Industry Experience with Aerating Turbines

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Abstract

This paper summarizes a recent EPRI study examining U.S. industry experience with aerating turbines used to improve levels of dissolved oxygen in turbine discharges. The total number of aerating turbines identified in the U.S. was 178 at 58 hydroplants, and 137 of these turbines were vertical Francis turbines rated at greater than 5 MW. A total of 16 aerating Francis units rated at less than or equal to 5 MW was identified, and this total included 5 vertical Francis turbines and 11 horizontal Francis turbines. The totals for aerating diagonal flow, fixed propeller, and Kaplan turbines were 11, 10, and 4, respectively. The paper reviews recent industry experience with aerating turbines; discusses application of aerating turbines for environmental flows; identifies facilities with aerating Francis, Kaplan, propeller, and diagonal flow turbines; and examines experience with environmental optimization of aerating turbines. Opportunities are identified for cost-effective plant efficiency improvements through improved optimization, and recommendations are made for additional research.

1.0 Introduction

1.1 Overview

Impoundments and flow releases from hydropower facilities can adversely impact the aquatic life upstream, downstream, and passing through the sites. In the United States, regional environmental concerns include the improvement of dissolved oxygen (DO) levels to protect aquatic habitat in tailwaters below dams.

Hydropower plants likely to experience problems with low DO include those with a reservoir depth greater than 15 m, power capacity greater than 10 MW, reservoir volume greater than 6.1×10^7 m^3, densimetric Froude number less than 7, and a retention time greater than 10 days [EPRI, 1990]. These plants typically have watersheds yielding moderate to heavy amounts of organic sediments and are located in climates where thermal stratification isolates bottom water from oxygen-rich surface water and organisms and substances in the water and sediments consume and lower the DO in the bottom layer. For plants with bottom intakes, this low DO water may create problems both within and downstream from the reservoir, including possible damage to aquatic habitat.

Before about 1980, detailed studies of the potential impacts of hydropower on water quality, including low DO, generally were not required prior to licensing. In 1986, however, the Electric Consumers Protection Act (ECPA) defined a process by which the development of hydropower must be balanced with concerns for the protection of environmental site characteristics. As a result of ECPA, and based on criteria developed by the U.S. Environmental Protection Agency, requirements for monitoring and maintaining DO levels have become a regular part of license agreements for affected hydro plants. Among the largest owners of affected hydro plants, however, are federal agencies, which are exempt from the licensing protocol of the Federal Energy Regulatory Commission (FERC). These include the U. S. Bureau of Reclamation (USBR), the U. S. Army Corps of Engineers (USACE), and the Tennessee Valley Authority (TVA).

1.2 Accelerated Development of Technologies for DO Enhancement

Under the self-imposed targets and deadlines of a five year, $50,000,000 Lake Improvement Program funded from power system revenues, TVA developed a variety of new technologies for increasing DO in turbine discharges and successfully resolved minimum flow and dissolved oxygen problems throughout the reservoir system. The minimum flow and water quality enhancements have been responsible for the recovery of 290 km of aquatic habitat lost due to intermittent drying of the riverbed and for DO improvements in more than 480 km of rivers below TVA dams [March and Fisher, 1999].

The technologies developed and deployed under the Lake Improvement Plan include minimum flow hydropower units, reliable line diffusers for cost-effective oxygenation of reservoirs upstream from hydro plants, effective labyrinth weirs and infuser weirs which provide minimum flows and aerated flows downstream from hydro plants, retrofitted turbine aeration systems, and self-aerating turbines. Self-aerating turbines, which use the low pressures created by flows through the turbines to induce additional air flows, are typically the most cost-effective DO enhancement technology for the Francis-type turbines typical of hydroplants with DO concerns [March, 2011; ORNL, 2012].

2.0 Updated Literature Review

2.1 Overview

In the past, several comprehensive reviews, covering a wide range of techniques and technologies for improving the dissolved oxygen (DO) levels in releases from hydroelectric plants, have been completed [Bohac et al., 1983; EPRI, 1990]. EPRI [2002] discusses hydrological conditions contributing to low DO levels in reservoirs, describes biological effects of low DO levels, provides a comprehensive summary of techniques and technologies for improving low DO levels, and discusses DO modeling and monitoring. EPRI [2002] also includes case studies for the aerating turbines at TVA's Norris Plant and the "second-generation" aerating turbines at Duke's Wateree Plant. EPRI [2009] focuses primarily on aerating turbine technologies for new Francis turbine installations and turbine upgrades.

This report supplements EPRI [2002] and EPRI [2009] by reviewing industry experience with aerating turbines for minimum and environmental flows; with aerating Kaplan, propeller, and diagonal flow turbines; and with environmental optimization of aerating turbines. In addition, the report discusses results from data analyses of the environmental and hydraulic performance of one facility's aerating Francis turbines over a wide range of operating conditions. The literature review in the following subsections of Section 2 follows the overall outline of the report and describes aerating turbine technologies reported during the period from 2010 through 2013.

2.2 Aerating Turbines for Minimum and Environmental Flows

Rohland et al. [2010] describe Voith Hydro aeration systems designed for a replacement powerhouse at Duke Energy's Bridgewater Plant near Nebo, North Carolina. Distributed aeration was the preferred solution, but the small size of the two main runners required the substitution of a combined system using both central aeration and peripheral aeration. Both central and peripheral aeration are used during periods of low flow operation, and only the peripheral aeration is used during periods of high flow operation requiring DO enhancement to minimize efficiency and power losses. The Bridgewater replacement powerhouse includes a small 1.5 MW horizontal Francis unit with peripheral aeration in the draft tube to provide continuous environmental flows.

March [2011] describes the upgraded station service units at Ameren Missouri's Osage Plant. The plant's original design included two small station service units, manufactured by Allis-Chalmers. Each of the station service units was operated at approximately 170 cfs and approximately 60% efficiency. The station service units were replaced in 2010 with Weir American Hydro units with peripheral aeration systems. The new units, rated for 3.6 MW and 450 cfs at 90 ft of head, operate at approximately 90% efficiency to provide the plant's increased minimum flow requirements.

Wolff et al. [2013] describe a new modeling tool for evaluating and minimizing the energy costs associated with providing minimum and environmental flows and meeting downstream dissolved oxygen requirements for small hydropower projects. Aeration components in the system aeration and energy model (AEM) include forebay oxygenation, turbine aeration, and aeration by spill flows or bypass flows. By automating the analyses, the AEM enables the evaluation of a wide range of inflow data and project options to identify cost effective approaches for meeting water quality requirements. The paper presents two case studies evaluated with the AEM, including a proposed hydro project at the Dresden Island Lock and Dam and a proposed hydro project at Tygart Dam.

2.3 Aerating Kaplan, Propeller, and Diagonal Flow Units

Foust and Coulson [2011] discuss aeration performance for central, peripheral, and distributed aeration systems. The paper presents a case study showing the prediction of dissolved oxygen uptake values using a Discrete Bubble Model (DBM) to ensure that aeration goals are met while minimizing the costs associated with aeration. DO uptakes associated with central, peripheral, and distributed aeration for a hydro plant located in the southern United States are predicted with the DBM. The DO uptake predictions are then utilized to size an aeration system that will meet water quality requirements. The paper also describes the design and installation of a peripheral aeration system for a Kaplan turbine. Kaplan turbines have deeper settings than typical Francis units, due to the cavitation requirements. In this example, the bottom of the discharge ring is located up to 6 ft below the tailwater elevation. The Kaplan turbine's peripheral aeration system provides up to 3 mg/l of DO uptake across the range of flows tested, exceeding the water quality requirements at the plant.

Douglas and Tong [2012] describe the addition of a 7.5 MW powerhouse to the existing USACE Dorena Lake Dam. The Dorena Lake Plant includes a 4.4 MW vertical Kaplan turbine and a 1.2 MW horizontal Francis turbine. The turbines are designed for peripheral aeration in the draft tubes, and additional diffusers are provided in the tailrace.

2.4 Aerating Francis Turbines

McIntosh et al. [2010] present information on the rehabilitation of Unit 3 at Consumers Energy's Hardy Plant. By installing a replacement turbine with central aeration, the plant achieved a 3.7% unit efficiency improvement, a 14% capacity increase, and over 1.5 mg/l improvement in the discharge dissolved oxygen.

Beaulieu et al. [2011] examine the relationship between bubble size and gas transfer in the context of improving the environmental and hydraulic performance of aerating turbines. The paper describes a Francis turbine with an aerating intermediate band as an effective solution for dissolved oxygen enhancement.

Ingram [2011] describes a variety of North American rehabilitation projects for hydroelectric facilities. Included in the project profiles are aerating Francis turbine installations at the USACE's John H. Kerr Plant and Ameren Missouri's Osage Plant.

Kirejczyk [2011] describes efforts of the American Society of Mechanical Engineers Performance Test Code Committee on Hydraulic Turbines and Pump-Turbines (PTC-18) in developing recommendations related to the environmental performance of aerating turbines. The goal of the Committee is to develop a set of "best practice" environmental recommendations that would help in establishing a fair distribution of responsibilities between plant owners and equipment suppliers, while satisfying environmental needs. The recommendations will reduce risks for the involved parties by helping them to define and verify the performance of aerating turbines.

March [2011] focuses primarily on aerating Francis turbine technologies for new turbine installations and turbine upgrades. Limited information on performance of retrofitted aeration systems is also presented for comparison purposes. Case studies are presented, with an emphasis on hydraulic performance (e.g., turbine efficiency with and without aeration) and environmental performance (e.g., air flows and DO increases). The paper discusses the development of aerating turbine technologies, describes some of the difficulties in assessing the performance of aerating turbines, provides detailed case studies for three aerating turbine technologies (central aeration, peripheral aeration, and distributed aeration), discusses the implications of the case study results for plant operation and optimization, and makes recommendations for additional related research.

