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Creating a Digital Twin for a Hydropower System through 3D Object Modeling

Alder Dam - FY2023

September 2023

Hongfei Hou
Osman Ahmed
Chitra Sivaraman

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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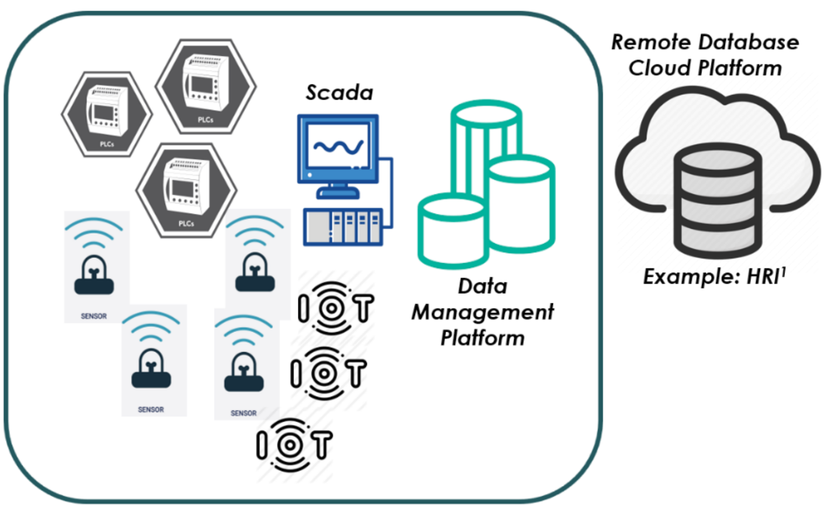
Abstract

Hydropower stands as the world's leading source of renewable electricity, with hydropower plants spanning the globe. A typical hydropower plant comprises essential components including the governor, excitation system, generator, thrust bearing, hydraulic turbine, transformer, main lead, metering and control devices, tailwater depression system, and dissolved oxygen monitoring. Each of these components undergoes various measures and monitoring procedures. These measurements are collected through a diverse array of systems, encompassing standalone sensors, programmable logic controllers (PLCs), Supervisory Control and Data Acquisition (SCADA) systems, Internet of Things (IoT) devices, and data acquisition and integration platforms like OSI/PI.

The data obtained from these measurements is frequently stored within the plant's data management platform, and numerous institutions employ cloud-based archival systems for this purpose. Notable examples include the Hydropower Research Institution (HRI), the U.S. Army Corps of Engineers (USACE), and the Columbia River Data Access in Real Time (DART) system.

Real Hydropower Plant Data Landscape



Object Modeling serves as a comprehensive framework for designing information systems, with a primary focus on objects, their actions, and the messages exchanged to trigger these actions. It distinguishes itself from network modeling, data modeling, and process modeling in several key aspects.

In Object Modeling, the primary emphasis lies in understanding the actions taken in response to information, the constituent objects shaping the system, the actions they execute, and the communication channels through which they exchange information. Conversely, network modeling delves into the specifics of where, when, and the volume of data transfer. Data modeling, on the other hand, hones in on the nature of the information itself and its destinations, while process modeling concerns itself with the mechanics of how and when data is transported.

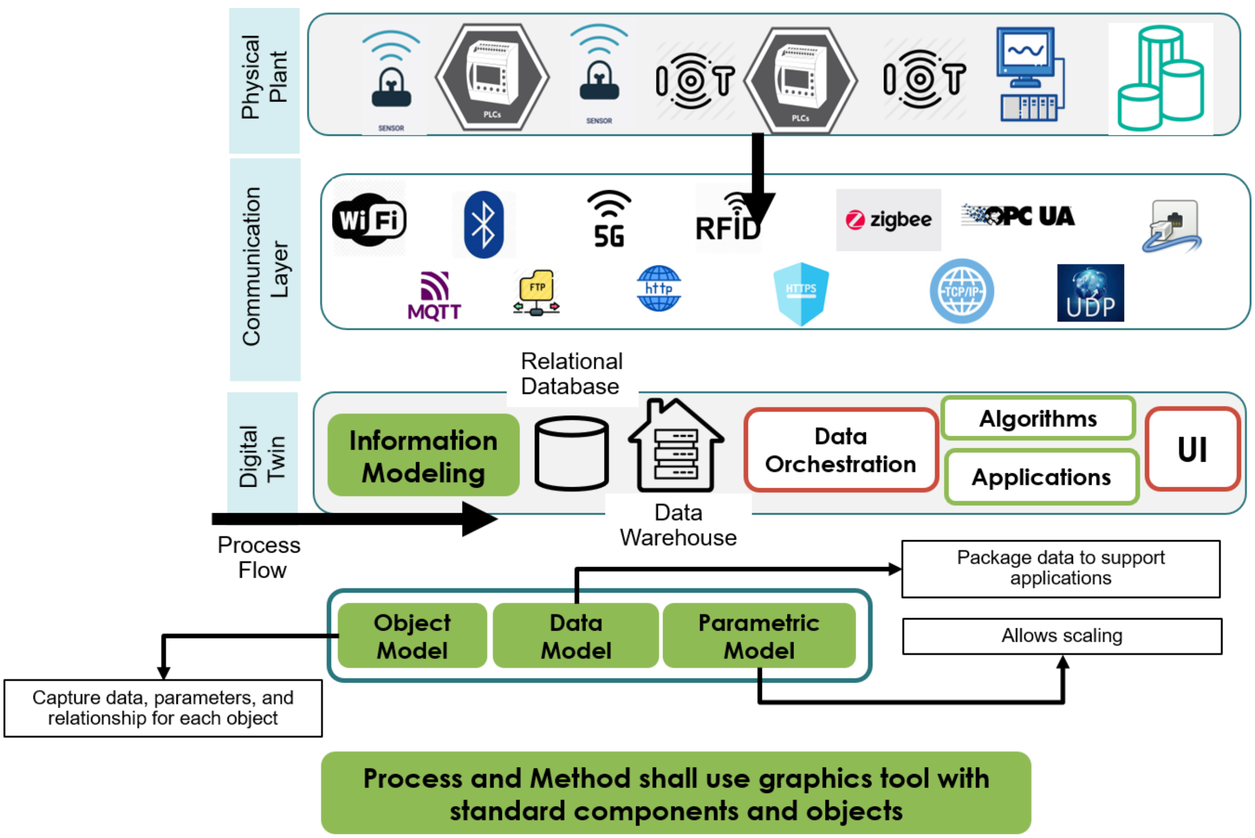
Object Modeling originated primarily as a tool for developing object-oriented systems and supporting object-oriented programming. It primarily characterizes the static structural elements within the system. The Object Modeling Technique is favored for its simplicity in both depiction and application, making it a logical choice for connecting physical hydropower plants to Digital Twin technology. It excels in recognizing objects and their interrelationships, identifying class attributes, and delineating their functions.

