Models for Hydropower Plant: A review

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Abstract

Hydro Power plant (HPP), being one of the most convenient options for power generation, has been modelled considering very wide aspects of their application. A model is simply a mathematical representation of a system and it may serve different purposes like dynamic simulation of hydro power, energy systems modelling involving policy making, condition monitoring, etc. The purpose of modelling HPPs may lead to various kind of models for a single Hydropower. This paper aims at reviewing hydropower models developed using different methods along with the purpose for modelling them. This will provide brief insights about state of the art on hydropower modelling and its emerging techniques. Furthermore, this paper presents in more detail about tracking the advancements in dynamic models for classical and variable speed hydropower plants highlighting the need for the development of more accurate models. The work mainly involves narrative review of published works on hydro power modelling techniques. Also, it includes systematic reviews about dynamic representation of hydropower plants. As this paper aims at presentation of hydro power models in a classified manner based on purpose of modelling, the areas of improvement in each type of model have been discussed. Models for control can be made to be more accurate by including more realistic featured like penstock dynamics, uncertainties, etc which further help in design of advanced control systems. There are several potential benefits of HPP modelling, such as optimizing plant performance, improving control, reducing maintenance costs, and enhancing overall system efficiency and reliability.

Nomenclature:

ANPC	Active Neutral Point Converter
CFD	Computational Fluid Dynamics
DFIC	Doubly Fed Induction Generators
FVM	Finite Volume Method
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Junction Transistor
MPC	Model Predictive Control
MMC	Multi-Level Converters
NPC	Neutral Point Converters
PMSG	Permanent Magnet Synchronous Generator
PSH	Pump Storage Hydropower
RLC	Resistance Inductance Capacitance
RTDR	Rotating Dynamic Response
SFR	Standstill Frequency Response

1 Introduction

Hydropower plants have been proven to be the most sustainable source of energy (Kumari Rupesh *et al.*, 2019; Shahgholian, 2020). Installed capacity of the hydropower all over the world comprises of approximately 20% of the world's electricity sources and 80% of the renewable sources (Shahgholian, 2020). This fact reflects the dire need to make the hydropower plants more efficient, more reliable and more economically viable. For this, more studies and research have to be performed, and more useful tools have to be developed. The primary step to be taken for this is to develop an appropriate model of hydropower systems which addresses the purpose of study.

Development of hydropower models has been carried out for different purpose and have undergone considerable improvement since the 90's. Accordingly, the methods used for modelling also vary to a wide category based on the application of the model. Some of them are developed for planning studies while others are developed for control, transient response, study of dynamics, condition monitoring, etc (de Mello *et al.*, 1992; Kishor, Saini and Singh, 2007; Valavi and Nysveen, 2018a; Liu *et al.*, 2019; Sapkota *et al.*, 2022). A single hydropower has many components starting from water reservoir and flow regions, mechanical rotating parts to the static electric parts in general(Quiroga OD, 2000; Rheinheimer *et al.*, 2023). Moreover, variable speed hydropower plants have converters as the additional elements and pump storage power plants have reversible pump-turbines (Nobile, Sari and Schwery, 2018a). Each component falling under the different disciplines of study aggregate to make