Papillon et al. [2011] review different turbine aeration methods to increase dissolved oxygen (DO) concentrations in discharges from hydroplants and describes the impacts of aeration on turbine performance. The paper describes aeration model tests, model to prototype scale-up, prediction of aeration performance, and parameters influencing oxygen transfer.

Crutchfield et al. [2012] primarily describes the application of a reservoir oxygen diffuser system. However, the paper provides additional information on the performance of turbine venting systems at the Blewett Falls Plant and the Tillery Plant.

ORNL and HPPi [2012] provide a best practices summary for Francis turbine aeration. The document includes best practices related to performance and efficiency and best practices related to reliability, operations, and maintenance.

2.5 Environmental Optimization of Aerating Turbines

Bier et al. [2011] provides details of the Hydropower Seasonal Concurrent Optimization for Power and the Environment (HydroSCOPE), which is a system-level simulation and optimization model. HydroScope combines a river/reservoir water quality model with optimization software for conducting tradeoff analyses with alternative hydropower operations. [Bier et al., 2012] describes the application of the HydroSCOPE tool to a case study of the Aspinall Unit, a three-reservoir system in the upper Colorado River basin.

Implementation of an advanced environmental optimization system for aerating turbines at Ameren Missouri's Osage Plant is described by March [2011]. EPRI [2012] and March et al. [2013] provide analysis results for the optimization of aerating turbines at a plant with significant environmental requirements, including mandated DO and TDG levels. Operation efficiency analyses demonstrated that the plant operates more efficiently under normal operations than under environmental operations for both steady and variable generation conditions. In addition, the plant operates more efficiently under steady generation conditions compared to variable conditions for both normal operations and environmental operations. Significant potential benefits were identified for this plant through improved environmental optimization.

Gasper et al. [2011] provide an overview for a suite of optimization tools currently under development, collectively called the Optimization Tool Set. Components include Hydrologic Forecasting, Day-ahead Scheduling and Real-time Operations, Environmental Performance, Unit and Plant Efficiency, and Seasonal Hydrosystems Analysis.

Veselka et al. [2011] outline the development of the Conventional Hydropower Energy and Environmental Systems (CHEERS) model, which is designed to optimize hydroplant day-ahead scheduling and real-time operations. The goal of the CHEERS model is to aid operators with decisions such as unit commitments and turbine-level operating points by using a system-wide approach to increasing hydropower efficiency and enhancing the value of power generation and ancillary services. The model determines schedules and operations that are constrained by physical limitations, characteristics of power plant components, operational preferences, reliability and security regulations, and environmental constraints.

3.0 Aerating Turbines for Minimum and Environmental Flows

3.1 Overview

Typically, hydroelectric power facilities are required to provide "minimum flows" to protect and enhance downstream environmental resources. Minimum flows have also been called "instream flows." A more descriptive term, "environmental flows," is often used. Facilities regulated by the Federal Energy Regulatory Commission (FERC) are required to meet state water quality standards, which can vary from state to state. Under §401 of the Clean Water Act, states issue Water Quality Certificates to hydro plants as a necessary part of the licensing process. Typical §401 Water Quality Certificates for hydroelectric power facilities include both minimum flow requirements and minimum dissolved oxygen requirements.

Minimum or environmental flows can represent a significant loss of generation due to direct discharge (e.g., sluiceways, spillways, etc.) or inefficient turbine operation at lower flows. Some owner/operators have added small aerating turbines at existing hydroelectric power facilities or designed new facilities to include small aerating turbines to achieve the dissolved oxygen targets during operations for minimum or environmental flows. Other facilities have adopted operational strategies with larger aerating turbines for the same purpose.

Figure 3-1 summarizes the known minimum and environmental flow operations using aerating turbines. Plants with dedicated aerating turbines for providing minimum and environmental flows and plants with other operational strategies are discussed below.

3.2 Dedicated Aerating Turbines for Minimum and Environmental Flows

Five aerating turbines dedicated to providing minimum and environmental flows were identified at four hydroelectric plants, as summarized in Figure 3-1. Future plans were identified at additional plants.

Originally, Ameren Missouri’s Osage Plant included two small station service units, manufactured by Allis-Chalmers. Each of the station service units was designed to operate at 170 cfs and approximately 60% efficiency. To meet the minimum flow and dissolved oxygen requirements in the new FERC license, Ameren Missouri replaced the station service units in 2010 with Weir American Hydro turbines including peripheral aeration. The replacement turbines are rated for 3.1 MW and 450 cfs at 90 ft of head, and the turbines operate at an efficiency of approximately 90% [March, 2011]. Figure 3-2 provides a cross-sectional view of the turbines, Figure 3-3 shows a photograph of a turbine and its air outlets after 10,000 hours of operation, and Figure 3-4 shows the aerated discharge from the minimum flow units.

Duke Energy’s new powerhouse for the Bridgewater Plant was designed to meet dissolved oxygen requirements and continuous environmental flow requirements. The Bridgewater Plant includes a small 1.5 MW horizontal Francis turbine with peripheral aeration, manufactured by Voith Hydro Inc., to provide environmental flows [Rohland et al., 2010].

The Tennessee Valley Authority (TVA) installed small aerating turbines for environmental flows at several plants in the early 1990s. TVA’s Blue Ridge Plant provides environmental flows with a small 1.2 MW aerating vertical Francis turbine which has supplemental oxygen diffusers at the turbine’s intake. TVA’s Nottely Plant provides environmental flows with a small 1 MW vertical Francis turbine equipped with a forced-air system and supplemented with aerating baffles in the small unit’s tailrace (see Figure 3-5).

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Providing Minimum and Environmental Flows
Alcoa Power Generating Inc. (APGI)	Narrows	Vertical Francis	29	2.92	Aerating units (U1, U2, and/or U4) operated
Ameren Missouri	Osage	Vertical Francis	23.5	?	Not operated for minimum flow
Ameren Missouri	Osage	Vertical Francis	29	?	Not operated for minimum flow
Ameren Missouri	Osage	Vertical Francis	28	?	Not operated for minimum flow
Ameren Missouri	Osage	Vertical Francis	3.1	?	Small 3.1 MW vertical Francis turbines with peripheral aeration (H1, H2)
Consumers Energy	Hardy	Vertical Francis	11.5	?	Aerating unit operated
Crisp County Power Commission	Warwick	Vertical Francis	4	?	Aerating unit operated
Duke Energy (Progress Energy)	Blewett Falls	Horizontal Francis	3.2 (U1 - U3); 5 (U4 - U6)	?	Aerating unit operated
Duke Energy	Bridgewater	Vertical Francis	15	2.44	Small 1.5 MW horizontal Francis turbine with peripheral aeration
Duke Energy	Bridgewater	Horizontal Francis	1.5	0.90	Small 1.5 MW horizontal Francis turbine with peripheral aeration
Duke Energy	Cedar Creek	Vertical Francis	14.3	3.80	Aerating units pulsing at best efficiency
Duke Energy	Dearborn	Vertical Francis	14	3.38	Aerating units pulsing at best efficiency
Duke Energy	Fishing Creek	Vertical Francis	9	3.18	Aerating units pulsing at best efficiency
Duke Energy	Mountain Island	Vertical Francis	15.5	3.38	Aerating units pulsing at best efficiency
Duke Energy	Oxford	Vertical Francis	18	3.53	Aerating units pulsing at best efficiency
Duke Energy	Rhodhiss	Vertical Francis	10.7	3.38	Aerating unit (U3) pulsing at best efficiency
Duke Energy (Progress Energy)	Tillery	Vertical Francis	22 (U1, U3); 18 (U2)	?	Aerating unit operated
Duke Energy (Progress Energy)	Tillery	Vertical fixed-blade propeller	22 (U4)	?	Aerating unit operated
Duke Energy	Wateree	Vertical Francis	16.3	3.86	Aerating units pulsing at best efficiency
Duke Energy	Wylie	Vertical Francis	17	3.80	Aerating units pulsing at best efficiency
Exelon Generation	Conowingo	Vertical Francis	48	4.93	Not operated for minimum flow
Exelon Generation	Conowingo	Vertical Francis	34.7	4.93	Aerating unit (U2 or U5) operated to provide seasonally-varying minimum flows

Figure 3-1: Industry Experience with Aerating Turbines Providing Minimum and Environmental Flows

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Providing Minimum and Environmental Flows
Exelon Generation (67% ownership)	Safe Harbor	Kaplan	31	5.59	Not operated for minimum flow
Exelon Generation (67% ownership)	Safe Harbor	Diagonal flow	37.5	6.10	Not operated for minimum flow
Friant Power Authority	Friant	Vertical Francis	7	?	Aerating unit operated (planned operation; expected completion in 2015)
Grand River Dam Authority (GRDA)	Pensacola	Vertical Francis	19.7	2.74	Not operated for minimum flow
Idaho Power	American Falls	Vertical fixed-blade propeller	37.5		Not operated for minimum flow
Idaho Power	Cascade	Kaplan	6.4		Not operated for minimum flow
Idaho Power	Brownlee	Vertical Francis	99.2	4.71	Not operated for minimum flow
Lower Colorado River Authority (LCRA)	Marshall Ford	Vertical Francis	38.1	3.45	Not operated for minimum flow, but can provide enhanced dissolved oxygen levels at a compliance location below a downstream plant
Lower Colorado River Authority (LCRA)	Buchanan	Vertical Francis	16.8	2.59	Not operated for minimum flow, but can provide enhanced dissolved oxygen levels at a compliance location below a downstream plant
Riverbank Power	Dorena Lake	Kaplan	4.4	?	Aerating unit operated; diffuser system in tailrace operated as needed
Riverbank Power	Dorena Lake	Horizontal Francis	1.2	?	Aerating unit operated; diffuser system in tailrace operated as needed
Southern	Bankhead	Vertical diagonal flow	54	5.91	Not operated for minimum flow
Southern	Harris	Vertical Francis	67.5	5.28	Not operated for minimum flow
Southern	Holt	Vertical fixed-blade propeller	46.9	5.89	Not operated for minimum flow
Southern	Jordan	Vertical Francis	25	4.52	Aerating unit operated
Southern	Lay	Vertical diagonal flow	29.5	6.91	Not operated for minimum flow
Southern	Lewis Smith	Vertical Francis	78.75	4.72	Two 24-inch eductors operated
Southern	Lloyd Shoals	Horizontal, Double-runner Francis	3	?	Aerating unit or units operated
Southern	Logan Martin	Vertical fixed-blade propeller	42.75	6.35	Not operated for minimum flow