Dynamic Modeling, within this framework, elucidates how objects respond to events, while Functional Modeling outlines the processes executed within objects and how data undergoes transformations during inter-object transfers. Object Modeling has found wide-ranging applications, spanning sectors such as telecommunications, transportation, and more.

Summary

Digital Twin encounters several notable challenges. The foremost among them is the imperative task of acquiring all real-time measured data, a critical component in facilitating informed decision-making, especially in a dynamic market environment that demands swift responses to changes and events. Real-time monitoring stands as a cornerstone feature of Digital Twin, playing a pivotal role in averting disasters and mitigating potential damages.

A second significant challenge revolves around the creation of a database that effectively encapsulates the intricate relationship between data and the understanding of how this data is physically distributed. In essence, it poses a formidable hurdle to construct a database equipped with the knowledge of the physical topology and hierarchical distribution of data.



Nonetheless, prevailing practices reveal that hydropower data is dispersed across diverse locations and exists in various formats. These data sources exhibit heterogeneity and are spread across a spectrum, ranging from individual sensors or emerging IoT platforms to comprehensive data management platforms. In the context of Digital Twin, the demand for data is two-fold: it must be real-time, and the scope of data requirements is extensive. To faithfully represent physical hydropower plants, an array of data types must be collected, encompassing weather data, meta-data, topological data, physical dimensional data, camera-generated data for 3D visualization, operational records, location data, among others.

In response to these challenges, we introduce the Digital Twin Hydropower System Open Platform Framework (DTHS-OPF). The overarching objectives of DTHS-OPF include the establishment of an open system architecture, the promotion of open sourcing practices, the

development of an open data integration platform, the facilitation of open interoperability, and the provision of an accessible user-friendly graphical interface for easy custom configuration employing object modeling and parametric modeling. DTHS-OPF is designed to be user-friendly, straightforward in operation, and cost-effective to implement and maintain. Furthermore, it is designed to be scalable to meet evolving market demands and flexible and adaptable to accommodate emerging technologies.

Acknowledgments

The study was funded by the U.S. Department of Energy Water Power Technologies Office.

