MyHPP Simulator, a didactic tool for transient phenomena in hydroelectric powerplant

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Abstract. A didactic software named "MyHPP Simulator" has been developed for training of collaborators in the operation of hydroelectric power plants. The simulator reproduces transient phenomena of hydraulic machines, hydraulic adductions, mechanical rotating masses, electrical machines, control systems, grid connection and their interactions. The user can take control of the virtual power plant and create events to simulate his own scenario. Various events are available such as units start-up, active and reactive power set point variations, normal, quick or emergency shutdown of the units, electrical short-circuit, voltage or frequency network variations. The consequence of each event can be visualized in real-time through time charts or synoptic diagrams replicating the SCADA interface of the power plants. This didactic tool has been deployed within the Compagnie Ivoirienne d'Electricité (CIE) since 2018. A feedback of the training seminars and related capacity building are presented.

Introduction

Digital twins are a real time digital replica of a physical system. Usually they are used for monitoring, diagnostics and prognostics to optimize the system performance and its operation. However, they can also be considered as a powerful didactic tool since the virtual environment gives access to data not physically available and gives opportunity to the user to assess the impact of any virtual modification on the system. In this training perspective of their collaborators, the Ivorian Electricity Company (CIE) has acquired two simulators of their own hydroelectric power plants (HPP): one equipped with Francis turbines and one equipped with Kaplan turbines. The purpose of these simulators is to reproduce transient phenomena of hydraulic machines, hydraulic adductions, mechanical rotating masses, electrical machines, control systems, grid connection and their interactions. To meet this purpose, Power Vision Engineering Sàrl has developed a didactic software named "MyHPP Simulator" which has been applied to these two HPP.

"MyHPP Simulator" performs real-time simulation based on SIMSEN software hydroelectric models of the power plant. The user can take control of the virtual power plant and create events to simulate his own scenario. Various events are available such as units start-up, active and reactive power set point variations, normal, quick or emergency shutdown of the units, electrical short-circuit, voltage or frequency network variations. The consequence of each event can be visualized in real-time through time charts or synoptic diagrams replicating the SCADA interface of the power plants. Moreover the user can create his own models by changing model parameters to assess their influence on the transient response of the HPP. "MyHPP Simulator" is a powerful didactic tool to i) increase knowledge about physical phenomena which drive the operation of the HPP, ii) to learn and train on the operation sequences of the HPP by simulating and analyzing scenarii which can occur in reality and iii) understand the technical issues of the operation of the HPP.

This paper presents the didactic tool "MyHPP Simulator" configured for the two HPP of the CIE: the Taabo and Ayamé-I power plants with an installed capacity of respectively 230MW for three Francis turbines and 22MW for two Kaplan turbines. First, the detailed hydroelectric modelling of the two power plants and the validation with site measurements are presented. Then, the different functionalities of the software "MyHPP Simulator" are illustrated for different scenarii. Finally, a feedback of the training seminars hold in Ivory Coast since April 2018 and related capacity building is presented. First trainings for Basic and Advanced levels were organized for 9 CIE collaborators to become trainers themselves. Then CIE trainers provided Basic level trainings to more than 300 CIE collaborators and third party companies.

1. MyHPP Simulator software solution

1.1. General Description

MyHPP Simulator is a physically based software solution which emulates the operation and dynamics of a specific hydroelectric power plant during normal, abnormal and emergency conditions. The simulator is a didactic tool to train internally collaborators. With MyHPP Simulator, they will (i) gain confidence and expertise, (ii) improve awareness of operation risks and (iii) increase knowledge and operator skills about hydroelectric transient phenomena. The simulator is based on a duly validated numerical model of the hydroelectric power plant under consideration and simulates in real time the dynamic behaviour of the plant subjected to actions sent by the user.

1.2. A SIMSEN based solution

The simulator is based on numerical models of the hydroelectric power plants which are preliminary built with the SIMSEN simulation software developed by the Ecole Polytechnique Fédérale de Lausanne [1]. This software allows to model the power plant as a whole, including hydraulic, mechanical, electrical and regulation components. Several models are provided with the simulator for different state of the power plant. The simulator allows to manage the different models of the power plants, to simulate them in real time with the SIMSEN simulation core, to modify the state of the power plant during the simulation by applying actions on the model, and to visualize the results of the hydroelectric transients induced by the user's actions. Moreover, from the simulator, the user can open the SIMSEN interface to edit the numerical models of the plants. The SIMSEN software version, supplied with the simulator, allows opening models whose topology cannot be modified by the user. The parameters of the different components of the model can nevertheless be changed for the purpose of a parametric study. This approach allows to build user defined models having the same topology as the native models, but with different set of parameters.

1.3. Control in real time your virtual power plant

MyHPP Simulator simulates in real time, hydroelectric transients of the scheme induced by user actions sent from the user interface. Simulating in real time allows the user to be aware of the time constants of the plant. The simulator is provided with models of the power plant ready to be simulated and configured for different user actions specific to the operation of the hydropower plant. The available user actions are given in *Table **1***.