Figure 3-2 (continued): Industry Experience with Aerating Turbines Providing Minimum and Environmental Flows

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Providing Minimum and Environmental Flows
Southern	Martin	Vertical Francis	45.8 (U1); 41 (U2); 40.5 (U3); 55.2 (U4)	4.57 (U4)	Not operated for minimum flow
Southern	Mitchell	Vertical fixed-blade propeller	50	6.76 (U5 - U7)	Not operated for minimum flow
Southern	Neely Henry	Vertical fixed-blade propeller	24.3	6.5	Not operated for minimum flow
Southern	Yates	Vertical Francis	22.75	4.95	Not operated for minimum flow
TVA	Apalachia	Vertical Francis	52.2 (U1); 41.4 (U2)	2.62	Aerating units pulsed at best efficiency
TVA	Blue Ridge	Vertical Francis	22	?	Small 1.2 MW aerating vertical Francis turbine with supplemental oxygen diffuser at intake
TVA	Boone	Vertical Francis	35.1	4.19	Aerating units pulsed at best efficiency
TVA	Cherokee	Vertical Francis	34.7	4.50	Aerating units pulsing at best efficiency, with coordinated operation of adjacent surface water pumps and selected line diffusers
TVA	Douglas	Vertical Francis	31	4.57	Aerating units pulsing at best efficiency, with coordinated operation of adjacent surface water pumps and selected line diffusers
TVA	Douglas	Vertical Francis	47.2	4.57	Aerating units pulsing at best efficiency, with coordinated operation of adjacent surface water pumps and selected line diffusers
TVA	Fontana	Vertical Francis	105.4	4.19	Not operated for minimum flow
TVA	Hiwassee	Vertical Francis	79.7	4.27	Not operated for minimum flow
TVA	Norris	Vertical Francis	62	4.29	Aerating units pulsing at best efficiency; Re-regulating weir with controlled discharge downstream; Supplemental oxygen system with line diffusers in forebay
TVA	Nottely	Vertical Francis	15	2.60	Small 1 MW turbine with compressors, supplemented by aerating baffles in tailrace
TVA	South Holston	Vertical Francis	38.5	3.58	Aerating unit pulsing at best efficiency; Aerating labyrinth weir with controlled discharge downstream
TVA	Tims Ford	Diagonal Flow	45	3.81	Sluice and/or spillway discharge or unit pulsing at best efficiency; Original reversed pump used as a 0.5 MW environmental flow turbine, now out of service
TVA	Watauga	Vertical Francis	28.8	2.68	Aerating units pulsing at best efficiency
USACE	Buford	Vertical Francis	58 (U1, U2); 7 (U3)	4.57 (U1, U2); 1.68 (U3)	Not operated for minimum flow
USACE	Bull Shoals	Vertical Francis	40 (U1 - U4); 45 (U5 - U8)	3.87	Not operated for minimum flow

Figure 3-3 (continued): Industry Experience with Aerating Turbines Providing Minimum and Environmental Flows

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Providing Minimum and Environmental Flows
USACE	Center Hill	Vertical Francis	45	4.58	Not operated for minimum flow
USACE	Dale Hollow	Vertical Francis	18	2.88	Not operated for minimum flow
USACE	Hartwell	Vertical Francis	84	4.88	Not operated for minimum flow
USACE	John H. Kerr	Vertical Francis	42	5.21	Not operated for minimum flow, but can provide enhanced dissolved oxygen levels at a compliance location below a downstream plant
USACE	Norfork	Vertical Francis	40	3.70	Not operated for minimum flow
USACE	Table Rock	Vertical Francis	50	4.05	Not operated for minimum flow; plant has small Francis (house) units; oxygen injection into house units has been studied but not implemented
USACE	Tenkiller Ferry	Vertical Francis	19.5	2.95	Not operated for minimum flow
USACE	Thurmond	Vertical Francis	65.7	4.52	Aerating units operated
USACE	Wolf Creek	Vertical Francis	45	4.45	Not operated for minimum flow
USBR	Canyon Ferry	Vertical Francis	16.7	?	Not operated for minimum flow, but can provide enhanced dissolved oxygen levels at a compliance location below a downstream plant

Figure 3-4 (continued): Industry Experience with Aerating Turbines Providing Minimum and Environmental Flows

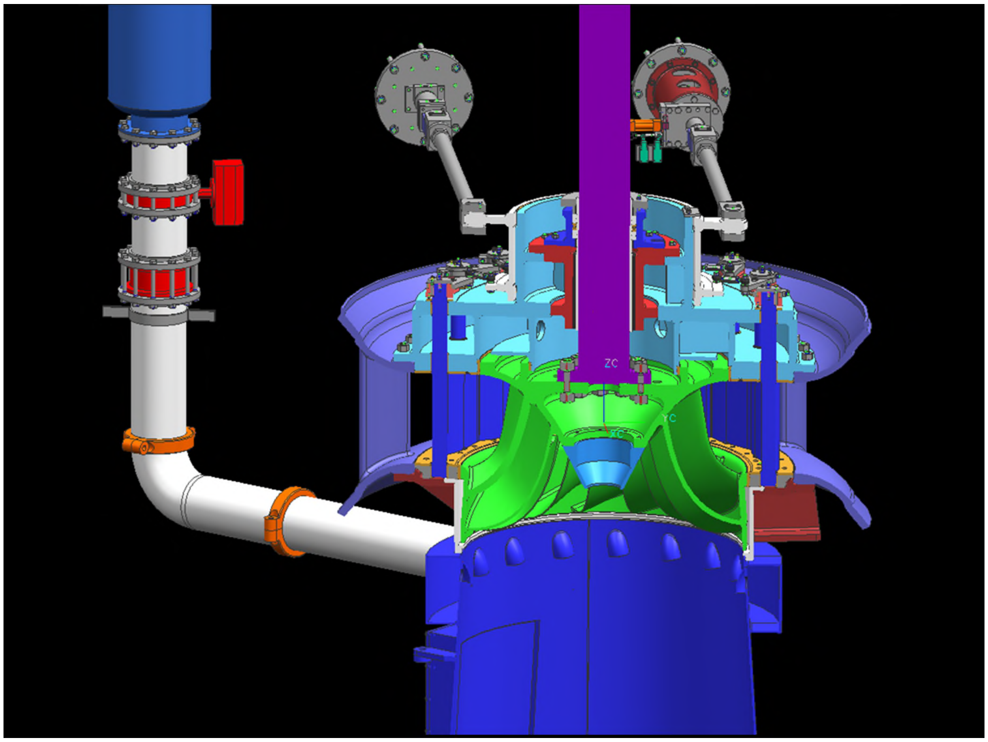

Figure 3-2: Cross-sectional View of Turbine and Peripheral Aeration System (courtesy of Weir American Hydro)

Figure 3-3: Photograph of Turbine and Peripheral Aeration System (courtesy of Weir American Hydro)

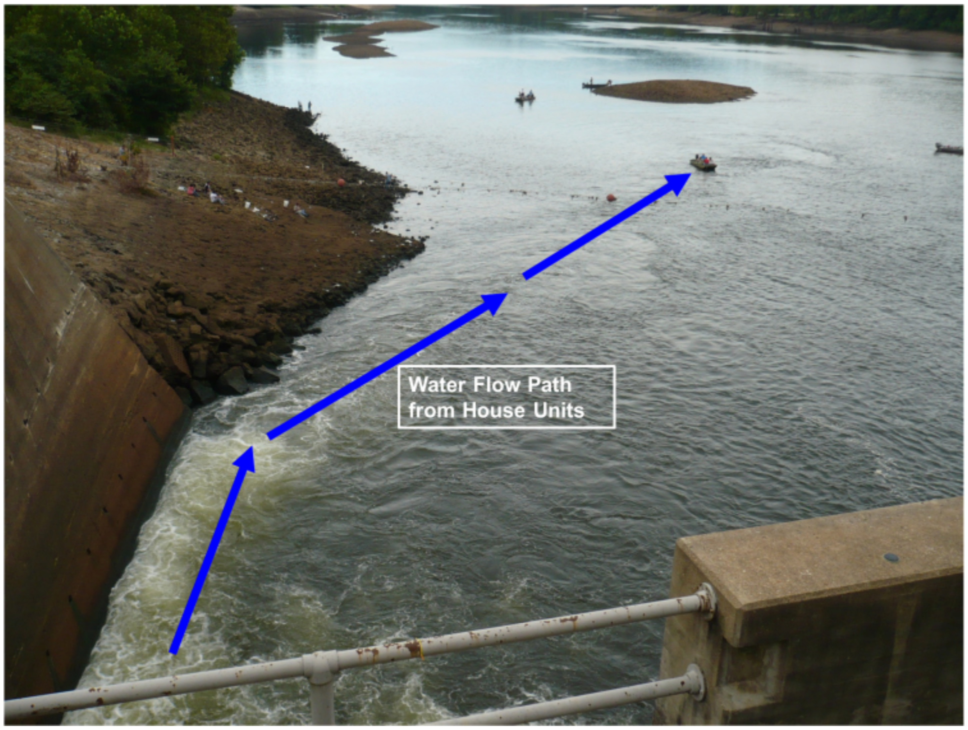

Figure 3-4: Photograph of Aerated Discharge from Minimum Flow Turbines (courtesy of Weir American Hydro)