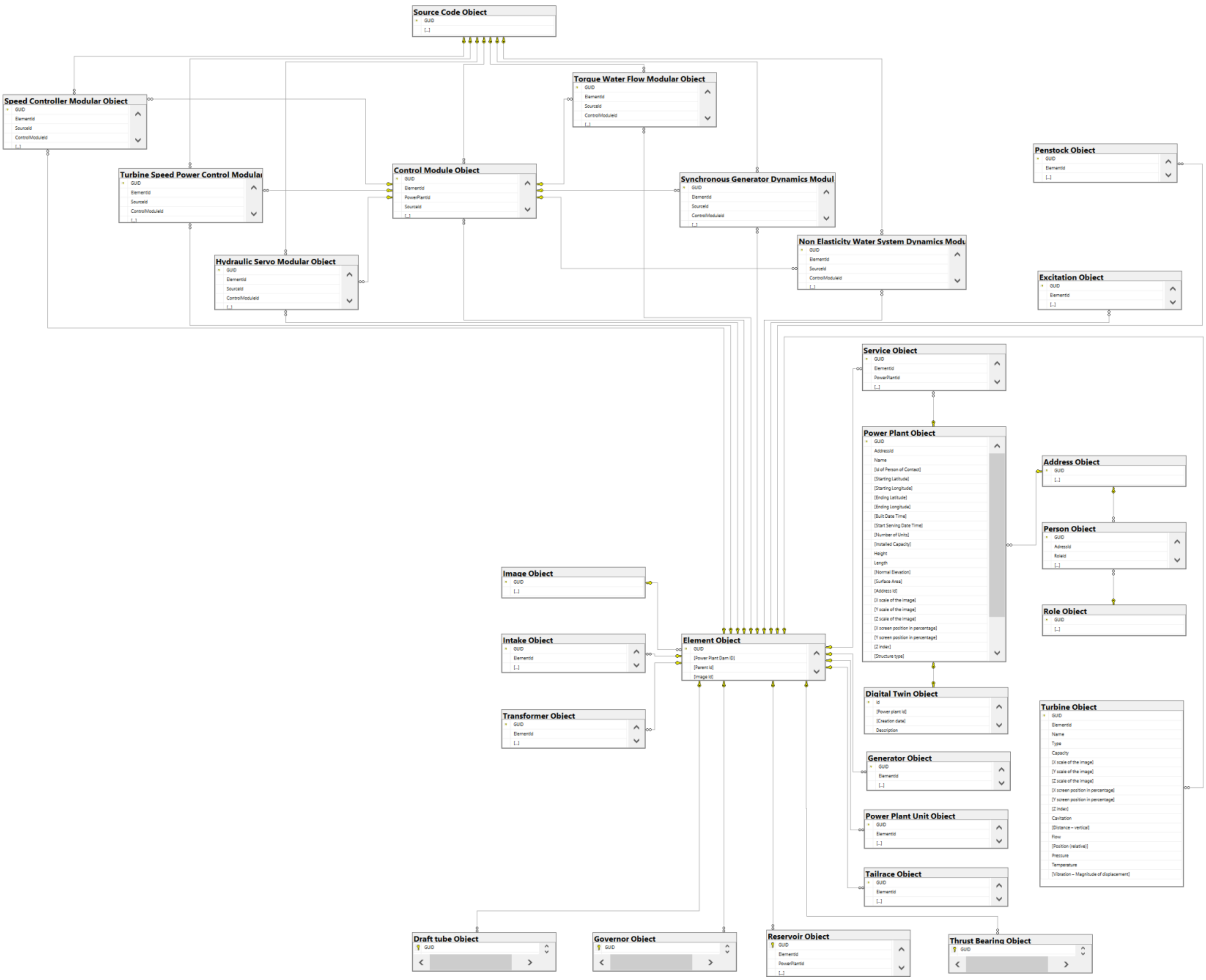
Acronyms and Abbreviations

2D	2 dimensional
3D	3 dimensional
KCFS	Kilo cubic feet per second
mm	Millimeter
Mils	Thousandths of an inch
m/s	Meter per second
MW	Megawatts
Nm	Feet/pound
RPM	Revolution per minute

Contents

1.0 Diagram

The relationships among the objects are shown in the following diagram.



2.0 Objects

These objects encompass both the tangible elements of hydropower plants, including details like location and dimensions, as well as the intangible components such as service logs and control modules.

2.1 Supportive objects

Supportive objects include the address object, role object, person object, and image object.

2.1.1 Address object

Address objects serve as representations of the location information for the related entities and can establish associations with multiple person-objects and hydropower plant objects.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	Office/Dam	
Street	Street number, street name	Yes
City	City of the location of the associated object.	Yes
State/Province	State/province of the location of the associated object.	Yes
Zip code	Zip code of the location of the associated object.	Yes
Country	Country of the location of the associated object.	Yes
Website	Website of the associated object.	
Phone	The phone number of the associated object.	
Fax	The fax number of the associated object.	

2.1.2 Role object

Role objects group together one or more privileges that can be assigned to users, for example, manager, technician, operators, and so on,

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	Name of the roles.	Yes
Description	Describing the privileges and duties of the role.	

2.1.3 Person object

Person objects represent the personal information of the managers, operators, technicians, and so on for the associated hydropower plants.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
First Name	The first name of the associated person.	Yes
Last Name	The last name of the associated person.	Yes
Role Id		Yes
Email	The email address of the associated person.	
Employee Id	The employee ID of the associated person.	
Work Phone	The work phone of the associated person.	

2.1.4 Image object

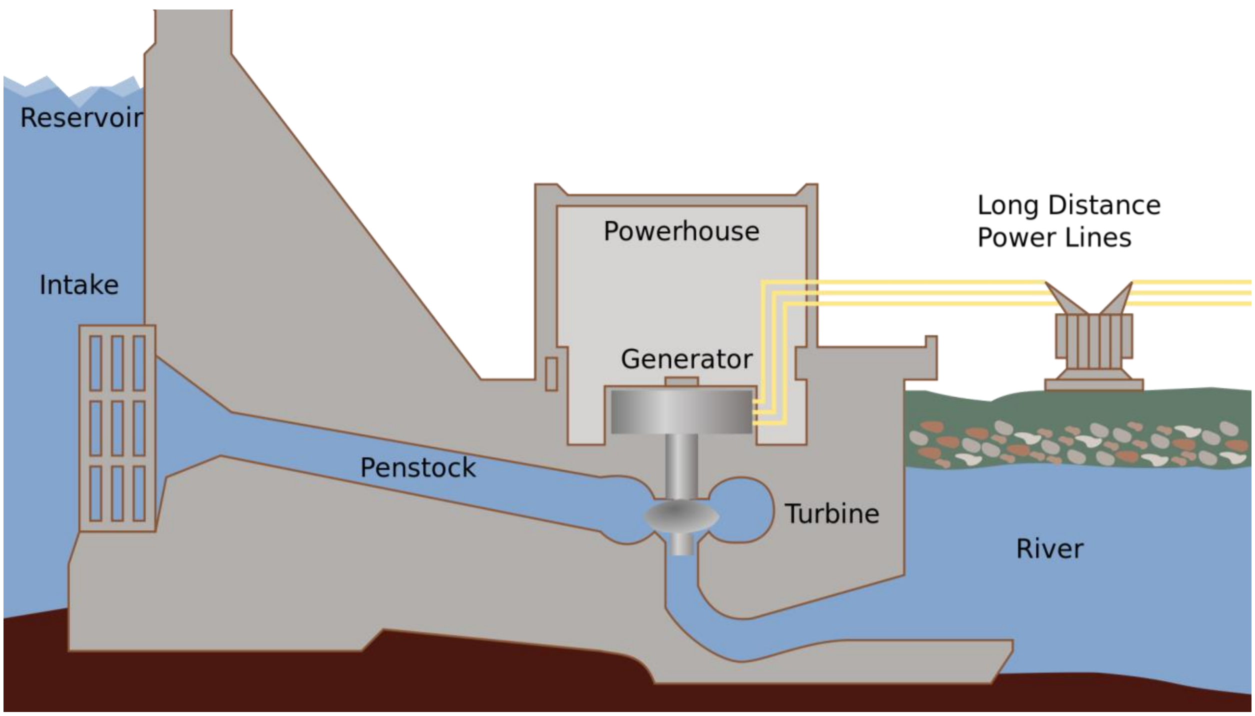
Image objects represent the images of the associated components of the hydropower plants. The image can be in the format of either 2D or 3D. If it is a 2D image, the width, height, and DPI would be required.

