

Frequency Sensitive Control Mode and Fatigue Assessment for Kaplan and Bulb Turbine Runners

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Abstract

With low inertia energy production sources, such as solar and wind energy, expanding in today's energy market share, there is a growing need for balancing power within the electrical grid. Consequently, hydroelectric power plants, including Kaplan and bulb turbines, are increasingly required to operate in flexible modes of operation, such as Automatic Generation Control (AGC) and Primary Frequency Control (PFC). When operating in PFC, in principle, any change in the grid frequency is expected to result in a change in power output to help maintain the desired grid frequency. This results in the turbine governor constantly adjusting the position of the actuators (wicket gates and runner blades). Due to this continuous movement, the internal blade operating mechanism components of Kaplan and bulb turbine runners experience high cycle loading which requires special attention to fatigue. It must be ensured that runner components can withstand operation in PFC for the intended design life without a fatigue failure. The following considerations are crucial to ensure safe operation for the intended design life:

1. Accurate estimation of operating cycles
2. Accurate estimation of design loading
3. Static stress assessment
4. Fatigue assessment
5. Adaptations for environmentally-friendly designs

This paper describes Voith's philosophy for fatigue assessment of the internal blade operating mechanism components of Kaplan and bulb turbine runners that are subject to high cycle fatigue loading due to operation in PFC. The key considerations mentioned above are discussed and case study results are presented.

A robust, reliable design relies on measurements, theoretical calculations, industry codes, and experience in the hydro industry.

Keywords

Primary Frequency Control, High Cycle Fatigue, Regulating Pressure Measurement, FKM, ASME

1 Introduction

1.1 Background

With low inertia energy production sources, such as solar and wind energy, expanding in today's energy market share, there is a growing need for balancing power within the electrical grid. Consequently, hydroelectric power plants, including Kaplan and bulb turbines, are increasingly required to operate in flexible modes of operation, such as Automatic Generation Control (AGC) and Primary Frequency Control (PFC). When operating in PFC, in principle, any change in the grid frequency is expected to result in a change in power output to help maintain the desired grid frequency. If the grid frequency increases, the power output has to be reduced and vice versa. As a result, the turbine governor constantly adjusts the position of the actuators (wicket gates and runner blades) [1].

The reliable operation of components within a Kaplan runner is defined by conditions such as wear and fatigue damage. Due to the requirement for increased flexibility in operating conditions, Kaplan runners typically experience a greater number of load cycles than in the past. This greater number of load cycles directly influences the wear and fatigue damage a Kaplan runner experiences.

1.2 Case Study of New Kaplan Runner

The case study presented in this paper reflects the modernization of an existing hydroelectric power plant. For this modernization, new oil-filled Kaplan runners were designed to replace the existing Kaplan runners currently in operation. The new Kaplan runners were designed for reliable operation in PFC for the intended design life without a fatigue failure.

2 Operating Cycles

2.1 Background

To ensure safe operation for the intended design life, the number of expected operating cycles must be accurately estimated and/or conservative values considered in the design of a Kaplan runner.

Historically, starts and stops, load rejections, and runaway occurrences were the primary design criteria for Kaplan runner design within customer technical specifications. These criteria are critical for ensuring reliable operation of structural components of the Kaplan runner (blades and hubs); however, for units operating in flexible modes of operation, such as PFC, they often are not the driving fatigue damage contributor. For a Kaplan runner operating in flexible modes of operation, the main

driver for safe and reliable operation is often limiting fatigue damage to the blade operating mechanism due to requested blade movement cycles.

The types of blade movement cycles that contribute the most to fatigue damage are those that cause full stress reversals in the blade operating mechanism, such as movements from open to close or close to open. These can be determined by measuring the differential pressure between the blade opening and blade closing chambers of the blade servomotor.

The number of blade movement cycles depends greatly on the mode of operation and the turbine speed governor system installed on the unit. Voith has successfully measured various modes of operation in Kaplan units by means of unit monitoring systems. Such real life data is presented in Figure 1 through Figure 4.