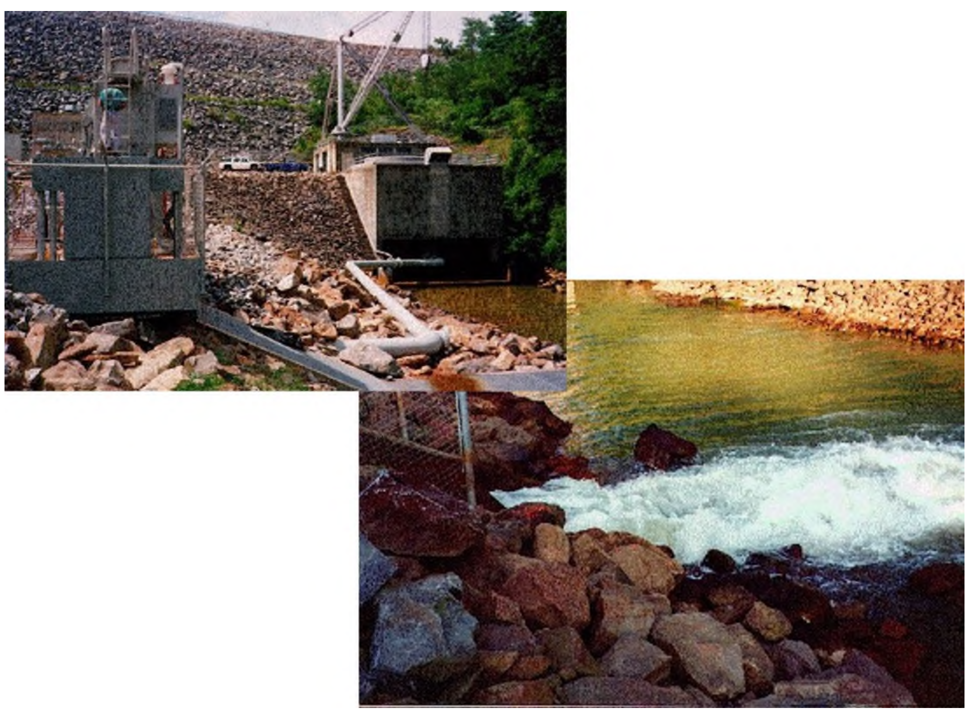

Figure 3-5: Photographs of Small Aerating Turbine and Aerated Discharge at TVA's Nottely Plant

The Friant Power Authority's plans for a new powerhouse at the USBR's Friant Dam includes a 7 MW aerating vertical Francis turbine which will provide generation and aerated minimum flows. The new powerhouse is expected to be operational by 2015. The USACE's Table Rock Plant includes two small Francis-type station service turbines. The feasibility of providing environmental flows and improving dissolved oxygen levels from these units by using oxygen injection into the station service turbines has been studied, but there are no current plans for implementation [TVA, 2010]. Future plans for using small aerating turbines to provide minimum and environmental flows were identified at several additional facilities.

3.3 Other Operational Strategies for Providing Minimum and Environmental Flows

A recent EPRI report summarizes industry experience with environmental flow options that also provide power generation, including environmental flow options with existing (primary) hydropower units, environmental flow options with dedicated environmental flow units, and potential environmental flow options with emerging turbine technologies [EPRI, 2014]. Operational strategies and technologies for providing aerated minimum and environmental flows were identified at numerous hydroelectric generating facilities, as summarized in Figure 3-1.

Alcoa Power Generating Inc.'s (APGI's) Narrows Plant includes four upgraded 29 MW vertical Francis turbines. Three of the turbines (i.e., U1, U2, and U4) include peripheral aeration systems [March, 2011]. Aerated environmental flows at Narrows are provided by operating one of these aerating units at reduced power. Measurements for regulatory compliance are taken below APGI's Yadkin Falls Plant, located just downstream from Narrows.

Consumers Energy's Hardy Plant includes an 11.5 MW aerating vertical Francis turbine, and the aerating unit is operated to provide minimum flows. Similarly, Crisp County Power Commission's Warwick Plant includes a 4 MW aerating vertical Francis turbine, and the aerating unit is operated to provide minimum flows.

Duke Energy has six hydroelectric facilities using aerating vertical Francis turbines to provide aerated flow releases, including the Fishing Creek, Oxford, Rhodhiss, Wateree, Wylie, and Cedar Creek Plants. In each of these plants, one (or more) of the aerating units is operated at best efficiency for a period of time, providing flow "pulses" of aerated water. Progress Energy (now merged with Duke Energy) has two hydroelectric facilities using aerating Francis turbines (Blewett Falls and Tillery) and a vertical fixed-blade propeller turbine (Tillery Unit 4, rarely-used for aeration) to provide aerated flow releases.

Exelon Generation's Conowingo Plant includes two updated turbines (U2, U5) with distributed (trailing edge) aeration. These turbines are designed for efficient operation while providing the minimum flow requirements for the plant.

Lower Colorado River Authority's (LCRA's) aerating vertical Francis turbines at the Marshall Ford (Mansfield) Plant and the Buchanan Plant are not specifically operated for minimum and environment flows, but these turbines do provide enhanced dissolved oxygen levels at the compliance location below the downstream Tom Miller Plant.

Southern Company's Jordan Plant has four vertical Francis turbines retrofitted to provide aeration, and an aerating turbine provides the minimum flows for the plant. Although Southern Company's Lewis Smith Plant has two vertical Francis turbines with blowers providing forced-air aeration to the draft tube, minimum flow requirements and dissolved oxygen requirements are met with two 24-inch eductors to avoid the costs associated with blower operation and low power operation of the turbines.

4.0 Aerating Francis, Kaplan, Propeller, and Diagonal Flow Turbines

4.1 Overview

As discussed in Section 2, hydropower plants likely to experience problems with low DO include those with a reservoir depth greater than 15 m. Francis-type turbines are typically encountered in the plants with DO concerns downstream. Figure 4-1 summarizes the known hydropower plants using aerating turbines. Figure 4-2 shows the distribution of the identified aerating turbines by turbine type. The total number of aerating turbines identified in the USA was 178, and 137 of these turbines are vertical Francis turbines rated at greater than 5 MW. A total of 16 aerating Francis units rated at less than or equal to 5 MW was identified, and this total includes 5 vertical Francis turbines and 11 horizontal Francis turbines. The totals for diagonal flow, fixed propeller, and Kaplan turbines are 11, 10, and 4, respectively.

4.2 Industry Experience with Aerating Kaplan, Propeller, and Diagonal Flow Turbines

The Safe Harbor Water Power Company's Safe Harbor Plant (67% ownership by Exelon Generation) includes three aerating turbines. Units 9 and 11 are diagonal flow turbines with retrofitted peripheral aeration systems in the draft tube. Unit 6 is a Kaplan turbine with a peripheral aeration system in the draft tube designed and installed by Voith Hydro Inc. in 2010. The Unit 6 system reportedly functions well [Foust and Coulson, 2011], but the system is infrequently operated because dissolved oxygen levels in the tailrace rarely require additional augmentation. The Unit 9 and Unit 11 aeration systems are not typically used unless Unit 6 is out of service. Figure 4-3 provides additional details for the Unit 6 aeration system [Hager, 2011].

Idaho Power's American Falls Plant includes 3 aerating fixed-blade propeller turbines. These turbines have been retrofitted with forced-air aeration systems using blowers to provide air to the draft tubes. Similarly, Idaho Power's Cascade Plant has 2 Kaplan turbines retrofitted with forced-air aeration systems using blowers to provide air to the draft tubes.

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Turbine Technologies for DO Improvement
Alcoa Power Generating Inc. (APGI)	Narrows	Vertical Francis	29	2.92	Replacement turbines with peripheral aeration (U1, U2, U4)
Ameren Missouri	Osage	Vertical Francis	23.5	?	Retrofitted central aeration with additional air piping through headcover (U2, U4)
Ameren Missouri	Osage	Vertical Francis	29	?	Replacement turbines with central aeration (U3, U5)
Ameren Missouri	Osage	Vertical Francis	28	?	Replacement turbines with distributed aeration (U1, U6, U7, U8)
Ameren Missouri	Osage	Vertical Francis	3.1	?	Replacement house turbines with peripheral aeration in draft tube (H1, H2)
Consumers Energy	Hardy	Vertical Francis	11.5	?	Replacement turbine with central aeration (U3)
Crisp County Power Commission	Warwick	Vertical Francis	4	?	Replacement turbine with central aeration (U1)
Duke Energy (Progress Energy)	Blewett Falls	Horizontal Francis	3.2 (U1 - U3); 5 (U4 - U6)	?	Retrofitted with peripheral aeration in draft tube (U1 - U6)
Duke Energy	Bridgewater	Vertical Francis	15	2.44	New turbines with central and peripheral aeration (U1, U2)
Duke Energy	Bridgewater	Horizontal Francis	1.5	0.90	New turbine with peripheral aeration (U3)
Duke Energy	Cedar Creek	Vertical Francis	14.3	3.80	Replacement turbines with central aeration (U1, U2, U3)
Duke Energy	Dearborn	Vertical Francis	14	3.38	Retrofitted with peripheral aeration through stay vanes and additional air piping through headcover (U1, U2, U3)
Duke Energy	Fishing Creek	Vertical Francis	9	3.18	Replacement turbines with central aeration (U2, U3, U5)
Duke Energy	Mountain Island	Vertical Francis	15.5	3.38	Retrofitted with peripheral aeration through stay vanes and additional air piping through headcover (U1, U2, U3, U4)
Duke Energy	Oxford	Vertical Francis	18	3.53	Replacement turbine with central aeration (U1); Replacement turbine with distributed aeration (U2)
Duke Energy	Rhodhiss	Vertical Francis	10.7	3.38	Retrofitted with peripheral aeration through stay vanes and additional air piping through headcover (U1, U2); Replacement turbine with distributed aeration (U3)
Duke Energy (Progress Energy)	Tillery	Vertical Francis	22 (U1, U3); 18 (U2)	?	Retrofitted with peripheral aeration using baffles in draft tube (U1 - U3, preferred for aeration); Forebay oxygen system with line diffusers
Duke Energy (Progress Energy)	Tillery	Vertical fixed-blade propeller	22 (U4)	?	Retrofitted with peripheral aeration using baffles in draft tube (U4, typically not used for aeration); Forebay oxygen system with line diffusers
Duke Energy	Wateree	Vertical Francis	16.3	3.86	Replacement turbines with distributed aeration (U1, U3)