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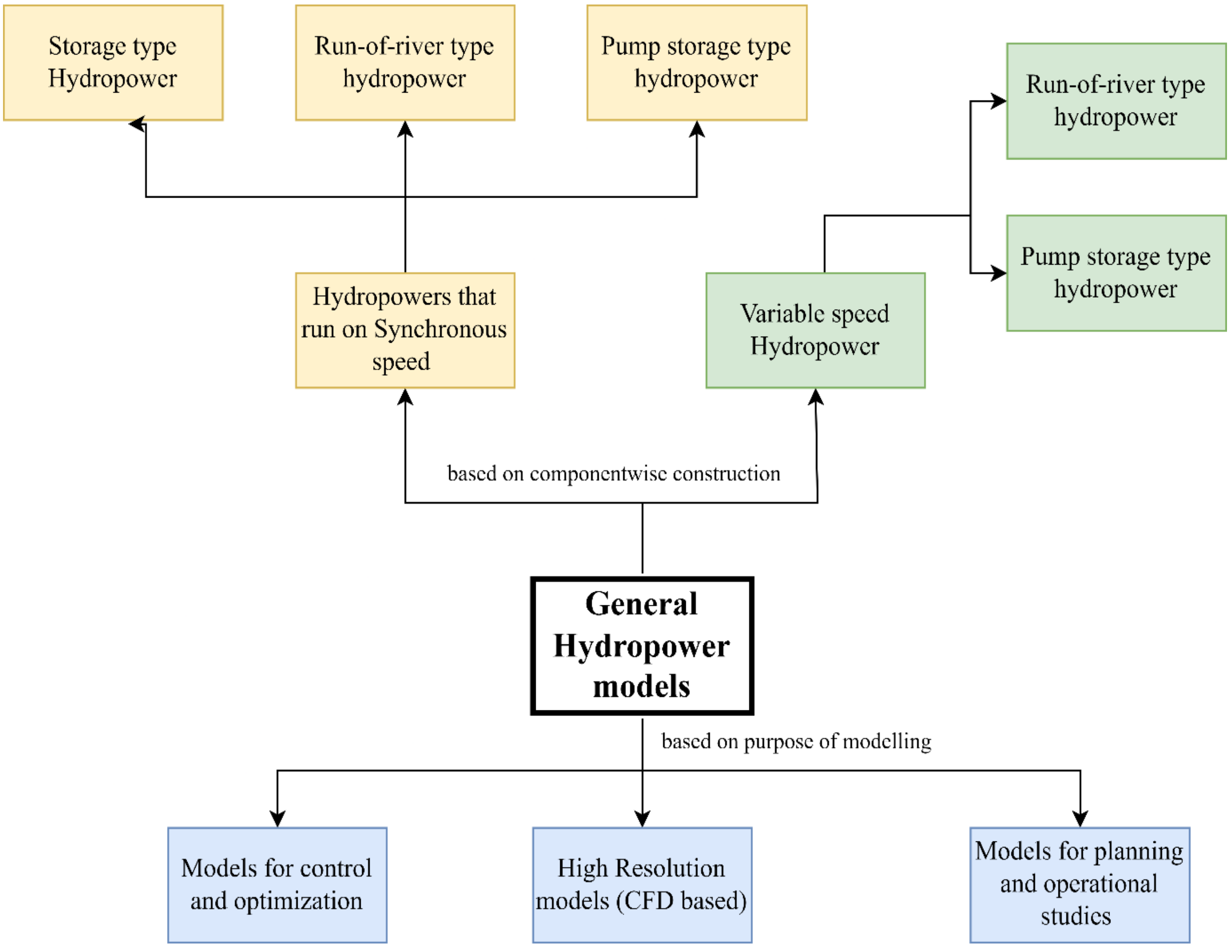


Figure 1 Classification of hydropower models

a whole hydropower system, but most of the modelling has been done focusing the kind of studies involved, making the task of a particular field easier.

A simple classification of the hydropower models is shown in Figure 1. The upper half of the figure shows the classification in terms of the components used. The hydropower plants that run with constant speed and variable speed are differentiated based on the availability of converters or governors for simple understanding. Also, both of these kinds can further be looked as Run of River (RoR), storage or pump storage type. Storage type of hydropower plants are less likely to be operated as variable speed and so, not shown in the classification of (Variable Speed Hydropower) VSHPs(Nobile, Sari and Schwery, 2018b; Valavi and Nysveen, 2018a; T. I. Reigstad and Uhlen, 2020)The lower half of the same figure classifies the available hydropower models based on their purpose of modelling. The models may have different requirements to enable us perform different analysis. For example, models for control and optimization ought to represent the dynamics of the system as accurately as possible, the models associated with planning are less concerned with dynamics and are more concerned with the amount of power produced, its availability, environmental constraints, etc. Computational Fluid Dynamics (CFD) models do not usually deal with other dynamics of the hydropower system as a whole but look at the fluid dynamics and its details for different components like turbines, guide vanes, etc. Models made for condition monitoring are concerned with the sensor data and its analysis (Z. Wenjing, 2017; Liu *et al.*, 2019; Tor Inge Reigstad and Uhlen, 2020a; Kerdphol *et al.*, 2021; Reigstad and Uhlen, 2021; Kincic *et al.*, 2022; Sapkota *et al.*, 2022)

This paper attempts to present a brief review of the hydropower models found widely in the literature by classifying them into three major categories which are (i) Models for Control and Optimization, (ii) High Resolution models (CFD models) and (iii) Models for planning and Operational studies. Although we may derive specific sub-categories even under these three major categories and critically review each of them, this paper is aimed at studying the 'Models for control and Optimization' in detail and will present only a brief overview and major modelling gap for the other two.

2 General Overview

In representing a hydropower system, the physical phenomenon behind the working of each component of a hydropower is necessary to understand. Firstly, the major components present in a hydropower which show the approximate path for the flow of power and energy conversion units like turbine and generator is discussed. Figure 3 shows a block diagram representation of a hydropower plant, trying to highlight differences in the major components present in a VSHP and a normal power plant. The governing principles for each component is briefly discussed in this section.