Attribute	Note	Required

Unique Id	Prefer to be a GUID.	Yes
Name	The name of the image. Can be the image file name.	Yes
Type	2D/3D	Yes
URL	Location of the 2D/3D image.	Yes
Width	Only applicable to 2D images.	
Height	Only applicable to 2D images.	
DPI	Only applicable to 2D images.	
Description	Describe the image information.	

2.2 Core objects

Core objects include the hydropower plant object and element object.



2.2.1 Digital twin for hydropower system object

The digital twin objects represent the digital twin of all the physical plants.

Attribute	Note	Required

Unique Id	Prefer to be a GUID.	Yes
Power plant Id	Foreign key of the power plant dam object	Yes
Creation date	The data of the creation of the digital twin	Yes
Description		

2.2.2 Power Plant Dam object

The power plant dam objects represent the information of the physical dams. Each dam should have only one power plant, and each hydropower plant should have at least one unit, a reservoir, intake, penstock, generator, turbine, and so on.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the dam, such as Alder Dam.	Yes
Structure type	Arch, Gravity, Arch-gravity, Barrages, Embankment, or Fixed-crest	
Size Type	Large, small, or Non-jurisdictional	
Usage type	Saddle, Weir, Check, Dry, Diversionary, Underground, or Tailings	
Material type	Steel, Timber, or other	
License expiration date	The expiration date of the current license	
Starting Latitude	The latitude of one side of the dam	Yes
Starting Longitude	The longitude of one side of the dam	Yes
Ending Latitude	The latitude of the other side of the dam	Yes
Ending Longitude	The longitude of the other side of the dam	Yes
Built Date Time	The date time when the power plant was built	Yes

Start Serving Date Time	The date time when the power plant started serving	Yes
Number of Units	The number of installed units of the associated hydropower plant.	Yes
Installed Capacity	The installed capacity of the associated hydropower plant.	Yes
Height	The height of the associated hydropower plant.	Yes
Length	The length of the associated hydropower plant.	Yes
Normal Elevation	The normal elevation of the associated hydropower plant.	Yes
Surface Area	The surface area of the associated hydropower plant.	Yes
Address Id	Foreign key of Address object	Yes
Id of Person of Contact	Foreign key of the Person's object	Yes

2.2.3 Element object

Element objects represent all physical and virtual components of the hydropower plants.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Power plant dam Id	Foreign key of the Power plant dam object	Yes
Parent Id	The ID of the component to which this element belongs to	
Id of Image	Foreign key of the Image object	Yes
X scale of the image	0.0 ~ 1.0	Yes
Y scale of the image	0.0 ~ 1.0	Yes
Z scale of the image	0.0 ~ 1.0	Yes
X screen position in percentage	The starting X position in percentage on the screen	Yes
Y screen position in percentage	The starting Y position in percentage on the screen	Yes

Z index	The layer on Z direction.	Yes
Type of 3D Modeling	Box modeling, Contour/Edge modeling, Spline/NURBS modeling, Subdivision modeling, Digital sculpting, Modular modeling, Kitbashing, Photogrammetry, Procedural modeling, Image-based modeling, Surface modeling, Boolean-modeling, Laser scanning	
Tool to open	Tools used to open/display the 3D image/file	
Viewpoint X	The initial display location of the 3D image/file in X direction	
Viewpoint Y	The initial display location of the 3D image/file in the Y direction	
Viewpoint Z	The initial display location of the 3D image/file in Z direction	
Angle X	The initial display angle of the 3D image/file in the X direction	
Angle Y	The initial display angle of the 3D image/file in the Y direction	
Angle Z	The initial display angle of the 3D image/file in Z direction	

2.3 Physical objects

Physical objects include all physical and virtual objects related to the hydropower plants.

2.3.1 Reservoir object

Reservoir objects represent the reservoir component of the hydropower plants.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the reservoir.	Yes
Element Id	Foreign key of the Element object	Yes

Type	The type of reservoir, such as valley-dammed, bank-side, and service reservoirs.	
Volume	The volume of the reservoir.	
Surface area	The surface area of the reservoir.	

2.3.2 Intake object

The intake objects represent the intake component of the hydropower plants.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the intake.	Yes
Element Id	Foreign key of the Element object	Yes
Type	The type of intake.	

2.3.3 Penstock object

The penstock objects represent the penstock component of the hydropower plants.