Historically, hydroelectric plants typically operated in two main modes of operation:

- Power control mode
- Flow control mode

Hydroelectric plants are increasingly required to operate in flexible modes of operation. When operating in flexible modes of operation, two main modes of operation have been observed in the operation of Kaplan runners:

- Automatic Generation Control (AGC)
- Primary Frequency Control (PFC)

In power control mode, the unit operates at set power outputs providing baseload power to the electrical grid. In this mode of operation, the number of blade movement cycles is typically low. Operational data presented in Figure 1 illustrates typical behavior when operating in power control mode.

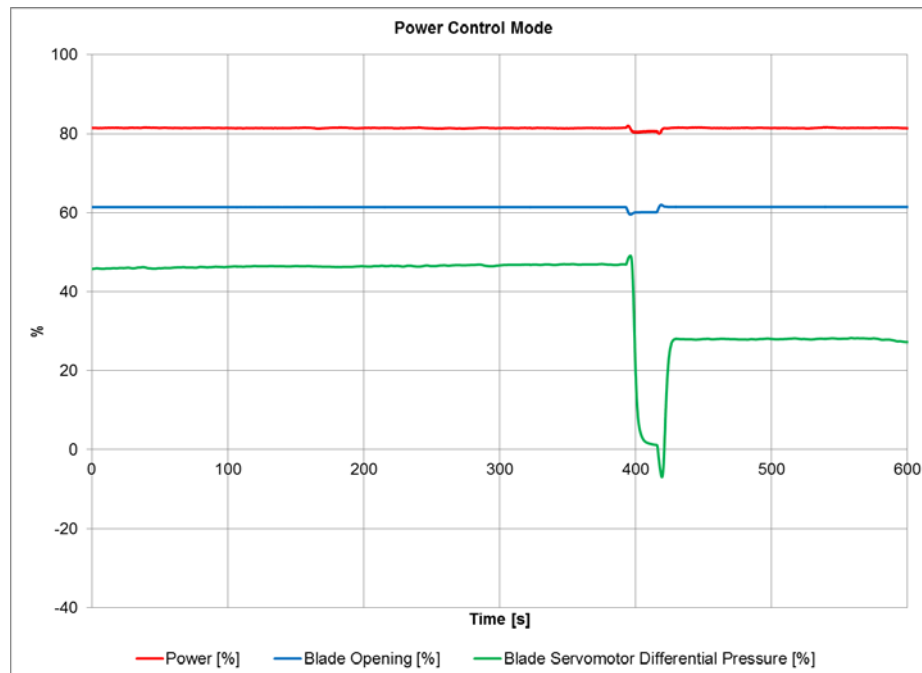


Figure 1: Operating data — power control mode

In flow control mode, the unit operates to pass a certain amount of water flow through the unit. Operation in flow control mode exhibits a similar number of blade movement cycles as compared to operation in power control mode.

When operating in flexible modes of operation, hydroelectric turbines often provide two services to the grid: secondary frequency control and primary frequency control.

Secondary frequency control maintains the minute-to-minute balance throughout the day and is used to restore the grid frequency to its desired value. The most common means of accomplishing secondary control is through Automatic Generation Control (AGC) [2]. For hydroelectric turbines operating in AGC, frequent large adjustments in the power set point are requested based on changes in power demand within the grid in order to help maintain the desired grid frequency. Operational data presented in Figure 2 illustrate such rapid, large changes in power set points.