- Upstream flow region (conduits and reservoirs): The first component in a hydropower model is upstream water flow region which connects the water flow from reservoir outlet to the surge tank (a kind of reservoir). This consists of pipes and reservoirs which are modelled based on different conservation principles in physics. Equations for mass and momentum conservation describe the flows in conduits, dynamic equilibrium requires the satisfaction of Newton's second law of motion and the condition of continuity requires that the available space inside a conduit be occupied by water at all times (de Mello *et al.*, 1992; Alexandra and Tenorio, 2010).
- Penstock: Penstock involves basic phenomenon of momentum balance and the mass is considered constant in a closed conduit like penstock. Also, penstock modelling is associated with water pressure balance due to gate closing and opening action(de Mello *et al.*, 1992; K. Nabd and A. Jesus Fraile, 2017).
- Turbine: Hydraulic turbines derive mechanical power from the force exerted by water as it falls from an altitude. May it be impulse or reaction turbines, the mechanical power developed by the turbine is usually dependent on the flow rate, head and the efficiency and is modelled based on law of conservation of energy in general(P. Kundur, 2009).
- Generator: Generator used in hydropower plants has two parts namely: stator (the stationary part) and rotor (the rotating part). The stator is generally represented using Park transformation which gives the equations for d-axis and q-axis parameters. And the rotor is represented using a second order differential equation known as Swing equation which relates the Power output from the generator with the rotation(P. Kundur, 2009).
- Converter: These are used in Variable speed Power plants and are modelled using power electronic components like Thyristor or IGBT with controlled switching. The control unit in switching action is designed to maintain the power output from VSHPs to have same frequency as the grid (Tiwari, Nilsen and Mo, 2021). These have been undergoing refinement for better performance lately.
- Governor: Governors for hydropower plants work on two basic principles, namely mechanical hydraulic action or electronic action. Mechanical hydraulic governors work by displacing the fluid and moving the piston and electronic governors generally work on PID control action. The governing mechanism of hydropower is evolving towards robust control strategies using adaptive and predictive control algorithms(Li and Zhou, 2011; Guo and Yang, 2018).

3 Research review

3.1 Models for Control and Optimization

Modelling the power plant for dynamic studies have been carried since many decades and has still been undergoing improvement. The following two sub-groups categorize the hydropower models available based on their speed.

3.1.1 Hydropower's that run on synchronous speed

A work by 'IEEE working group on Prime mover and energy supply models for system dynamic performance studies' in 1992 marks the framework for hydraulic turbine and its control models are practised until now (de Mello *et al.*, 1992). Authors in this work have developed a non-linear turbine model assuming a non-elastic water column in penstock which is linearized about an operating point later on. The effect of friction losses is also included in this representation. The linearized models are claimed to be useful in the studies of control system using linear analysis tools like frequency response, eigenvalue, etc. however, the non-linear models are required for large disturbance studies and large transients.

This is the baseline for the models working with prime movers including water supply conduit and prime mover speed controls. Figure 2 shows the general relationship among mechanically rotating parts and the water flow channels of a hydropower plant which controls the dynamics of a hydropower plant. Many recent graduate and doctoral thesis works have used this representation and baseline and proposed further improvements in the models (Alexandra and Tenorio, 2010; Splavska, 2017a; Z. Wenjing, 2017; Reigstad Tor Inge, 2021).

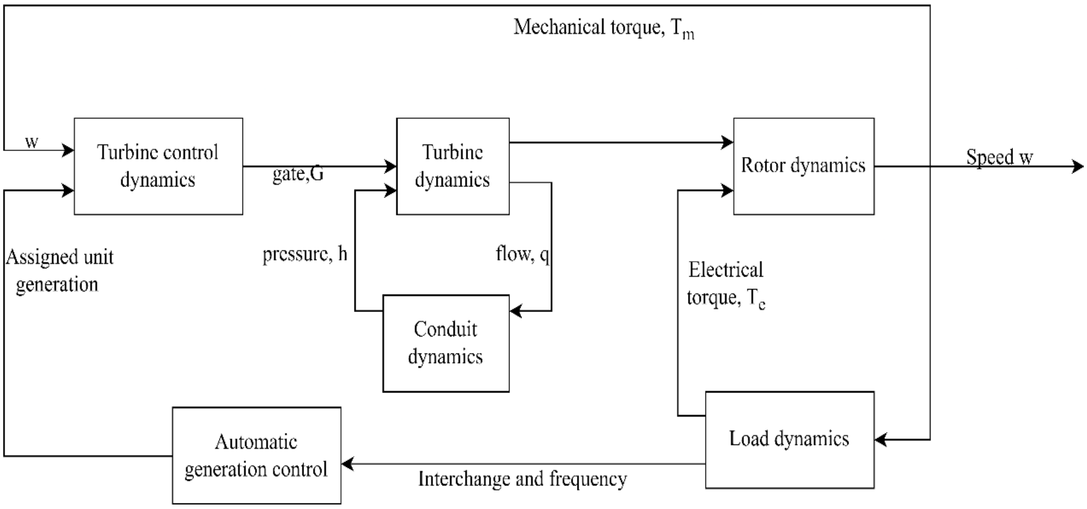
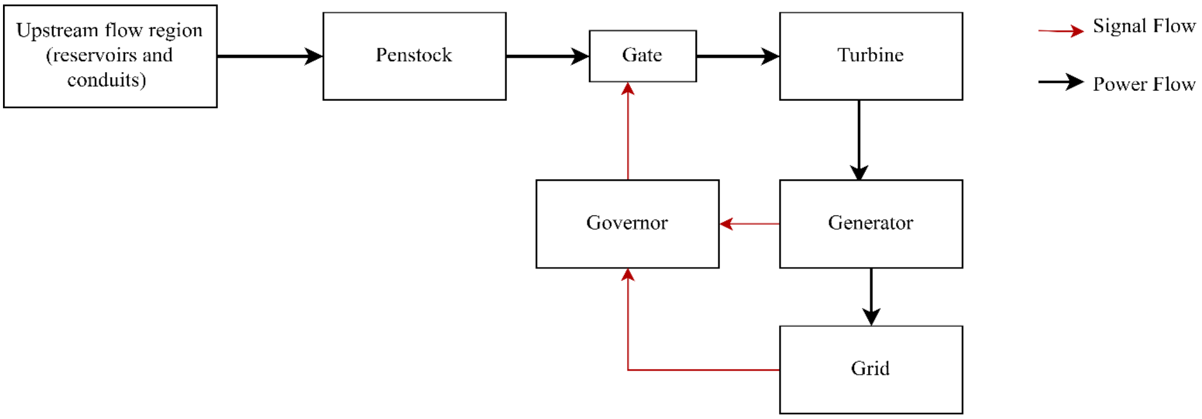