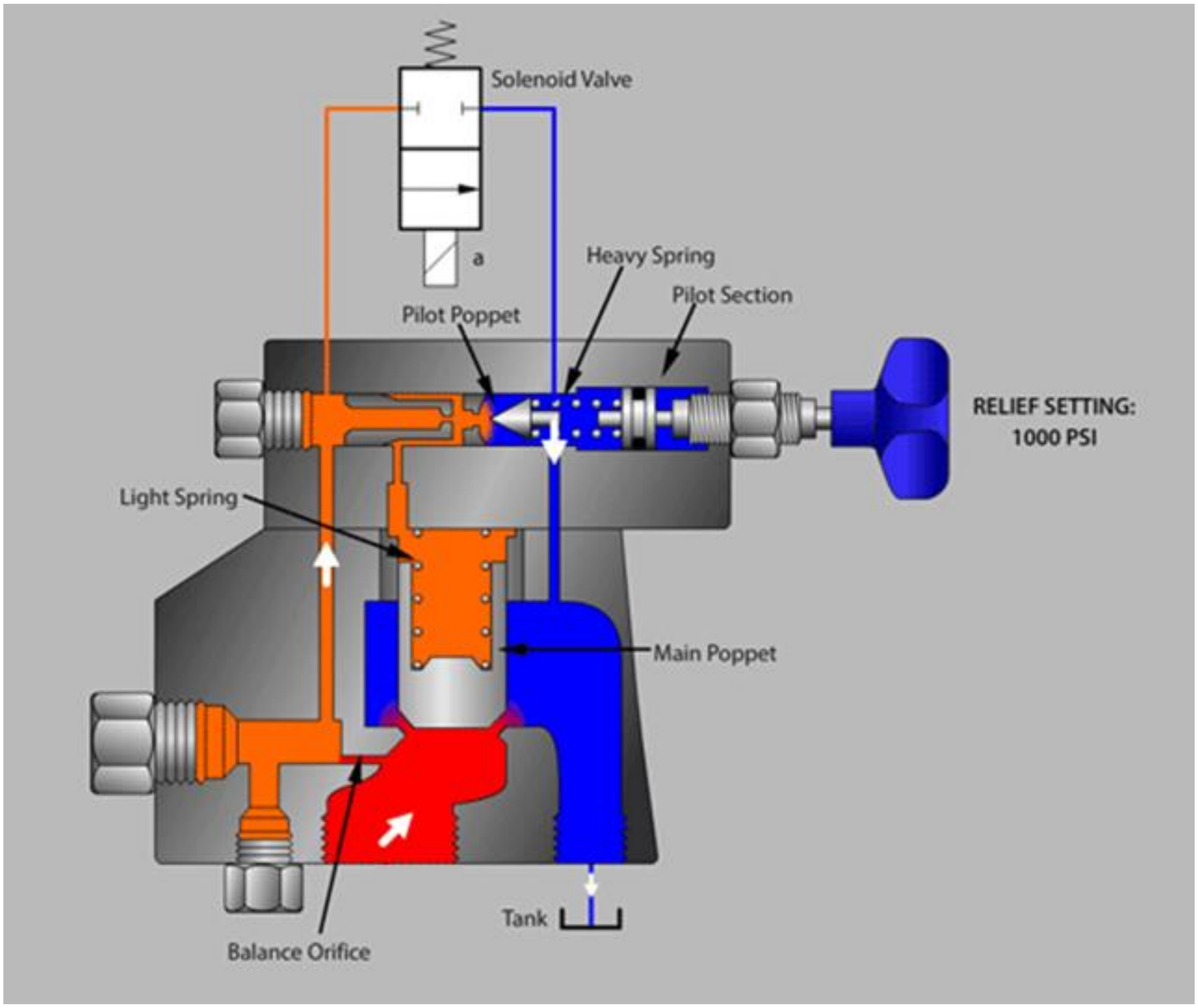
Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the penstock.	Yes
Element Id	Foreign key of the Element object	Yes
Type	The type of penstock.	Yes

2.3.4 Power Plant Unit object

The power plant unit objects represent the installed units of the hydropower plants.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the hydropower plant unit.	Yes
Element Id	Foreign key of the Element object	Yes
Display Parameters:		

Real-time power generated	*MW*	
Real-time speed	*RPM*	
Real-time temperature	*Fahrenheit*	
Real-time flow	*KCFS*	
Real-time head	*Feet*	
Real-time atmospheric pressure	*kPa*	
Real-time Wicket gate opening percentage	*%*	
Real-time voltage	*Volts*	
Real-time Generator Torque	*Nm*	



2.3.5 Governor object

The governor objects represent the governor components of the hydropower plant units.