Figure 4-1: Industry Experience with Aerating Turbines

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Turbine Technologies for DO Improvement
Duke Energy	Wylie	Vertical Francis	17	3.80	Replacement turbines with central aeration (U2, U3)
Exelon Generation	Conowingo	Vertical Francis	48	4.93	Turbines retrofitted with peripheral aeration (U1, U3, U4, U6, U7)
Exelon Generation	Conowingo	Vertical Francis	34.7	4.93	Replacement turbines with distributed aeration (U2, U5)
Exelon Generation (67% ownership)	Safe Harbor	Kaplan	31	5.59	Retrofitted peripheral aeration in draft tube (U6); aeration system infrequently operated
Exelon Generation (67% ownership)	Safe Harbor	Diagonal flow	37.5	6.10	Retrofitted peripheral aeration in draft tube (U9, U11); aeration system infrequently operated
Friant Power Authority	Friant	Vertical Francis	7	?	Replacement turbine with central aeration (New powerhouse under construction with expected completion in 2015)
Grand River Dam Authority (GRDA)	Pensacola	Vertical Francis	19.7	2.74	Peripheral aeration in draft tube (U1 - U5)
Idaho Power	American Falls	Vertical fixed-blade propeller	37.5		Forced-air aeration with blowers providing air to draft tube (U1 - U3)
Idaho Power	Cascade	Kaplan	6.4		Forced-air aeration with blowers providing air to draft tube (U1, U2)
Idaho Power	Brownlee	Vertical Francis	99.2	4.71	Replacement turbines with distributed aeration (U1 - U4); Contract awarded but project not yet complete
Lower Colorado River Authority (LCRA)	Marshall Ford	Vertical Francis	38.1	3.45	Peripheral aeration in draft tube (U2)
Lower Colorado River Authority (LCRA)	Buchanan	Vertical Francis	16.8	2.59	Peripheral aeration in draft tube (U3); aeration capability not currently used
Riverbank Power	Dorena Lake	Kaplan	4.4	?	Peripheral aeration in draft tube; diffuser system in tailrace
Riverbank Power	Dorena Lake	Horizontal Francis	1.2	?	Peripheral aeration in draft tube; diffuser system in tailrace
Southern	Bankhead	Vertical diagonal flow	54	5.91	Peripheral aeration using deflector plates in draft tube (U1)
Southern	Harris	Vertical Francis	67.5	5.28	Peripheral aeration using deflector plates in draft tube (U1, U2); Movable skimmer weir used to affect upstream withdrawal zone (U1, U2)

Figure 4-1 (continued): Industry Experience with Aerating Turbines

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Turbine Technologies for DO Improvement
Southern	Holt	Vertical fixed-blade propeller	46.9	5.89	Peripheral aeration using deflector plates in draft tube (U1)
Southern	Jordan	Vertical Francis	25	4.52	Original turbine with central aeration through vacuum breaker (U1); Original turbines with central aeration through retrofitted headcover piping (U2 - U4) and peripheral aeration using deflector plates in draft tube (U2 - U4)
Southern	Lay	Vertical diagonal flow	29.5	6.91	Original turbines with central aeration through vacuum breaker (U1 - U6)
Southern	Lewis Smith	Vertical Francis	78.75	4.72	Forced-air aeration with blowers providing air to draft tube (U1, U2)
Southern	Lloyd Shoals	Horizontal, Double-runner Francis	3	?	Original turbines with peripheral aeration using deflector plates in draft tube (U2, U3, U4)
Southern	Logan Martin	Vertical fixed-blade propeller	42.75	6.35	Peripheral aeration using deflector plates in draft tube (U1, U2, U3)
Southern	Martin	Vertical Francis	45.8 (U1); 41 (U2); 40.5 (U3); 55.2 (U4)	4.57 (U4)	Peripheral aeration using deflector plates in draft tube (U1 - U4) and central aeration through retrofitted headcover piping (U1 - U4)
Southern	Mitchell	Vertical fixed-blade propeller	50	6.76 (U5 - U7)	Peripheral aeration using deflector plates in draft tube (U5, U6, U7)
Southern	Neely Henry	Vertical fixed-blade propeller	24.3	6.5	No aeration currently; Forced-air aeration with blowers providing air to draft tube (U1, U2, U3) has been designed
Southern	Yates	Vertical Francis	22.75	4.95	Peripheral aeration using deflector plates in draft tube (U1, U2)
TVA	Apalachia	Vertical Francis	52.2 (U1); 41.4 (U2)	2.62	Central aeration with retrofitted hub baffles (U1, U2)
TVA	Blue Ridge	Vertical Francis	22	?	No turbine aeration; Forebay oxygen system with line diffusers
TVA	Boone	Vertical Francis	35.1	4.19	Replacement turbines with distributed and central aeration (U1, U2, U3)
TVA	Cherokee	Vertical Francis	34.7	4.50	Central aeration with retrofitted hub baffles (U1, U2, U3, U4); Forebay oxygen system with line diffusers; Forebay surface water pumps
TVA	Douglas	Vertical Francis	31	4.57	Replacement turbines with central aeration (U1, U3); Forebay oxygen system with line diffusers; Forebay surface water pumps
TVA	Douglas	Vertical Francis	47.2	4.57	Replacement turbines with peripheral aeration (U2, U4); Forebay oxygen system with line diffusers; Forebay surface water pumps
TVA	Fontana	Vertical Francis	105.4	4.19	Replacement turbines with central aeration (U1, U2, U3)

Figure 4-1 (continued): Industry Experience with Aerating Turbines

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Turbine Technologies for DO Improvement
TVA	Hiwassee	Vertical Francis	79.7	4.27	Replacement turbine with central aeration (U1); Forebay oxygen system with line diffusers
TVA	Norris	Vertical Francis	62	4.29	Replacement turbines with central, distributed, and peripheral aeration (U1, U2); Supplemental forebay oxygen system with line diffusers; Downstream-re-regulating weir
TVA	Nottely	Vertical Francis	15	2.60	Forced-air aeration with blowers providing air to the larger unit (U1) and compressors providing air to the small unit
TVA	South Holston	Vertical Francis	38.5	3.58	Central aeration with retrofitted hub baffles; Aerating labyrinth weir downstream
TVA	Tims Ford	Diagonal Flow	45	3.81	Forced-air aeration with blowers providing air to draft tube, scroll case, or both; Supplemental oxygen system with line diffusers in forebay
TVA	Watauga	Vertical Francis	28.8	2.68	Central aeration with retrofitted hub baffles (U1, U2)
USACE	Buford	Vertical Francis	58 (U1, U2); 7 (U3)	4.57 (U1, U2); 1.68 (U3)	Replacement turbines with central aeration (U1 - U3)
USACE	Bull Shoals	Vertical Francis	40 (U1 - U4); 45 (U5 - U8)	3.87	Central aeration with retrofitted hub baffles (U1 - U8)
USACE	Center Hill	Vertical Francis	45	4.58	Central aeration with retrofitted hub baffles (U1 - U3)
USACE	Dale Hollow	Vertical Francis	18	2.88	Central aeration with retrofitted hub baffles and additional air piping through headcover (U1 - U3)
USACE	Hartwell	Vertical Francis	84	4.88	Central aeration with retrofitted hub baffles (U1 - U5)
USACE	John H. Kerr	Vertical Francis	42	5.21	Replacement turbines with peripheral aeration (U2 - U7)
USACE	Norfork	Vertical Francis	40	3.70	Central aeration with retrofitted hub baffles (U1, U2)
USACE	Table Rock	Vertical Francis	50	4.05	Central aeration with retrofitted hub baffles (U1 - U4); direct oxygen injection into penstocks (U1 - U4)
USACE	Tenkiller Ferry	Vertical Francis	19.5	2.95	Central aeration with retrofitted hub baffles (U1, U2)
USACE	Thurmond	Vertical Francis	65.7	4.52	Replacement turbines with distributed aeration (U1-U7); Forebay oxygen system with line diffusers
USACE	Wolf Creek	Vertical Francis	45	4.45	Central aeration with retrofitted hub baffles (U1, U3, U5)
USBR	Canyon Ferry	Vertical Francis	16.7	?	Forced-air aeration with blowers providing air to draft tube (U3); aeration system is infrequently operated