Figure 2 Block diagram representation of hydro-prime mover system and controls(de Mello *et al.*, 1992)

The earlier models were considered adequate for typical first swing stability simulations, but more issues like longer transient stability problems simulation, low frequency oscillations, islanded operation, load rejection, system restoration, water hammer dynamics, pump storage generation with complex hydraulic structures, etc. had to be addressed with the wide practise of using hydropower (de Mello *et al.*, 1992; Fang *et al.*, 2008; Acakpovi, Hagan and Fifatin, 2014; Yang *et al.*, 2015; Guo and Yang, 2018; Rheinheimer *et al.*, 2023).

For the case with long penstocks, the pressure differences and water compressibility generate significant dynamic behaviour which must be taken into modelling consideration. The water pressure is assumed to be analogous to sound waves propagation in water and the wave propagation principle is used to model the long penstocks in (de Mello *et al.*, 1992) which is termed as method of characteristic modelling in (Alexandra and Tenorio, 2010). This wave propagation model introduces a tan hyperbolic function to represent the water hammer effect in the long penstocks. This makes the functioning of the penstock non-linear. Also, the authors in (Alexandra and Tenorio, 2010) use two more methods to model the penstock, namely: Finite volume method (FVM) and electrical circuit equivalent method. FVM is associated with discretizing the main governing equations making it representable in suitable PDEs form to apply Model predictive control (MPC) algorithms. Electrical circuit equivalent method says that the flow of water is analogous to flow of current in a RLC circuit. The pressure flow is assumed analogous to travelling waves in transmission lines and the equivalent R, L and C values are derived based on penstock parameters. Most of the research until now use these methods to model the water hammering in penstocks while studying the dynamic behaviour of hydropower (P. Kundur, 2009; H. Ardul Munoz, M. Petrous and J. Dewi Ieuan, 2013; Li *et al.*, 2016; K. Nabd and A. Jesus Fraile, 2017; Guo and Yang, 2018; Cassano *et al.*, 2021; Reigstad Tor Inge, 2021; Zhang *et al.*, 2022). Also, multiple penstocks supplied from a common water column are modelled just based on the flow in the upper manifold to be equal to the flow in each penstock and the governing principles remain the same (de Mello *et al.*, 1992; H. Ardul Munoz, M. Petrous and J. Dewi Ieuan, 2013). Based on water hammer consideration in penstock modelling as described in (de Mello *et al.*, 1992; P. Kundur, 2009; H. Ardul Munoz, M. Petrous and J. Dewi Ieuan, 2013; K. Nabd and A. Jesus Fraile, 2017; Cassano *et al.*, 2021; Zhang *et al.*, 2022), the hydropower models are classified as the ones with 'elastic water column models' and 'inelastic water column models' which have significant differences in dynamic the response of hydropower plants.

One more significant component in the upstream flow region is the surge tank which is proven to be of utmost importance while studying the dynamic behaviour of hydropower plants. This is why the presence or absence of surge tank brings huge difference in planning the control of hydropower plant (P. Kundur, 2009; H. Ardul Munoz, M. Petrous and J. Dewi Ieuan, 2013). The surge tank model is derived from the continuity of flow at the two junctions which can further consider pressure balance, mass balance, momentum balance and forces acting on the surge tank(Alexandra and Tenorio, 2010; Pandey and Lie, 2021; Reigstad Tor Inge, 2021; Pandey *et al.*, 2022). Time domain models and s-domain models of surge tanks are in wide practice for the models used for control. (de Mello *et al.*, 1992; Fang *et al.*, 2008; Alexandra and Tenorio, 2010; H. Ardul Munoz, M. Petrous and J. Dewi Ieuan, 2013) present the s-domain model of surge tank which approximates the storage constant of surge tank and predict the dampening of water hammer in the penstock while the authors in(Splavska, 2017a; Pandey and Lie, 2021; Pandey *et al.*, 2022) present time domain model of the