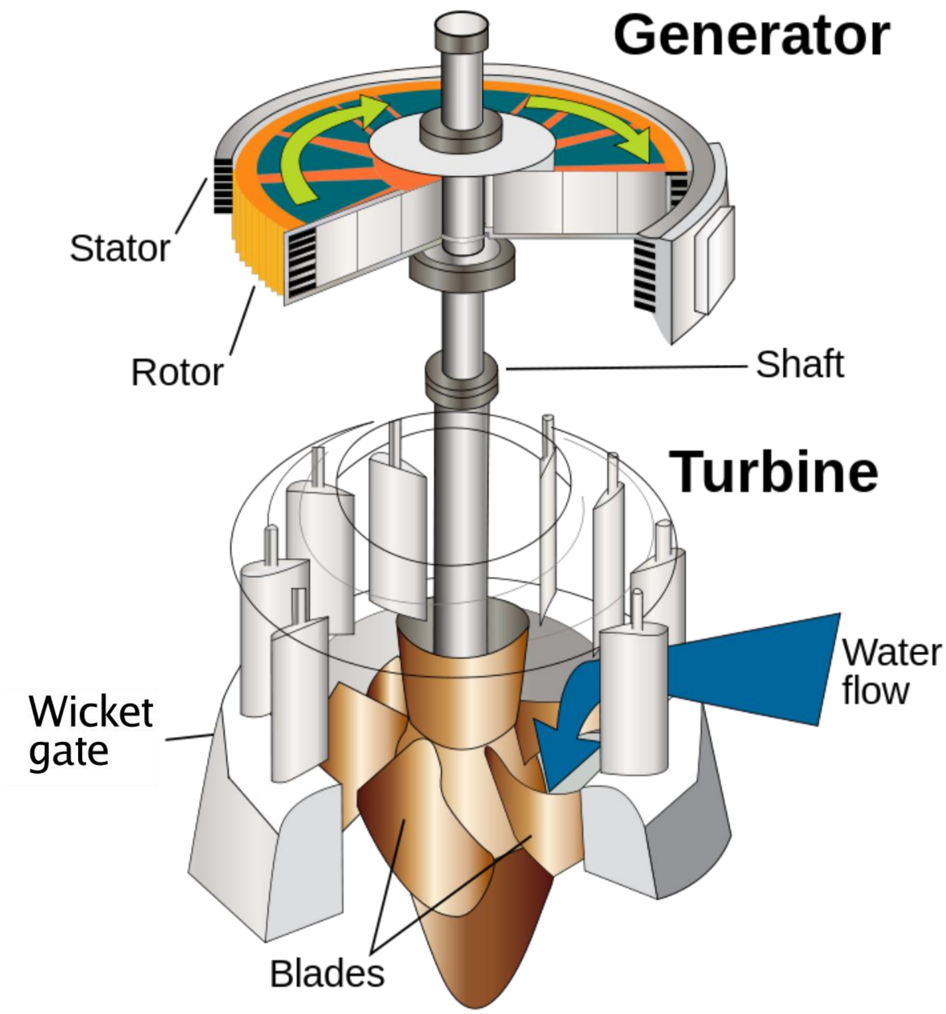
Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the governor.	Yes
Element Id	Foreign key of the Element object	Yes
	Parameters:	
Distance – vertical	*mm*	
Flow	*KCFS*	

Frequency	*Hertz*	
Position (relative)	*degrees*	
Pressure	*Pascals*	
Speed	*RPM*	
Temperature	*Fahrenheit*	

2.3.6 Excitation object

The excitation objects represent the excitation component of the hydropower plant units.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the excitation.	Yes
Element Id	Foreign key of the Element object	Yes
	Parameters:	
Vibration – Magnitude of displacement	*Mils (thousandths of an inch)*	



2.3.7 Generator object

The generator objects represent the generator component of the hydropower plant units.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the generator.	Yes
Element Id	Foreign key of the Element object	Yes
	Parameters:	
Air gap	*mm*	

Current	*amps*	
Distance – vertical	*mm*	
Flow	*KCFS*	
Flux	*Gaus*	
Frequency	*Hertz*	
Position (relative)	*degrees*	
Pressure	*Pascals*	
Reactive Power	*MW*	
Real Power	*MW*	
Temperature	*Fahrenheit*	
Vibration – Magnitude of displacement	*Mils*	
Vibration – Velocity	*m/s*	
Voltage	*Volts*	
Generator Torque	*Nm*	

2.3.8 Thrust Bearing object

The thrust-bearing objects represent the thrust-bearing components of the hydropower plant units.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the thrust-bearing.	Yes
Element Id	Foreign key of the Element object	Yes
	Parameters:	
Distance – vertical	*mm*	
Flow	*KCFS*	
Pressure	*Pascals*	

Temperature	*Fahrenheit*	
Vibration – Magnitude of displacement	*Mils*	

2.3.9 Turbine object

The turbine objects represent the turbines of the hydropower plant units.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the turbine.	Yes
Element Id	Foreign key of the Element object	Yes
Type	Kaplan/Francis, etc.	Yes
Capacity	The capacity of the turbine.	Yes
Parameters:		
Cavitation	*None*	
Distance – vertical	*mm*	
Flow	*KCFS*	
Position (relative)	*degrees*	
Pressure	*Pascals*	
Temperature	*Fahrenheit*	
Vibration – Magnitude of displacement	*Mils*	

2.3.10 Draft tube object

The draft tube objects represent the draft tubes of the connected turbines.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the draft tube.	Yes
Element Id	Foreign key of the Element object	Yes
Type	Conical draft tube, Simple elbow draft tube, Moody spreading draft tube, and	

	Elbow draft tube with a varying cross-section.	
	Parameters:	
Flow	*KCFS*	
Pressure	*Pascals*	
Temperature	*Fahrenheit*	

2.3.11 Tailrace object

The tailrace objects represent the tailrace of the hydropower plant unit.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the tailrace.	Yes
Element Id	Foreign key of the Element object	Yes
	Parameters:	
Elevation	*feet*	
Flow	*KCFS*	
Temperature	*Fahrenheit*	

2.3.12 Transformer object

The transfer objects represent the transformers of the hydropower plant unit.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the transformer.	Yes
Element Id	Foreign key of the Element object	Yes
	Parameters:	
Distance – vertical	*mm*	
Flow	*KCFS*	

Frequency	*Hertz*	
Position (relative)	*degrees*	
Pressure	*Pascals*	
Speed	*RPM*	
Temperature	*Fahrenheit*	