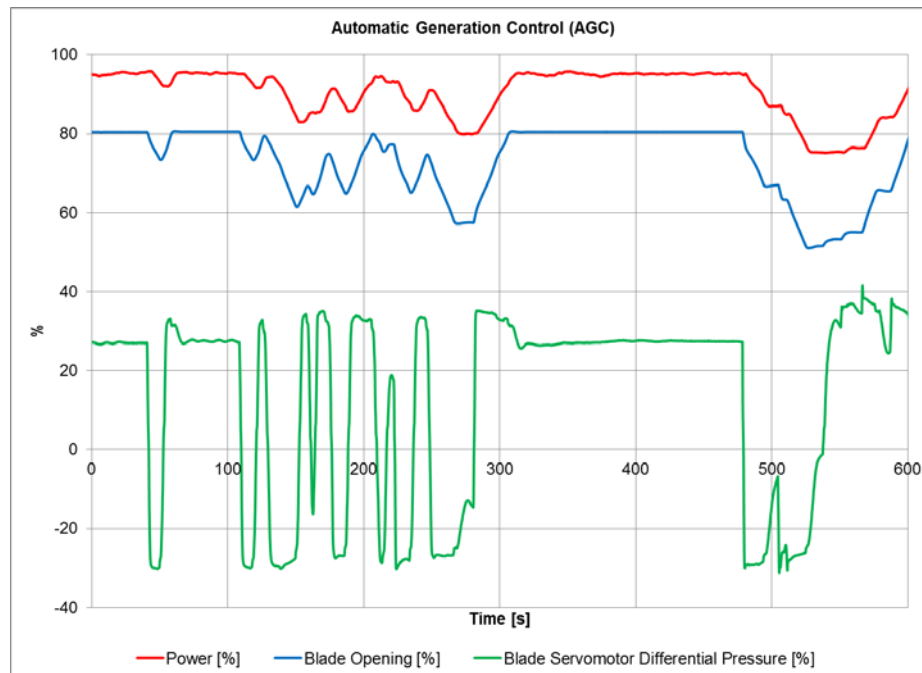


Figure 2: Operating data — AGC

Primary Frequency Control (PFC) occurs within the first few seconds following a change in system frequency to stabilize the grid [2]. For hydroelectric turbines operating in PFC, frequent, normally small adjustments in the power set point are coupled with changes in the grid frequency. In PFC, any change in the grid frequency is expected to result in a change in power output of the unit in order to help maintain the desired grid frequency. If the grid frequency increases, the power output has to be reduced and vice versa. Typically, these changes in power set point are small in magnitude; however, high in quantity.

The number of blade movement cycles associated with operation in PFC is highly influenced by local grid conditions and by governor parameters such as controller constants, dead band, dead time and even noise in measurement circuits. Voith has developed specialized Quantizer and non-linear filtering logic able to reduce the number of blade movement cycles by a factor of 10 while operating in PFC mode [1].

Operational data presented in Figure 3 illustrates how, with the Quantizer filter inactive, the blade operating mechanism experiences nearly continuous changes in blade servomotor differential pressure. This indicates a near continuous adjustment of the blade operating mechanism and results in a very large number of blade movement cycles. Notice that the actual blade movement is very small.

