a metric for control systems is that most models and simulations do not model the mechanical/electrical failure of the control system very well. This means that some combination of experimental and numerical analysis will be needed to evaluate failure rates. Since this would involve extensive testing, one wouldn't normally expect much empirical evidence to be available for a new control design technique. Therefore, failure rates are usually employed as a metric of performance in well-established control designs with extensive field performance data.

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