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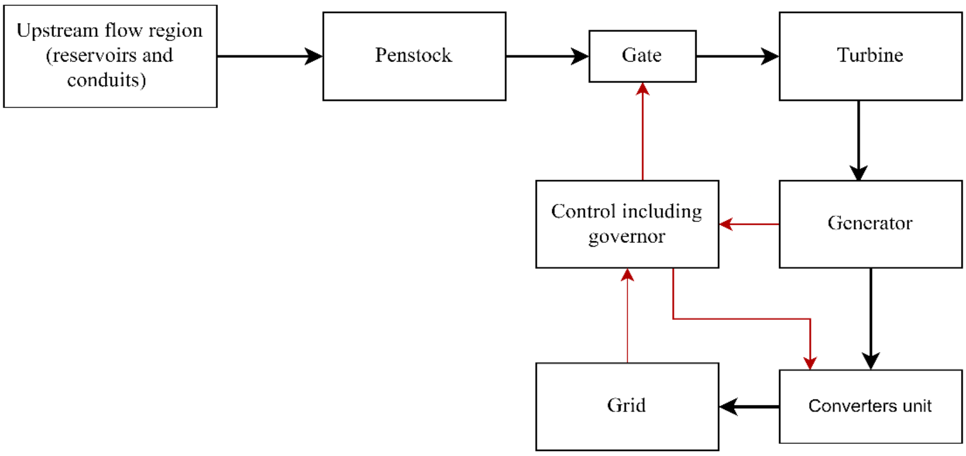

figure b

Figure 3 Block diagram representation of (a) General Hydropower (b) Variable Speed Hydropower

surge tank which is represented as a differential equation. (Pandey and Lie, 2021; Pandey *et al.*, 2022) have developed the models' representation in modellica and is available as open HPL.

Turbine modelling is necessary because the hydraulic turbine dynamics seem to have considerable effect on power system stability. As can be seen form Figure 2 the turbine dynamics have direct influence on rotor dynamics of generator. Authors in(P. Kundur, 2009) talk about grid stability in terms of rotor angle, which directly varies according to the turbine rotation dynamics. The functioning of turbine is non-linear because of the action of water pressure and head on it. The major governing principle behind turbine modelling is the balance of mechanical power represented by the equation

$$P = \eta * \rho * q * g * h$$

where P=Mechanical Power generated, ρ=Water density, Q= discharge, g = acceleration due to gravity and h = head.

Hydro turbines have non-linear performance in reality but are studied by linearizing the mathematical models as well. (Cassano *et al.*, 2021) presents the performance of linearised models of hydropower which implements linearised Francis and Kaplan turbine equations. Linearization based on first order Taylor expansion is claimed to give more tractable alternative to non-linear models and also can be used for model predictive control based on convex optimization.

Authors in (P. Kundur, 2009) derive the transfer function of turbine with certain assumptions which falls under the linearized model type. The non-linear behaviour is carried by the assumption that mechanical power is directly proportional to the square root of the head. Also, authors in the same book define water starting time as the amount of time required for a head to accelerate water in the penstock from standstill to the rated value, which is one of the important factors in turbine dynamic-study. This helps us predict the change in water flow and pressure with respect to unit gate opening. The usage of water starting time is widely found in turbine modelling studies as in (Kishor, Singh and Raghuvanshi, 2007; Alexandra and Tenorio, 2010; Zhou, Lie and Glemmstad, 2011; Yang *et al.*, 2015;

Li *et al.*, 2016; K. Nabd and A. Jesus Fraile, 2017; Guo and Yang, 2018; Reigstad Tor Inge, 2021). Furthermore, (de Mello *et al.*, 1992) is one of the earliest literature making the baseline for modern turbine dynamic models which starts with non-linear modelling and ends with the linearized turbine models about an operating point assuming both elastic and inelastic water columns. This concept has been studied until today (Kishor, Saini and Singh, 2007; Acakpovi, Hagan and Fifatin, 2014; K. Nabd and A. Jesus Fraile, 2017; Cassano *et al.*, 2021; Gao *et al.*, 2021). The non-linear models of turbine are further represented in the form of ordinary or partial differential equations which make it easier to implement the modern control methods. Linearized turbine models are seen as a set of six partial differential equations(Z. Wenjing, 2017) while non-linear turbines are modelled using Euler's equations. (Nielsen, 2015; Splavska, 2017b; Reigstad Tor Inge, 2021). Also, some authors model turbine as simple non-linear function in the form of analytic expression as a function of wicket gate, water head and speed (Li and Zhou, 2011; Li *et al.*, 2016).