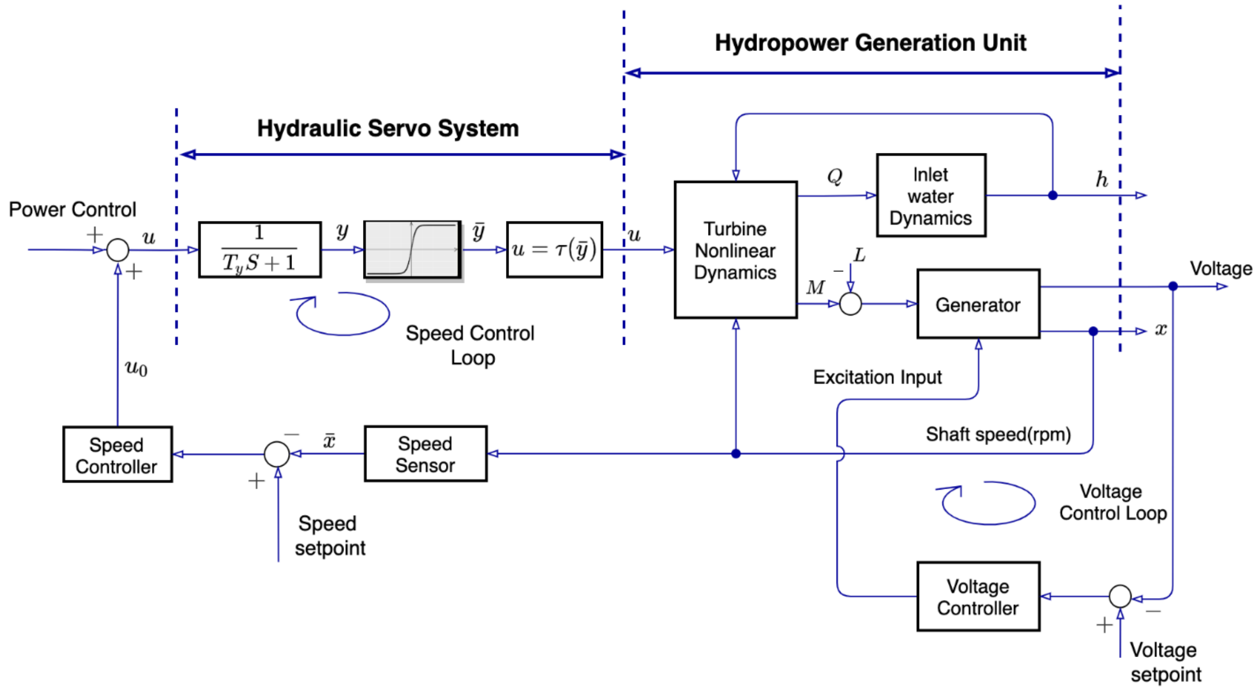
2.4 Virtual objects

Virtual objects include all virtual objects related to the hydropower plants.

2.4.1 Service object

The service objects represent the service/maintenance log of the hydropower plant units.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Title	The title of the service.	Yes
Service starting Date	The starting date of the service.	Yes
Service ending Date	The ending date of the service.	
Description	The description of the service.	
Comments	The notes of the service.	
Service person Ids	The person ID is the foreign key of the person object. The person IDs and service IDs can be stored in a separate table/object.	
Element Id	Foreign key of the Element object	Yes



2.4.2 Source_Code object

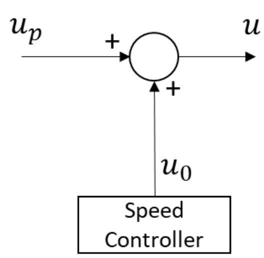
The source code objects represent the source code information for each control module.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the source code.	Yes
Programming Language	The programming language used to develop the source code.	
Programming Language Version	The version of the programming language used to develop the source code.	
Code	The source code.	
Source Code Version	The version of the source code.	
Execution Order	The sequence number to execute the source code.	
Comments	The notes of the source code.	

2.4.3 Control_Module object

The control module object contains modules of simulations, such as a closed-loop Hydropower Turbine Speed Control System.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the control module.	Yes
Description	The description of the control module.	
Element Id	Foreign key of the Element object	Yes
Source Code Id	Foreign key of Source Code object	

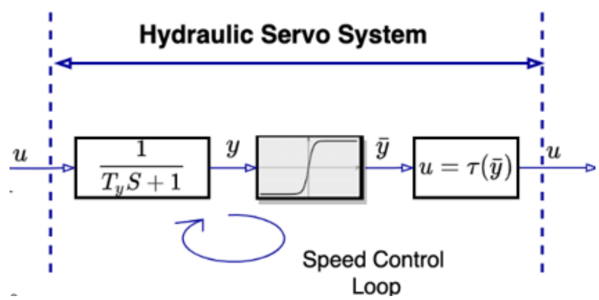


2.4.4 Turbine_Speed_Power_Control_Modular object

Take the guided vane opening for inlet water which is generated based on the opening variable from the speed controller and the setpoint of active power for the power flow control to the grid to generate the output for the Hydraulic Servo System.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the modular.	Yes
Control Module Id	Foreign key of Control Module object	Yes
Element Id	Foreign key of the Element object	Yes

Inputs		
u_0	*Time-varying variable*	*The output of the speed controller*
u_p	*Time-varying variable*	*The setpoint of active power which reflects the power demand from the grid*
Outputs		
u	*Time-varying variable*	*The setpoint to the hydraulic servo for the guided vane opening*

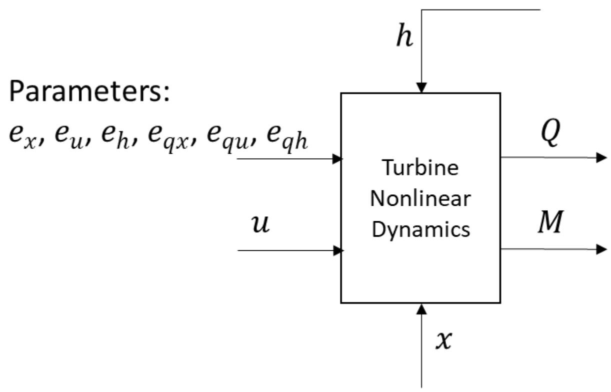


2.4.5 Hydraulic_Servo_Modular object

The Hydraulic Servo System is used to amplify the control signals and provide mechanical power to operate the guided vane opening.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the modular.	Yes
Control Module Id	Foreign key of Control Module object	Yes
Element Id	Foreign key of the Element object	Yes
Inputs		

u	*Time-varying variable*	*The output from turbine speed (frequency) and power controller in-taker. This is also the input to the servo system*
Ty	*Parameter*	*The equivalent time constant of the hydraulic servo system that depends on the specification of the hydraulic servo*
s	*Complex Laplace variable*	
	Outputs	
u	*Time-varying variable*	*The output from turbine speed (frequency) and power controller in-taker. This is also the input to the servo system*