Figure 4-1 (continued): Industry Experience with Aerating Turbines

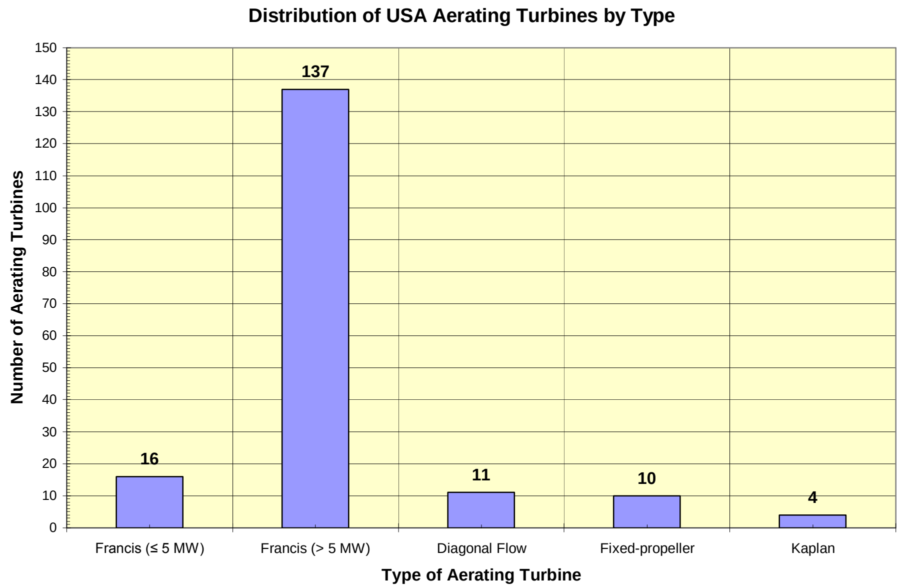

Figure 4-2: Distribution of Aerating Turbines by Turbine Type

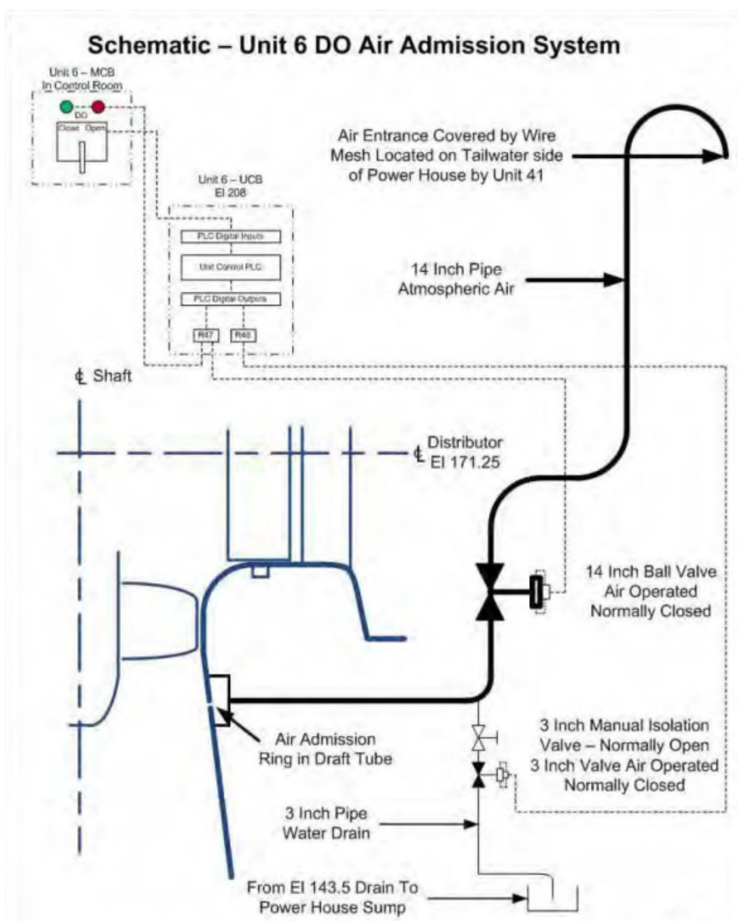

Figure 4-3: Safe Harbor Unit 6 Peripheral Aeration System [Hager, 2011]

Southern Company's Holt, Logan Martin, and Mitchell Plants have vertical fixed-blade propeller turbines retrofitted with peripheral aeration systems using deflector plates in the draft tube. The Neely Henry Plant currently has no aeration for its vertical fixed-blade propeller turbines, but a forced-air aeration system using blowers to provide air to the draft tubes has been designed. Southern Company's Bankhead and Lay Plants have diagonal flow turbines retrofitted with peripheral aeration systems using deflector plates in the draft tube.

TVA's Tims Ford Plant has a single diagonal flow turbine retrofitted with multiple aeration systems, including forced-air aeration with blowers providing air to the draft tube, the scroll case, or both, and a supplemental oxygen system with line diffusers in the forebay.

5.0 Environmental Optimization of Aerating Turbines

5.1 Overview of Environmental Optimization

Mattice [1991] provides a comprehensive overview of the environmental effects from hydropower facilities. Impoundments and flow releases from hydropower facilities can adversely impact the aquatic life upstream, downstream, and passing through the sites. Important environmental concerns in North America include the improvement of dissolved oxygen (DO) levels and minimum flows to protect aquatic habitat in tailwaters below dams [March and Fisher, 1999]. These environmental concerns typically reduce hydroelectric generation, which can adversely impact the multi-purpose benefits of a project and increase production costs. However, progressive owner/operators are upgrading turbines and control systems to "environmentally friendly" designs as a part of their programs for generation improvements, maintenance improvements, and relicensing.

Comprehensive environmental optimization involves time scales and complexities that are beyond the capabilities of current models and optimization methods. Section 5 focuses on limited environmental optimization for efficient generation and ancillary services operation with aerating turbines implemented to improve levels of dissolved oxygen in turbine discharges. This includes the relatively simple objectives of achieving desired dissolved oxygen levels through turbine aeration while minimizing adverse effects on plant efficiency.

Hydroelectric plants vary in their degree of automation but typically include both human operators and sophisticated control systems. Plants may use optimization systems that provide advice to operators. For real-time or near real-time optimization, plants typically utilize operational rules embedded in the control systems or optimization software integrated into the control systems. Figure 5-1 summarizes known industry experience with environmental optimization of aerating turbines.

For the 58 hydroelectric facilities identified with aerating turbines, simple rules-based manual or remote operation is used in 31 facilities, operational rules in the control systems are used in 11 facilities, optimizers integrated with the control systems are used in 14 facilities, and optimizers are used as advisory systems in 2 facilities (see Figure 5-2). For the 178 aerating turbines identified, simple rules-based manual or remote operation is used for 96 aerating turbines, operational rules in the control systems are used for 27 aerating turbines, optimizers integrated with the control systems are used for 43 aerating turbines, and optimizers are used as advisory systems for 12 aerating turbines (see Figure 5-3).

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Optimization of Aerating Turbines
Alcoa Power Generating Inc. (APGI)	Narrows	Vertical Francis	29	2.92	Rules-based manual operation
Ameren Missouri	Osage	Vertical Francis	23.5	?	Pre-optimized operational rules included in the control system for both aerating and non-aerating operation
Ameren Missouri	Osage	Vertical Francis	29	?	Pre-optimized operational rules included in the control system for both aerating and non-aerating operation
Ameren Missouri	Osage	Vertical Francis	28	?	Pre-optimized operational rules included in the control system for both aerating and non-aerating operation
Ameren Missouri	Osage	Vertical Francis	3.1	?	Pre-optimized operational rules included in the control system for both aerating and non-aerating operation
Consumers Energy	Hardy	Vertical Francis	11.5	?	Rules-based manual operation
Crisp County Power Commission	Warwick	Vertical Francis	4	?	Rules-based manual operation
Duke Energy (Progress Energy)	Blewett Falls	Horizontal Francis	3.2 (U1 - U3); 5 (U4 - U6)	?	Rules-based manual or remote operation
Duke Energy	Bridgewater	Vertical Francis	15	2.44	Operational rules included in the control system
Duke Energy	Bridgewater	Horizontal Francis	1.5	0.90	Operational rules included in the control system
Duke Energy	Cedar Creek	Vertical Francis	14.3	3.80	Operational rules included in the control system
Duke Energy	Dearborn	Vertical Francis	14	3.38	Operational rules included in the control system
Duke Energy	Fishing Creek	Vertical Francis	9	3.18	Operational rules included in the control system
Duke Energy	Mountain Island	Vertical Francis	15.5	3.38	Operational rules included in the control system
Duke Energy	Oxford	Vertical Francis	18	3.53	Operational rules included in the control system
Duke Energy	Rhodhiss	Vertical Francis	10.7	3.38	Operational rules included in the control system
Duke Energy (Progress Energy)	Tillery	Vertical Francis	22 (U1, U3); 18 (U2)	?	Rules-based manual or remote operation
Duke Energy (Progress Energy)	Tillery	Vertical fixed-blade propeller	22 (U4)	?	Rules-based manual or remote operation
Duke Energy	Wateree	Vertical Francis	16.3	3.86	Operational rules included in the control system
Duke Energy	Wylie	Vertical Francis	17	3.80	Operational rules included in the control system
Exelon Generation	Conowingo	Vertical Francis	48	4.93	Optimization software integrated into the control system
Exelon Generation	Conowingo	Vertical Francis	34.7	4.93	Optimization software integrated into the control system
Exelon Generation (67% ownership)	Safe Harbor	Kaplan	31	5.59	Rules-based manual operation
Exelon Generation (67% ownership)	Safe Harbor	Diagonal flow	37.5	6.10	Rules-based manual operation
Friant Power Authority	Friant	Vertical Francis	7	?	Rules-based manual operation

Figure 5-1: Industry Experience with Environmental Optimization of Aerating Turbines

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Optimization of Aerating Turbines
Grand River Dam Authority (GRDA)	Pensacola	Vertical Francis	19.7	2.74	Rules-based manual operation
Idaho Power	American Falls	Vertical fixed-blade propeller	37.5		Rules-based manual or remote operation; limited optimization in central dispatch
Idaho Power	Cascade	Kaplan	6.4		Rules-based manual or remote operation; limited optimization in central dispatch
Idaho Power	Brownlee	Vertical Francis	99.2	4.71	Rules-based manual or remote operation; limited optimization in central dispatch
Lower Colorado River Authority (LCRA)	Marshall Ford	Vertical Francis	38.1	3.45	Operational rules included in the control system
Lower Colorado River Authority (LCRA)	Buchanan	Vertical Francis	16.8	2.59	Operational rules included in the control system
Riverbank Power	Dorena Lake	Kaplan	4.4	?	Rules-based manual or remote operation
Riverbank Power	Dorena Lake	Horizontal Francis	1.2	?	Rules-based manual or remote operation
Southern	Bankhead	Vertical diagonal flow	54	5.91	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Harris	Vertical Francis	67.5	5.28	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Holt	Vertical fixed-blade propeller	46.9	5.89	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Jordan	Vertical Francis	25	4.52	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Lay	Vertical diagonal flow	29.5	6.91	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Lewis Smith	Vertical Francis	78.75	4.72	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Lloyd Shoals	Horizontal, Double runner Francis	3	?	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Logan Martin	Vertical fixed-blade propeller	42.75	6.35	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Martin	Vertical Francis	45.8 (U1); 41 (U2); 40.5 (U3); 55.2 (U4)	4.57 (U4)	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Mitchell	Vertical fixed-blade propeller	50	6.76 (U5 - U7)	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Neely Henry	Vertical fixed-blade propeller	24.3	6.5	Rules-based manual or remote operation; limited optimization in central dispatch
Southern	Yates	Vertical Francis	22.75	4.95	Rules-based manual or remote operation; limited optimization in central dispatch
TVA	Apalachia	Vertical Francis	52.2 (U1); 41.4 (U2)	2.62	Optimization software integrated into the control systems
TVA	Blue Ridge	Vertical Francis	22	?	Optimization software integrated into the control system; Supplemental oxygen system is also controlled
TVA	Boone	Vertical Francis	35.1	4.19	Optimization software integrated into the control system