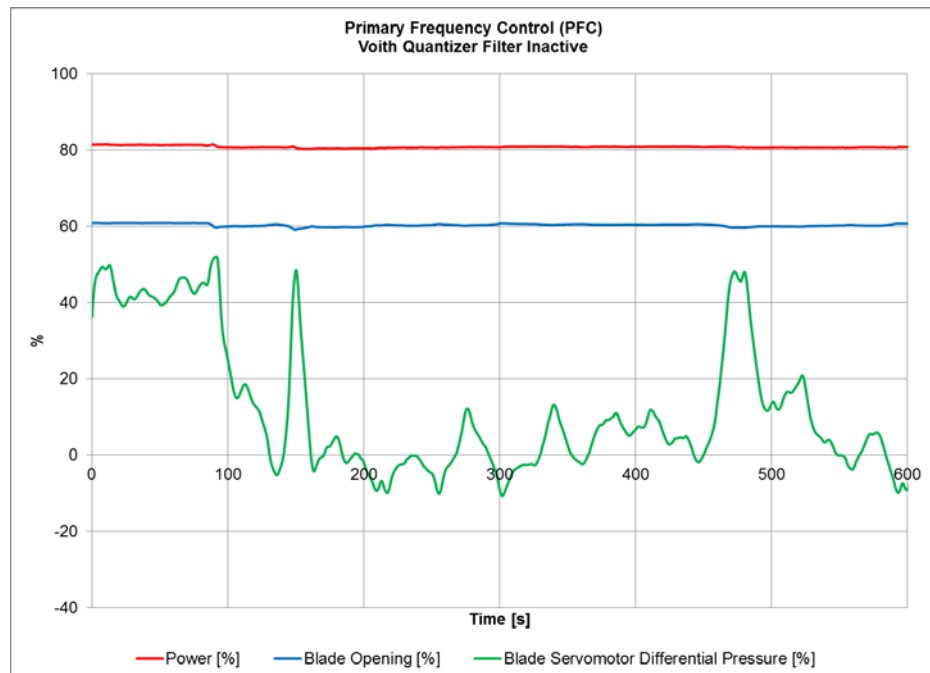


Figure 3: Operating data — PFC with Voith Quantizer filter inactive

Operational data presented in Figure 4 illustrates how, with the Quantizer filter active, the blade operating mechanism experiences discrete changes in blade servomotor differential pressure. This indicates limited adjustment of the blade operating mechanism and results in significant improvement in fatigue life for units regularly operating in PFC.

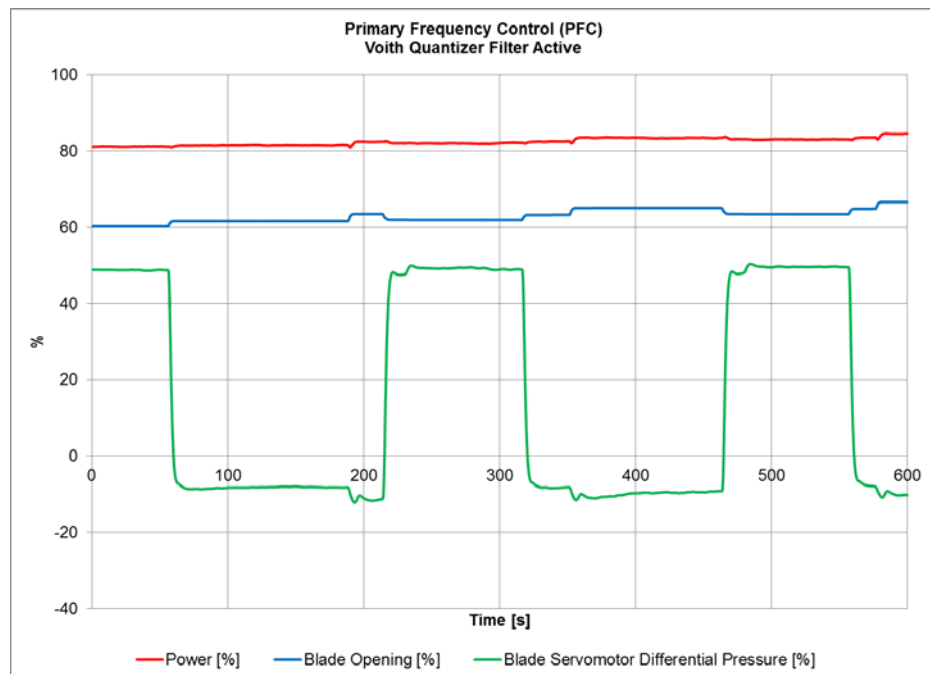


Figure 4: Operating data — PFC with Voith Quantizer filter active

Through unit monitoring, Voith has successfully measured blade movement cycles for Kaplan units. These real life measurements contribute to Voith's knowledge and experience for designing Kaplan runners capable of reliably operating in flexible modes of operation and form the basis of the case study that is presented in Section 2.2.

2.2 Case Study of New Kaplan Runner

Prior to the design of the new replacement Kaplan runner, a modern Voith digital governor and monitoring system was installed. This system allowed for blade moment cycles to be measured for various operating modes, including PFC.

These measurements, along with Voith's global experience in the hydro industry, formed the basis for defining an accurate and conservative fatigue load universe to design the new replacement Kaplan runner. This ensures the internal components of the new Kaplan runner can reliably operate in PFC for the intended design life.