The generators used in hydropower are synchronous generators. The modelling of synchronous machines has been worked on and undergone considerate degree of improvement back in 1920s and 1930s itself (P. Kundur, 2009). It is modelled using Park's transformation to represent voltage equations in the form of d-axis and q-axis parameters. Then comes the rotor swing equation which relates electrical power and rotor swing (P. Kundur, 2009; H. Ardul Munoz, M. Petrous and J. Dewi Ieuan, 2013; Guo and Yang, 2018; Brezovec, Kuzle and Krpan, 2022). Generator models are more widely used in transient stability studies for power system to test the system's robustness against electrical and mechanical faults(P. W. Sauer and M. A. Pai, 2006; HM Gibson *et al.*, 2019; Brezovec, Kuzle and Krpan, 2022). Furthermore, standstill frequency response (SFR) and rotating dynamic response (RTDR) are two methods currently used to derive the generator parameters. These provide further flexibility and enables to handle the non-linearities with less computational burden(Fonseka, de Silva and Dong, 2021). Also, some generators used in VSHPs are permanent magnet synchronous generators (PMSG) which requires the representation of stator equations in dq form (Gao *et al.*, 2021).

Despite of wide availability of hydropower models for control and application of numerous control algorithms, there is always a room for improvement. The models implementing robust control, most preferably the ones with time-domain dynamic representation have been worked upon very less. Though some time-domain models for synergetic control studies and state space models of hydropower and (Pump Storage Hydropower) PSH have been explored in (Zhang *et al.*, 2022) and (Dong *et al.*, 2020), transient studies for grid side have been studied more than for the generator side. With the concern for reliable and resilient power system, the control for hydropower must be adequate from all the possible aspects. This demands for more accurate dynamic models and even undertaking probabilistic dynamics as well.

3.1.2 Variable Speed Hydropower (VSHP)

Development of variable speed plants dates back to early 1990s in Japan (Valavi and Nysveen, 2018b). Since then, VSHPs have been undergoing pioneering achievements and becoming popular because of their capability to provide additional ancillary services to the grid apart from power production. Figure 3 represents the major components reflecting the difference between normal hydropower plants and variable speed hydropower plants. VSHP consist of a converter in addition to a normal hydropower component which are either operated as full size or partially when needed. The converters' main task is to fed the power to the grid maintaining constant frequency despite of changing generator speed (Tiwari and Nilsen, 2020; Tiwari, Nilsen and Nysveen, 2020, no date). The turbine is allowed to deviate from its normal rotating speed enabling itself to vary the output power very quickly because of the fast-acting converter technology (Nobile, Sari and Schwery, 2018b). Though popular in pump storage plants because of the ability to control frequency in pumping mode, variable speed plants are not limited to PSH only. They can also be used in HVDC connected hydropower facilities because the frequency of the generator is not tied to the grid and hence the operation of plant can be optimized by adjusting rotational speed (Camacho, 1997). Furthermore, small hydropower with considerable head and flow variations can benefit implementing variable speed operation as maintenance of high efficiency is possible (Borkowski and Majdak, 2020).

The turbine is modelled using Euler's turbine equations which have considered rotational speed along with guide vane opening to find the torque and flow in (Nielsen, 2015). A one-dimensional numerical model of Francis turbine tuned with test data for VSHP operation is presented in (Nag and Lee, 2018). With the consideration of turbine side only and utilizing the water column and reservoirs models previously presented, author in (T. I. Reigstad and Uhlen, 2020) has compared four different hydraulic models namely: Hygov model, IEEE model, Euler's model and Linearised model for VSHP operation. The paper discusses that when the models are linearised, all four models have a similar performance for governor control however Euler and IEEE models add dynamics to the penstock. This is also stated in other literatures (P.

W. Sauer and M. A. Pai, 2006; P. Kundur, 2009; Nielsen, 2015). A simple turbine model does not consider the relationship of turbine efficiency with rotational speed, which is crucially important in VSHP turbines. So, Euler's model is considered as most suitable for simulating transients and variation in rotational speed in VSHP which have significant impact in fast frequency response of gird (Nielsen, 2015; Nobile, Sari and Schwery, 2018b; Tor Inge Reigstad and Uhlen, 2020a; Reigstad and Uhlen, 2021). But the interaction of this model with the power system also needs to be studied before considering it to be the most suitable one.

The other major component of VSHP is the converter. Authors in (Tiwari, Nilsen and Nysveen, 2020) and (Tiwari, Nilsen and Nysveen, no date) talk about the converters for variable speed pump storage power plants. Neutral point converters (NPC), multilevel converters (MMC) and full sized active neutral point converters (ANPC) have been in application for both synchronous machines and doubly fed induction machine (DFIC) in pump storage plants (Tiwari, Nilsen and Nysveen, no date; Tiwari, Nilsen and Mo, 2021). ANPC are claimed to have high starting torque which is essential requirement for machine side application in VSHP application but is threatened by the converter losses (Tiwari and Nilsen, 2020). Precise control strategies like hierarchical control and optimization algorithms, model predictive control, stator flux regulatory control, etc. for these converters have been discussed in many literatures such as in (J. Kristansen Noland, J. Hagset and Stavnesli, no date; S. K. Peter *et al.*, 2014; Tor Inge Reigstad and Uhlen, 2020b; Tiwari, Nilsen and Mo, 2021), but the models for coordinated control are still lacking.