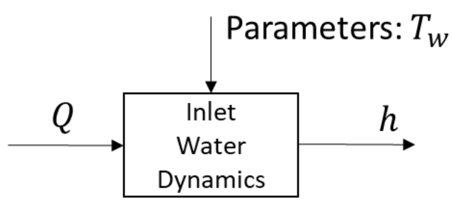


2.4.6 Torque_Water_Flow_Modular object

Take the guided vane opening, the shaft speed, and the water height to generate the output as the turbine torque and water flow rate.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the modular.	Yes
Control Module Id	Foreign key of Control Module object	Yes
Element Id	Foreign key of the Element object	Yes
	Inputs	
u	*Time-varying variable*	*The incremental guided vane opening which is also the output from the hydraulic servo*

h	*Time-varying variable*	*The incremental water pressure*
x	*Time-varying variable*	*The incremental turbine speed*
e_x, e_h, e_u	*Torque parameters*	*Linearized coefficients for the torque generation calculated at a fixed operating point O*
e_{qx}, e_{qh}, e_{qu}	*Water flow parameters*	*Linearized coefficients for the water flow calculated at a fixed operating point O*
$O = \{\omega_0, H_0, Q_0, u_0\}$	*Parameters*	*The definition of a selected and fixed operating point for the hydropower generation unit connected to the grid*
$\omega = 2\pi f$	*Time-varying variable*	*Turbine speed in rad/sed*
f	*Time-varying variable*	*Turbine-generator frequency. This frequency is fixed at 60Hz when the hydropower generation unit is connected to the grid*
Q, H, ω	*Time-varying variables*	*Water flow rate, water head, and turbine speed/frequency. These variables can be calculated using O and the incremental variables, q, h, and x*
	Outputs	
M	*Time-varying variable*	*turbine torque*
Q		*water flow-rate*

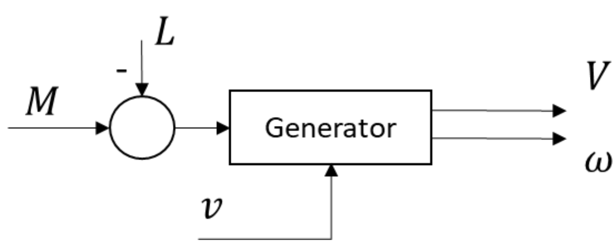


2.4.7 Non_Elasticity_Water_System_Dynamics_Modular object

The low-water head penstock system takes the normalized water head as input and generates outputs as the normalized water flow rate.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of modular.	Yes

Control Module Id	Foreign key of Control Module object	Yes
Element Id	Foreign key of the Element object	Yes
	Inputs	
q	*Time-varying variable*	*The incremental variable for the water flow rate*
Tw	*Parameter*	*The water starting time constant can be calculated using the equations*
	Outputs	
h	*Time-varying variable*	*The incremental variable for water head*

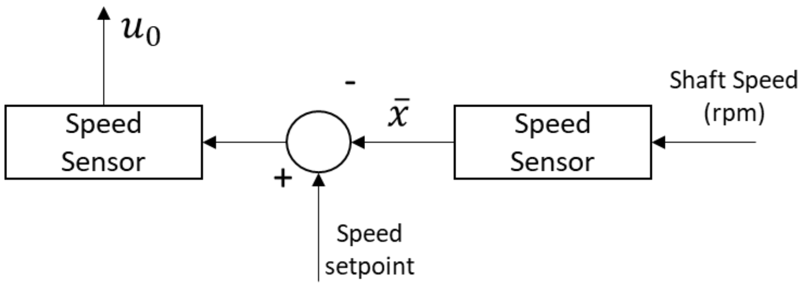


2.4.8 Synchronous_Generator _Dynamics_Modular object

The Synchronous generator modular represents the dynamic relationship between the turbine shaft frequency in rad/s, the torque, and the load (when connected to the grid).

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name	The name of the modular.	Yes
Control Module Id	Foreign key of Control Module object	Yes
Element Id	Foreign key of the Element object	Yes
	Inputs	
M	*Time-varying variable*	*Mechanical torque as a result of water flow to the turbine chamber*
L	*Time-varying variable*	*Equivalent load when connected to the grid*

Outputs		
J	*Parameter*	*Equivalent inertia for all the rotational parts with the shaft of the hydropower generation unit*



2.4.9 Speed_Controller_Modular object

The speed controller modular generates the time-varying variable as the speed controller.

Attribute	Note	Required
Unique Id	Prefer to be a GUID.	Yes
Name		Yes
Control Module Id	Foreign key of Control Module object	Yes
Element Id	Foreign key of the Element object	Yes
Inputs		
e_{speed}	*Time-varying variable*	*The tracking error of the incremental speed control for the incremental shaft speed*
K_p	*Parameter*	*The proportional gain*
K_I	*Parameter*	*The integral gain*
Outputs		
u_0	*Time-varying variable*	*The output of the speed controller*

3.0 References

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