Blade movement cycles during continuous operation are not the only cycles to consider. The total number of starts and stops, load rejections, and runaway occurrences the unit may experience should also be considered. Typically, such occurrences do not have as much of an impact on fatigue life as blade movement cycles for units operating in PFC due to the frequency of occurrence; however, these conditions must also be included in the calculation to determine the total combined effect on the components.

A load universe representative of the conditions of the studied plant is presented below in Table 1. It must be noted that the actual number of blade movement cycles for a given plant and generating unit is highly dependent on intended modes of operation, operating hours in each mode of operation, and local grid conditions. As such, a conservative load universe for use in the design of the new Kaplan runner was chosen.

Fatigue Load Case	Cycles (Normalized)
LF 1 — Operation in Primary Frequency Control	73,000
LF 2 — Operation in Power Control	14,600
LF 3 — Load Changes	912
LF 4 — Start-Stops	91
LF 5 — Load Rejection	1

Table 1: Studied load universe (normalized)

3 Loading

3.1 Background

The fatigue life of the components within a Kaplan runner is defined by both the *quantity* of operating cycles and *magnitude* of operating stresses.

During the design phase, operational loading of the components within a Kaplan runner are determined by calculation models using hydraulic loading as inputs. The hydraulic loading input into the calculation model is determined through the use of both scaled hydraulic model testing and Computational Fluid Dynamics (CFD) analysis. Using the hydraulic loading, operating forces and torques are determined for the Kaplan runner blade operating mechanism for multiple operating points and blade movement directions.

Operation in PFC substantially increases the quantity of blade movement cycles and the dynamic response of operating the blades. This factor has motivated a measurement campaign that utilizes strain gauges to measure operational stresses within Kaplan runner blade operating mechanisms while operating in PFC. The recorded data, correlated with detailed analysis by analytical calculations, Finite Element Method (FEM), CFD analysis, and transient simulations, allows for more accurate prediction and evaluation of the stresses, wear, and fatigue characteristics of Kaplan runners operating in PFC [3].

3.2 Case Study of New Kaplan Runner

The operational loading of the components within the new Kaplan runner were determined by calculation models using hydraulic loading of the new Kaplan runner as inputs. The critical normal operation Load Cases (LC) for operation in FCM and the associated normalized loadings are presented in Table 2.

Operating Point	Static Stress Load Case	Head	Blade Position	Speed	Power	Thrust	Blade Torque	Blade Movement Direction
$H_{\max}, P_{\max}$	LC 1	100	87	100	100	100	52	Open
	LC 2	100	87	100	100	100	52	Close
$H_{\min}, P_{\max}$	LC 3	81	97	100	91	81	100	Close
$H_{\min}, P_{\min}$	LC 4	81	24	100	38	81	39	Open

Table 2: Critical normal operation Load Cases (LC) and loading (normalized - %)

For the studied plant, operation at maximum head ($H_{\max}$) and maximum power ($P_{\max}$) represents the operating point that results in the greatest stress amplitudes within the blade operating mechanism when operating in PFC. Operation at minimum head ($H_{\min}$) represents the operating head that results in the greatest stress amplitudes within the blade operating mechanism when performing load changes at a fixed head.

4 Static Stress Assessment

4.1 Background

Using the calculated operating forces, static stresses for various blade operating mechanism components are determined either analytically or by FEM using ANSYS.

Analytical methods are commonly applied for components with geometries that have well-defined stress concentration factors in published literature. For more complex geometries or in cases where the stiffness and deflection of interfacing components is of importance, analysis by FEM is performed. Figure 5 provides an example of a normalized stress distribution for a blade lever analyzed by FEM.