Research have been performed to improvise the models for more accurate representation of power plant dynamics both from load side and the turbine side since many decades. Also, the grid side interactions like frequency reserves, ROCOF, transient analysis, etc. have been studied a little, but the uncertainties that might occur during the plant operation, particularly for VSHPs have still been left behind. With the prevailing examples of grid failures because of changing environmental conditions and other known or unknown uncertainties, there is a dire need to develop models which can represent these environmental and other disturbances threatening the grid. The probabilistic disturbances can be modelled and added to the existing models. This enables to come up with the control plans in cases of such unprecedented conditions. For robust control of hydropower plants, the models used for designing these controllers should be able to reflect the effect of uncertainties on the system. Thus, describing the uncertainties during the modelling phase is needed. Furthermore in (Dong *et al.*, 2020) a concept called quaternary PSH which involves bifurcated penstock system is introduced, but description of a coordinated control of multiple hydropower plants operating from a single water channel is not yet available in open literature.

3.2 High Resolution Models (CFD)

Computational Fluid Dynamics (CFD) is used to look at the effect of fluid dynamics on several component of the power plant. The most extensively studied component in CFD analysis is the turbine (Tiwari *et al.*, 2020). Authors in (Lain and Mejia, 2022) claim that physical modelling have gradually been replaced by CFD modelling techniques which are used to study hydro-kinetic along with hydro-dynamic studies. With the increasing popularity of PSH as energy storage elements and a good ancillary service provider for electric grid, CFD simulation of model turbine as a pump has been performed in (Deng *et al.*, 2022) to quantify energy loss and entropy generation. Furthermore, studies about change in guide vane air foil on the flow characteristics of draft tube for improvement of energy recovery, vibrations intensity, stable operation of turbine, design methods of multiphase pumps for hydrodynamic and structural points of view, etc. have been performed widely in the past (Benavides-Morán, Rodríguez-Jaime and Laín, 2022; Niebuhr *et al.*, 2022; Peng *et al.*, 2022).They conclude that the power coefficient is affected by presence of free surface. Similarly, authors in (Lopez Mejia *et al.*, 2021) propose practise guidelines for CFD simulations in turbines studying the performance standard of vertical axis and horizontal axis turbines and those in (Xiong, Deng and Chen, 2021) study about flapping motion in tail edge which is found to present a better stability for turbine. Although it is said that high level high-order models like CFD are not practical in modelling the whole hydropower, a few low order models are studied for the purposes like fault occurrence, estimation of number and geometry of components for hydropower, etc in practice(Li *et al.*, 2021; YoosefDoost and Lubitz, 2021; Saeed *et al.*, 2022). Furthermore, optimization of hydraulics for a Kaplan turbine at different operating conditions is studied in (Benigni *et al.*, 2014) and also the curved paddles in the wheel enhanced generation by 10-20 % is described in (Akinyemi and Liu, 2015).

CFD models mainly deal with component-wise performance in detail rather than looking at the whole hydropower. With the evidence that CFD models are mainly concerned with turbine study, we still find a gap in the study of small details like labyrinth seals study, pressure balance in draft tube for Kaplan turbines, etc.

3.3 *Models for Planning and Operational Studies*

The operation modes of hydropower are widely varying in recent times and so the operating models are pushed toward the boundary. Hydropower models developed for operation and planning studies generally consider nominal water availability only and the environmental constraints like headwater limits variation, average flow variation, etc are not incorporated in the models. This might lead to inaccurate long term and short-term system studies like erroneous transmission flow and response to contingencies. A few gaps in the order of priority have been identified which are listed as follows(Kincic *et al.*, 2022)

- Water availability not properly represented in system models
- Interdependencies among hydro projects and environmental constraints are not properly represented in system models
- Rough zones are not represented in the power system model so generation dispatch in system studies might not be realistic
- Many dynamic models of hydro generation turbines are outdated
- Inaccuracy in frequency response during simulation studies
- Data issues and incorrect parameters values in dynamic models
- Advanced pumped storage models are not widely available

Each of these gaps have been critically analysed and several ways to model the hydropower have been suggested more accurate results. Water availability issue stated above can be addressed by collecting more precise and granular data, representation of constraints within production cost models and capacity expansion models with watershed models. The authors in (Kincic *et al.*, 2022) further state that the base case models also known as power flow models used for power system studies only maximum generated power. However, this might not always be the case as the generation keeps varying with seasonal water variations. Also, authors in the same report come up with the fact the water levels affect the droop and governor response as well which might lead to over representation of turbine-governor response to system frequency events, voltage stability, and transient stability issues. The simulation studies have been done in the HYGOV4 governor dynamic model implemented with a gas turbine which shows that 5-10% variation in head value can significantly affect the dynamic response and frequency recovery of the source.

Water basins have different interdependencies like tailwater and forebay level change rate limits for flood regulation, effect on aquatic ecosystem, water ratio maintenance for cascaded plants which are required to be coupled in software but are not.