Figure 5-1 (continued): Industry Experience with Environmental Optimization of Aerating Turbines

Owner/Operator	Plant	Aerating Turbine Type	Unit Rated Power (MW)	Unit Diameter (m)	Technologies for Optimization of Aerating Turbines
TVA	Cherokee	Vertical Francis	34.7	4.50	Optimization software integrated into the control system; Surface water pumps and forebay line diffusers are also controlled
TVA	Douglas	Vertical Francis	31	4.57	Optimization software integrated into the control system; Surface water pumps and forebay line diffusers are also controlled
TVA	Douglas	Vertical Francis	47.2	4.57	Optimization software integrated into the control system; Surface water pumps and forebay line diffusers are also controlled
TVA	Fontana	Vertical Francis	105.4	4.19	Optimization software integrated into the control system
TVA	Hiwassee	Vertical Francis	79.7	4.27	Optimization software integrated into the control system
TVA	Norris	Vertical Francis	62	4.29	Optimization software integrated into the control system; Forebay line diffusers are also controlled
TVA	Nottely	Vertical Francis	15	2.60	Optimization software integrated into the control system
TVA	South Holston	Vertical Francis	38.5	3.58	Optimization software integrated into the control system
TVA	Tims Ford	Diagonal Flow	45	3.81	Optimization software integrated into the control system; forced-air and oxygen system are also controlled
TVA	Watauga	Vertical Francis	28.8	2.68	Optimization software integrated into the control system
USACE	Buford	Vertical Francis	58 (U1, U2); 7 (U3)	4.57 (U1, U2); 1.68 (U3)	Rules-based manual operation; limited optimization in central dispatch
USACE	Bull Shoals	Vertical Francis	40 (U1 - U4); 45 (U5 - U8)	3.87	Rules-based manual operation; limited optimization in central dispatch
USACE	Center Hill	Vertical Francis	45	4.58	Rules-based manual operation; limited optimization in central dispatch
USACE	Dale Hollow	Vertical Francis	18	2.88	Rules-based manual operation; limited optimization in central dispatch
USACE	Hartwell	Vertical Francis	84	4.88	Optimization software available to operators in control room (Note: Optimization system was removed in Feb. 2013 due to network security concerns; units are now manually controlled)
USACE	John H. Kerr	Vertical Francis	42	5.21	Rules-based manual operation; limited optimization in central dispatch
USACE	Norfork	Vertical Francis	40	3.70	Rules-based manual operation; limited optimization in central dispatch
USACE	Table Rock	Vertical Francis	50	4.05	Rules-based manual operation; limited optimization in central dispatch
USACE	Tenkiller Ferry	Vertical Francis	19.5	2.95	Rules-based manual operation; limited optimization in central dispatch
USACE	Thurmond	Vertical Francis	65.7	4.52	Optimization software available to operators in control room for aerating and non-aerating operation; Supplemental forebay oxygen system is also controlled (Note: Optimization system was removed in Feb. 2013 due to network security concerns; units and oxygen system are now manually controlled)
USACE	Wolf Creek	Vertical Francis	45	4.45	Rules-based manual operation; limited optimization in central dispatch
USBR	Canyon Ferry	Vertical Francis	16.7	?	Rules-based manual operation; limited optimization in central dispatch

Figure 5-1 (continued): Industry Experience with Environmental Optimization of Aerating Turbines

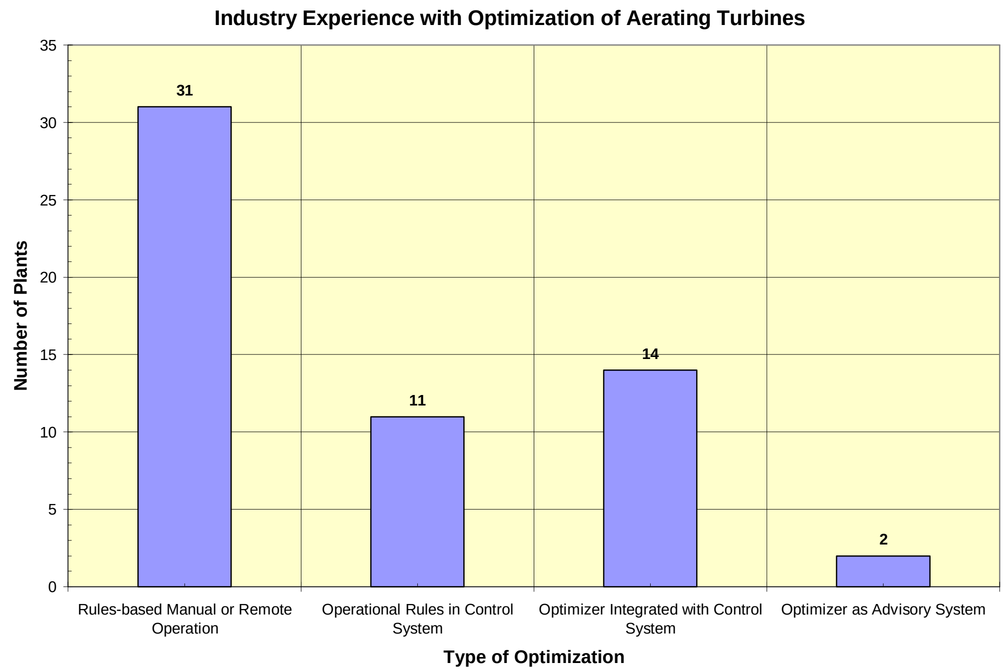

Figure 5-2: Industry Experience with Optimization of Aerating Turbines (by Plant)

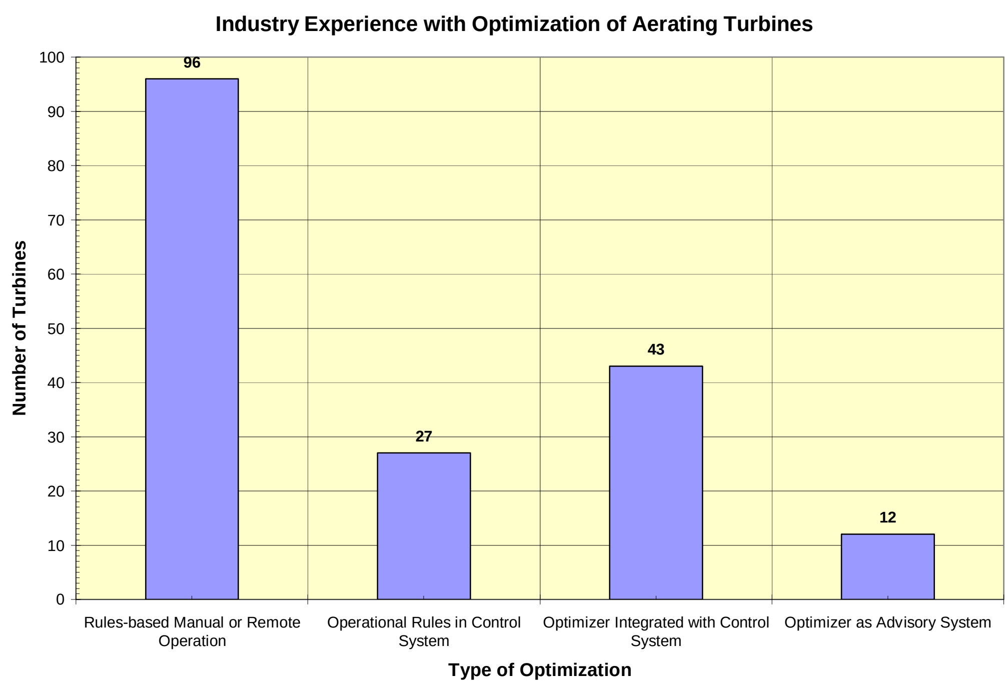

Figure 5-3: Industry Experience with Optimization of Aerating Turbines (by Turbine)

5.2 Rules-based Manual or Remote Operation

As shown in Figures 5-2 and 5-3, over half of the aerating turbines in the USA (i.e., 96 units at 31 plants) are operated manually or remotely with limited rules and little or no optimization. This represents a significant opportunity for owner/operators to achieve cost-effective efficiency improvements through improved optimization.

5.3 Operational Rules in the Control System

Operational rules in the control system provide limited optimization for 27 aerating turbines at 11 plants. Typical rules include minimum and maximum power levels, information on the effects of head on the most efficient power levels for the turbines, operational bands around the most efficient power levels, vibration avoidance zones, and ramp rates. Duke Energy, for example, uses operational rules in the control system for aerating turbines at the Bridgewater, Cedar Creek, Dearborn, Fishing Creek Mountain Island, Oxford, Rhodhiss, Wateree, and Wylie Plants. The Lower Colorado River Authority uses operational rules in the control system for aerating turbines at the Buchanan and the Marshall Ford (Mansfield) Plants.

Neither owner/operator currently includes aeration effects on unit performance in the control system rules. Previous studies have demonstrated that plants with optimizers integrated into the control systems typically operate more efficiently than the plants incorporating optimization rules in the control systems under both steady and variable generation. The suboptimization for the plants using control system rules is about two times greater than the suboptimization for the plants with integrated optimization systems [EPRI, 2012; March et al., 2013]. This represents a significant opportunity for owner/operators to achieve cost-effective efficiency improvements through improved optimization.