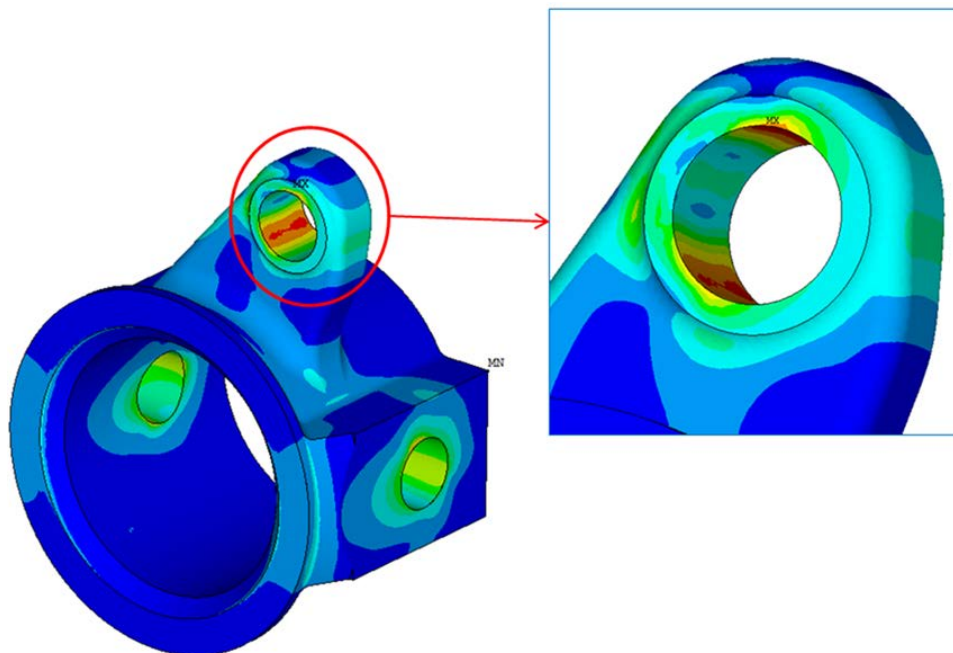


Figure 5: Normalized von Mises stress distribution for a blade lever analyzed by FEM

4.2 Case Study of New Kaplan Runner

The calculated operating forces for the new Kaplan runner were used to determine static stresses for various blade operating mechanism components.

Different components within the blade operating mechanism are subjected to different stress magnitudes and loading modes. For the studied plant, the critical components of the blade operating mechanism were the link and blade lever. For the two critical components, chosen materials are presented in Table 3. These materials are commonly used for Kaplan runners. Normalized static stress results for the two critical components are presented in Table 4 and Table 5.

Component	Material
Link	Forged High Strength Carbon Steel
Blade Lever	Cast High Strength Carbon Steel

Table 3: Materials of critical components

Load Case	Peak von Mises Stress (Normalized)	Allowable von Mises Peak Stress (Normalized)	% of Allowable
LC 1	0.02	1.00	2%
LC 2	0.36	1.00	36%
LC 3	0.44	1.00	44%
LC 4	0.02	1.00	2%

Table 4: Static stresses for critical load cases and locations (normalized) — link

Load Case	Peak von Mises Stress (Normalized)	Allowable von Mises Peak Stress (Normalized)	% of Allowable
LC 1	0.08	1.00	8%
LC 2	0.20	1.00	20%
LC 3	0.23	1.00	23%
LC 4	0.08	1.00	8%

Table 5: Static stresses for critical load cases and locations (normalized) — blade lever

5 Fatigue Assessment

5.1 Background

In the North American hydro industry, the ASME Boiler and Pressure Vessel Code Section VIII, Division 2 (ASME Code) offers the most commonly used method for calculating fatigue damage. The ASME Code fatigue design curves account for the effects of surface roughness, surface treatment, corrosion, as well as other factors. This approach permits neglecting the mean stress part and focuses only on the stress

amplitude because the ASME design fatigue curves are adjusted for the maximum possible effect of mean stress and strains; therefore, an adjustment for mean stress effects is not required. These design curves also include a minimum safety factor of 2 on the allowable stress or 20 on the allowable number of cycles [4], whichever is the most limitative. This is called the 2/20 rule. As such, these design fatigue curves are intended to be used without consideration of any further reduction factors or modifications.