Authors in (Dong *et al.*, 2019) talk about problems in reliability because of oscillation phenomena in the hydropower operating in rough zones. The turbine undergoes a mechanism called vortexing which leads to oscillations in power systems, but there is no knowledge of these restricted zones (that lead to oscillations) of operation in power system simulation studies.

Incorrect parameters values in the models also have a huge role in generating inaccurate results for the planning studies. This can lead to the models being too optimistic or too pessimistic. Talking about dynamic performance as stated in (Pereira *et al.*, 2003; Kou *et al.*, 2016; Soni, 2016), the incorrect parameters used for governor-generator modelling has impacts on turbine gain constant and frequency of the system. Turbine gain constant is directly associated with the mechanical power generated by the turbine which is one of the key parameters for grid studies ranging from stability to planning. Furthermore, the same issue with data leads to false frequency nadirs which projects wrong frequency response in the grid (Pereira *et al.*, 2003; Soni, 2016). This is a huge threat to the grid operating stability and for decision making regarding expansion planning, contingency and line flows.

Pump storage hydropower (PSH) plant is already a mature energy storage technology but there still exist gaps in developing advanced PSH models which anticipate the real-time operation on PSH. In many existing software, the pumping mode of a PSH is modelled as motor and generating mode is developed as a hydro-generator but the transition between them is often ignored (Kincic *et al.*, 2022). Models in generating and pumping modes are different and need to take into consideration the water hammer, throttling of the wicket gate for pump starting and shutting down, etc(Nobile, Sari and Schwery, 2018a). Furthermore, adjustable speed PSH can out space conventional PSH which may lead to huge market growth and installation (Valavi and Nysveen, 2018a). User defined models have been developed in (J. Feltes *et al.*, 2013) which try to resolve the above stated issues but these models have not been validated and commercialized. As seen from the models with operation and planning studies, the deterministic approaches for grid resiliency and reliability have been performed both from grid and load side. Moreover, much attention has been given to the load models and market operation strategies. But there is a need to conduct studies from probabilistic approach as well. The unanticipated changes in load or operating conditions of hydropower have not been taken into consideration much.

A simplified brief about the development of hydropower models from the past to the present is shown in Table 1.

Table 1 Hydropower models: chronological brief

Classifications	1992-2010 (Past)	2010-2023(current)	Future Prospects
Models for Control and Optimization	- Basis for hydro-turbine control models for dynamic studies applied until present context - Dynamic models mathematics for transient and control study - Grid support using hydropower - Studies in frequency domain, mainly using classical control methods	-Concept of variable speed hydropower emerged - Intermittency of renewables balancing using hydropower -Importance of grid support using hydropower and pump storage flourished -Dynamic models for transient and control study with increased detail in models -Studies both in s-domain and t-domain along with the application of robust control	- Dynamic models which can represent uncertainties - Models representing multiple hydropower in same channel for control studies
High resolution models (CFD)	- Turbine models for cavitation studies - Physical models gradually replaced by CFD models	- Turbine models covered the area of pump turbines as well - variable speed model components study - Condition monitoring of the components	- Labyrinths seals' study - more insights on variable speed power plants
Models for planning and operational studies	- Nominal steady state operations considered - Less attention on environmental constraints - Electricity market operation strategies	-Consideration of load models -Use of AI for numerical models -Reliability studies -Electricity market deregulation and flexibility	- More focus on probabilistic reliability studies along with the ongoing deterministic

4 Conclusion

This paper presents a surficial picture about the existing hydropower models, linking the commonly seen classification to the classification of models for purpose. The types of models based on purpose of modelling have been stated as: Models for control, models based on CFD and models for operation and planning.

The paper provides more broader overview about models for control which are found to be developed on the basis of principles of physics like mass, continuity and energy balance representing the dynamics of the system associated. Despite of having the same mathematics, way of presenting the models varies as per the requirement. For example: the non-linearity brought about by the water pressure behaviour in the penstock is ignored in some models whereas considered to be important in some other models. Also, the models developed for modern control implementation are found to be more detailed and those involving non-linear optimization are preferred to be developed in time-domain. The dynamic models developed are also popularly used for transient studies. Furthermore, VSHP models also have been developed for control purpose among which PSH models are more popular. The converters implemented in VSHPs have become very popular for their ability to change the output power very fast with the changing speed capability which can improve the frequency response in grid.

Moreover, considerable amount of work has been done in CFD modelling and the models for planning studies. The model developed using CFD re also used for control, but most of its application has been found in the component wise analysis and a single component control rather than coordinated control. Also, models for operating and planning are mostly used to study about the grid impact and environmental impact. The scope extends a bit to economy and the society as well.

With the study of the available models and their application, the major work that can be done immediately is the inclusion of probabilistic analysis of uncertain events in all three fields. Focusing on control, the optimization of performance or operation in the presence of uncertainty can be an interesting field for future research since control system can make the hydropower more capable to support the grid thereby improving the resiliency and reliability of the overall power system.

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