5.4 Environmental Optimization with Integrated Optimizers

Optimization software integrated into the control system is used for 43 aerating turbines at 14 plants. Typically, environmental monitoring systems provide data on the operations of environmental systems, monitor compliance, and provide environmental data for use in models and decision support systems. Environmental parameters include water temperatures, incoming DO values, downstream DO values, total dissolved gas, multiple differential pressures and corresponding air flow rates, oxygen flow rates (where appropriate), barometric pressure, and air temperatures. Hydraulic performance-related parameters, including unit status, power, flow rate, headwater level, tailwater level, gate opening, and efficiency are often monitored or computed as well. Using this timely information on both environmental conditions and unit operating conditions, a simple form of environmental optimization for dissolved oxygen improvement can provide increased DO levels in the turbine discharges with minimum energy losses.

Exelon Generation's Conowingo Plant uses optimization software integrated into the control system. The Conowingo Plant includes 7 aerating turbines and additional non-aerating turbines.

The Tennessee Valley Authority uses optimization software integrated into the control system for all of its turbines, including its 26 aerating turbines. Typically, a monitoring and optimization system at each plant integrates with the plant's automation control system to monitor operational and environmental parameters and to receive optimization requests (e.g., power, flow, automatic generation control) from the control system. Under varying reservoir conditions and unit operating conditions, the monitoring and optimization system chooses the optimized combination of units to meet the target DO level, minimize the aeration-induced efficiency losses, and satisfy the optimization request. The recommended unit power settings are then returned to the automated control system for execution. TVA's Apalachia, Boone, Fontana Hiwassee, Nottely, South Holston, and Watauga Plants operate in the described manner. The monitoring and optimization systems at TVA's Blue Ridge, Cherokee, Douglas, Norris, and Tims Ford Plants have additional control functions, such as controlling supplemental oxygen systems, forebay line diffusers, surface water pumps, and forced-air aeration systems. For example, if a unit is brought on line in the aerating mode at the Cherokee and Douglas Plants, the corresponding forebay line diffusers and surface water pumps are also activated and controlled.

Because the aeration-induced efficiency losses are typically low, only non-aerating performance characteristics are included in the monitoring and optimization systems at Conowingo and TVA. Some small efficiency improvements under aerating conditions could potentially be achieved by including the aerating performance characteristics in the optimization systems.

AmerenUE implemented an "Advanced Features Control System" (AFCS) at its Osage Plant to optimize overall plant efficiency while ensuring that overriding constraints such as license compliance and environmental compliance were also met. The AFCS includes unit (i.e., turbine and generator) performance matrices that provide flow versus power data over the head range for non-aerating and aerating operation. The AFCS control algorithm receives a plant power setting from the Midwest Independent System Operator (MISO), calculates the optimum method to dispatch each of the eight main units, and automatically adjusts the power on each unit to meet the time-varying power setting. As the head changes, the AFCS maintains each operating unit within a narrow band of its most efficient operating point and automatically brings units from condensing operation or reduced power to generating operation or from generating operation to condensing operation or reduced power as required to meet the total plant power demand.

For operations under aerating conditions, an Air Order Model (AOM) was implemented to control and optimize the airflows to the eight main units at Osage. A Discrete Bubble Model (DBM) is incorporated into the AOM. The DBM predicts the rate of oxygen transfer from a single bubble traveling through the draft tube and tailrace as a function of flow rate, air/water ratio, and other factors. The DBM, which was calibrated based on DO uptake tests at the plant, uses real-time data to determine the amount of air that is needed to attain DO targets in the tailrace. The input data includes inflow DO, unit flow rates, tailrace elevation, temperature, and total dissolved gases (TDG). Using the DBM results, the AOM balances airflows among unit, utilizing the most efficient units first, and controls valves on the air intake piping for each unit to ensure that both DO and TDG targets are attained. The AOM and DBM self-adjust based on the travel time between the powerhouse discharge and the downstream DO and TDG monitor, which is located about 1 mile downstream from the powerhouse, and feedback data from the monitor [March, 2011].

This combination of the Advanced Features Control System, the discrete Bubble Model, and the Air Order Model represents the most advanced system identified for environmental optimization of aerating turbines. Previous evaluations have shown that the plant operates more efficiently under normal operations than under aerating operations for both steady and variable generation conditions. In addition, the plant operates more efficiently under steady generation conditions compared to variable conditions for both normal operations and environmental operations [March et al., 2013]. Consequently, benefits could be potentially achieved through further improvements to the environmental optimization system.

5.5 Optimization-based Advisory Systems

At the USACE's Hartwell Plant and Russell Plant, real-time operational and environmental data and optimization software were available to plant managers and to operators in the control room as an advisory system. At the USACE's J. Strom Thurmond Plant, real-time operational and environmental data, optimization software, and control of the supplemental forebay oxygen system were available to plant managers and to operators in control room as an advisory system. The JST optimization software included unit characteristics for non-aerating operation of the distributed aeration systems for JST's seven turbines.

Results from analyses of JST hourly data before adoption of the optimization-based advisory system and after adoption of the advisory system are presented elsewhere [March et al., 2003; March, 2006; EPRI, 2013]. Before adoption of the advisory system, significant optimization improvements were identified [March, 2006], with an average efficiency improvement of 3.8% (12,000 MWh of additional annual generation). After adoption of the advisory system, only limited optimization improvements were identified, with an average efficiency improvement of 0.6% (1,900 MWh) under both aerating and non-aerating operations [EPRI, 2013].

The optimization-based advisory systems at the Hartwell, Russell, and Thurmond Plants were removed in February 2013 due to network security concerns. The units at Hartwell, Russell, and Thurmond are now manually controlled without input from the advisory system. Results from additional performance analyses of JST hourly data for January 2012 through March 2015 show a significant increase in JST suboptimization, corresponding to a cumulative generation loss of approximately 5,600 MWh, after removal of the JST advisory system, presumably due to the loss of information on optimized plant operation by unit operators and plant managers [March et al., 2015].

6.0 Recommendations for Additional Research

6.1 Overview

To further assist turbine manufacturers, agencies, and utilities in their efforts to evaluate and improve the hydraulic and environmental performance of aerating turbines, recommendations for additional research are provided in this section. The recommendations in the following subsections follow the general outline of the paper, including aerating turbines for minimum and environmental flows; aerating Kaplan, diagonal flow, and propeller turbines; and environmental optimization of aerating turbines.

6.2 Aerating Turbines for Minimum and Environmental Flows

Recommendations related to aerating turbines for providing minimum and environmental flows include:

1. Detailed hydraulic and environmental performance analyses should be conducted for representative aerating minimum flow turbines (e.g., Ameren Missouri's Osage Plant, Duke's Bridgewater Plant).
2. An industry webinar on aerating turbines, with an emphasis on small plants and aerating minimum and environmental flow turbines, should be developed and conducted.
3. Research should be conducted to develop robust environmental models for scenario analyses related to environmental flows, DO levels, TDG levels, and temperatures.

6.3 Aerating Kaplan, Diagonal Flow, and Propeller Turbines

Recommendations related to aerating Kaplan, diagonal flow, and propeller turbines include:

1. Owners with aeration needs and significant fleets of Kaplan, diagonal flow, and propeller turbines (e.g., Southern Company, Idaho Power) should be encouraged to work with turbine manufacturers to develop and implement advanced turbine designs to achieve good environmental performance with a minimal impact on operating efficiencies.
2. Detailed hydraulic and environmental performance analyses should be conducted for the recently installed peripheral aeration system on the Unit 6 Kaplan turbine at the Safe Harbor Plant.

6.4 Environmental Optimization of Aerating Turbines

Recommendations related to environmental optimization of aerating turbines include:

1. Accurate unit and plant performance characteristics under aerating and non-aerating conditions are essential for proper plant operation and optimization of aerating turbines. Owner/operators' improved attention to unit flow measurements could improve operational efficiencies and generation for aerating turbines.
2. Significant benefits can be achieved through improved optimization, including improved environmental optimization. Research should be conducted to enhance environmental optimization tools for a range of time scales from near real-time to seasonal.

3. Suboptimization of aerating turbines under variable generation versus steady generation and under both normal operations and environmental operations should be more thoroughly investigated [EPRI, 2012; March et al., 2013].

6.5 Other Recommendations

Other related recommendations include:

1. A study should be conducted to survey turbine manufacturers and utilities and to compile hydraulic and environmental performance data and incremental cost information, including energy costs associated with aerating and non-aerating operation, for various aerating turbine technologies.
2. The hydropower industry should establish a national database of cost-related data and hydraulic and environmental performance data for all types of aerating turbines. The national database could be funded by EPRI, DOE, USACE, or other appropriate sponsors and maintained by a national laboratory with related experience, such as Oak Ridge National Laboratory.
3. Additional hydraulic and environmental performance information should be solicited from South American, European, Asian, and African utilities and agencies as aerating turbine solutions are applied in those areas.
4. ASME PTC-18's continuing efforts for the development and standardization of a comprehensive test code for aerating turbines should be encouraged and financially supported by the hydropower industry [ASME, 2011; EPRI, 2011; Kirejczyk, 2011]. The test code should include guidance on representative measurements for incoming DO and discharge DO.
5. Long term monitoring, data archiving, and subsequent data analyses for various aerating turbine technologies should be conducted to provide hydraulic and environmental performance results over a much wider range of conditions. For example, TVA's archival data from environmental and operational monitoring of aerating turbines (as well as other technologies for DO enhancement) should be systematically analyzed to benefit the hydropower industry.
6. Research should be conducted to provide useful aeration-related scaling relationships between physical models and prototypes of aerating turbines. This will likely require improved numerical modeling of both model and prototype turbines.
7. Research should be conducted to improve numerical models for predicting draft tube effects on decreases in turbine efficiency under non-aerating and aerating conditions and for predicting gas transfer and resulting DO and TDG levels.
8. Research should be conducted to develop more cost-effective, low maintenance methods to measure DO in reservoirs and reservoir releases.

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