In Europe, the Forschungskuratorium Maschinenbau (FKM) Guideline [5] is widely used to analyze hydraulic turbines. In the North American hydro industry, use of the FKM Guideline is becoming more prevalent. Several characteristics of the analyzed component are considered in the assessment, including: material properties (e.g., fatigue strength factor for completely reversed normal stress), design parameter (e.g., surface roughness, surface treatment, and stress gradient in notch), component fatigue limit for taking mean stress into account, consequences of failure, inspection frequency of the component, and safety factors of material (e.g., steel and ductile cast iron) [5]. Degrees of utilization for the individual stress types are calculated.

5.2 Case Study of New Kaplan Runner

For the new Kaplan runner, fatigue assessment was performed for the critical components of the blade operating mechanism utilizing both the ASME Code and the FKM Guideline. Operating cycles and stress results used for the assessments are those presented in Sections 2.2 and 4.2.

ASME design fatigue curves were applied directly with no reduction factors. Total damage sums for the two critical components of the blade operating mechanism are presented in Table 6. The greatest damage sum for either of the components presented is 2.02E-02. As the damage sum is less than 1.0, the components are unlikely to form fatigue cracks in the critical areas analyzed due to operation in PFC for the intended design life.

Component	Damage Sum
Link	2.02E-02
Blade Lever	1.41E-03

Table 6: Damage sum per ASME for critical components

The FKM Guideline was applied and the factors considered include: surface roughness, surface treatment, corrosion influence, consequences of failure, and inspection frequency of the component. Degrees of utilization for the two critical components of the blade operating mechanism are presented in Table 7. The greatest degree of utilization is 7.29E-1. As the degrees of utilization are less than 1.0, the components are unlikely

to form fatigue cracks in the critical areas analyzed due to operation in PFC for the intended design life.

Component	Degree of Utilization
Link	7.29E-1
Blade Lever	6.55E-1

Table 7: Degree of utilization per FKM for critical components

Both the ASME Code and the FKM Guideline indicate that the components are unlikely to form fatigue cracks in the critical areas analyzed due to operation in PFC for the intended design life. The use of both methods to evaluate the design is not intended to be used to determine which method is more conservative or more accurate. The results of fatigue assessment using the ASME Code and the FKM Guideline are not directly comparable. Both methods were used to evaluate the design in order to show consensus that the design is safe using two well-known and widely applied methods within the hydro industry.

5.3 Sensitivity Study

For a Kaplan runner operating in flexible modes of operation, such as AGC and PFC, the main driver for safe and reliable operation is often fatigue damage due to requested blade movement cycles. Typical customer specifications do not include such considerations when defining the intended design life and loading cycles. Starts and stops, load rejections, and runaway occurrences are typically the primary design criteria for Kaplan runner design within customer specifications.

Table 8 presents a comparison of a typical load universe defined in a customer specification and representative load universes for units operating in power control mode and PFC. In Table 8 and Figure 6, it is seen that the number of blade movement cycles due to operation in PFC is orders of magnitude greater than those when operating in power control mode or as defined in a typical customer specification. For units operating in PFC, it is assumed the unit operates a portion of its daily operating time in PFC and the remainder of the time in power control mode.

Figure 6 also illustrates that operation in PFC has a significant impact on the fatigue life of Kaplan runner blade operating mechanism components. For units operating in PFC, load cycles due to operation in this mode are the primary fatigue damage contributor.

Fatigue Load Case	Cycles (Normalized)		
	Typical Customer Specification	Power Control	Primary Frequency Control
LF 1 — Operation in Primary Frequency Control	0	0	73,000
LF 2 — Operation in Power Control	0	21,900	14,600
LF 3 — Load Changes	912	912	912
LF 4 — Start-Stops	91	91	91
LF 5 — Load Rejection	1	1	1

Table 8: Load universe for fatigue sensitivity study for different modes of operation

As discussed in Section 2, the actual number of operating cycles a unit experiences depends greatly on intended modes of operation and local grid demands. Thus, to achieve reliable operation in flexible modes of operation, it is important that the plant owner carefully considers the modes of operation the plant will experience. Further, the planned modes of operation and expected number of cycles must be clearly communicated to the turbine manufacturer.

With Kaplan runners having intended design lives in the range of 30 years or more, owners must consider how changes in modes of operation could affect the reliability of existing equipment. Voith has experience in residual life assessment for existing Kaplan runners operating in flexible modes of operation, such as AGC and PFC. Such residual life assessments can provide valuable information for long-term planning of maintenance, rehabilitation, and modernization schedules.

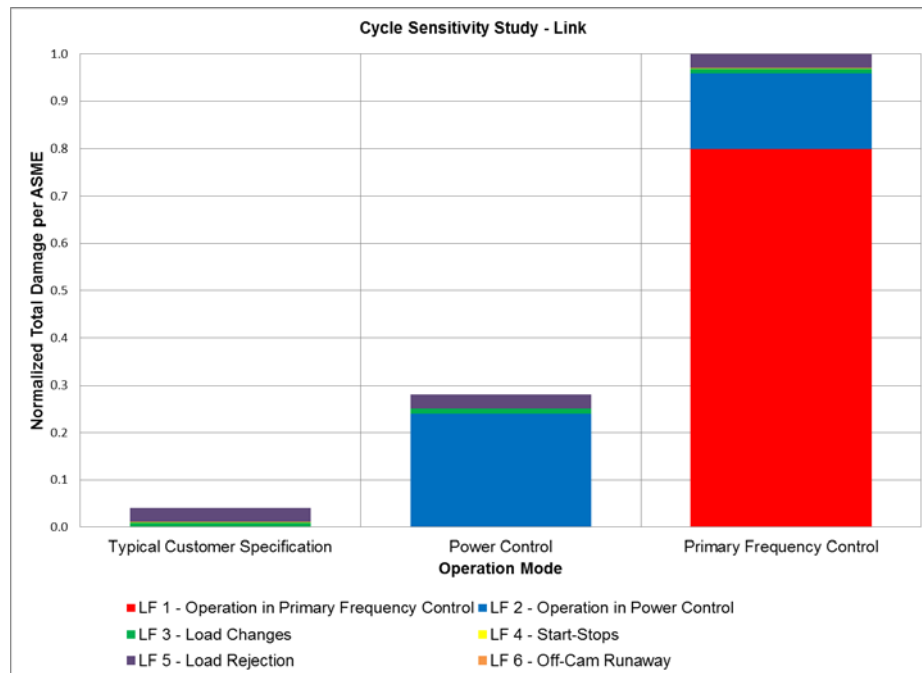


Figure 6: Blade movement cycles sensitivity study per ASME (normalized) — link

6 Adaptations for Environmentally-Friendly Designs

Interest in water-filled Kaplan runners has increased in the United States due to their reduced risk of environmental contamination.

Within water-filled Kaplan runners, key blade operating mechanism components are exposed to water. Even with the selection of corrosion resistant materials, such as stainless steel, no endurance limit data exists for such components when placed in a corrosive environment, such as water. As such, the design of all water-filled Kaplan runners, especially those intended for use in flexible modes of operation, such as AGC and PFC, must pay special attention to material selection and fatigue life assessment.

Voith has broad experience in the United States and internationally with water-filled runners, including those operating in flexible modes of operation, such as PFC.

7 Conclusion

This paper describes Voith's philosophy for fatigue assessment of the internal components of Kaplan and bulb turbine runners that are subject to high cycle fatigue loading due to operating in flexible modes of operation, such as AGC and PFC. The key issues of operating cycles, loading, static stress assessment, fatigue assessment, and adaptations for environmentally-friendly designs were discussed.

To ensure safe operation for the intended design life, the number of expected operating cycles must be accurately estimated and/or conservative values considered in the design of a Kaplan runner. Voith's Quantizer filter can be applied in applications where

the unit operates in PFC to greatly reduce the number of blade movement cycles and thus extend fatigue life.

The case study presented illustrates Voith's knowledge and experience for designing Kaplan runners capable of reliably operating in flexible modes of operation, such as AGC and PFC.

A robust, reliable design relies on measurements, theoretical calculations, industry codes, and experience in the hydro industry.

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