Table 1: Description of the possible user interactive actions

User Action Category	User Action Type
Start-up of units	Start-up and synchronization Black-start
Normal operation of the plant	Active power setpoint variation of units Voltage variation at the stator of the units equivalent to a reactive power variation Normal shutdown of the units
Plant faults	Quick shutdown of the units Load rejection of units Emergency shutdown of the units Electrical short circuit at the stator of the generator Electrical short circuit
Network events	Grid frequency variation Grid voltage variation Active and reactive power variation of local electrical load Active power setpoint variation of equivalent group modeling islanded grid
Activation of electrical protections	Stator overcurrent, overvoltage, undervoltage Energy feedback Maximum, minimum, frequency

The real-time simulations allow the user to define actions in an interactive way with the simulator and to be aware of the time constants of the scheme. The results can be visualized both with graphs in time and with a "SCADA" type representation. This latter representation allows the user to have a graphical representation of the state of the whole plant with its different components. On each of these graphic components, their status is updated in real time by numerical values.

1.4. Creation of user model

In addition to real time simulations performed with the provided numerical models of the powerplant, MyHPP Simulator allows to create user defined models. These models are created from the models provided with the Simulator. The user can only change parameters of the base model and not its topology which means that no element can be added or removed from the model. The user can make a parametric study by changing model parameters such as:

- Boundary conditions like reservoir elevation, unit power set points;
- Physical and geometric parameters: wave velocity, pipe length and diameter, inertia, power line impedance;
- Regulation structure parameters;
- Maneuvering times of safety devices.

1.5. Overview of the simulator user interface

After selecting a simulator model or a user defined model, a real time simulation can be run and the user can create an event among the actions listed in *Table **1***. Once simulation is running, the main user interface of MyHPP Simulator software is shown in *Figure **1***. From the right panel, the user can apply different actions by clicking on different buttons. The actions are classified into different categories represented by panels that can be hidden or not by clicking on the category name. The modified state of the hydropower plant by the user actions can be viewed on the left panel either with time charts like in *Figure **1*** or with SCADA type diagrams like in *Figure **2***. The arrangement of the time charts is fully configurable by the user whereas the SCADA type diagrams are predefined when the simulator is delivered.

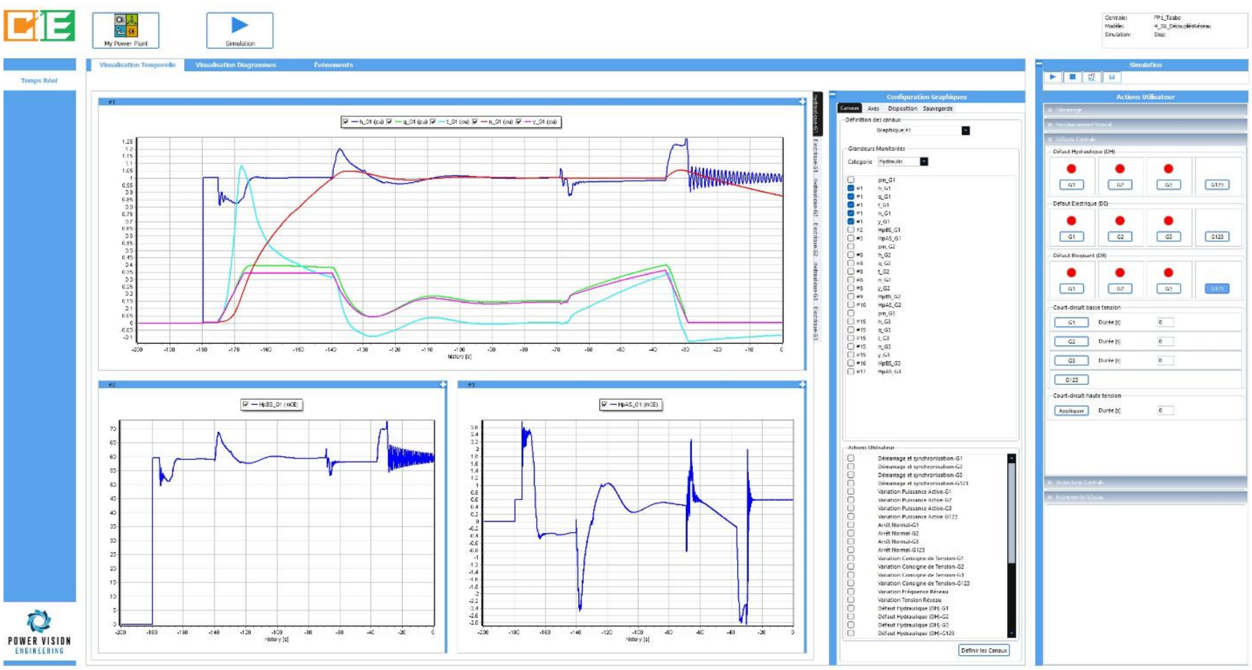


Figure 1: Visualization of hydroelectric transients results with time charts in MyHPP Simulator user interface with turbine parameters time evolution in case of turbine start-up, synchronization, loading and emergency shutdown (with h: net head (blue), q: discharge (green), t: torque (cyan), n: rotational speed (red) and y: guide vane opening (pink) (all in per unit (pu))).

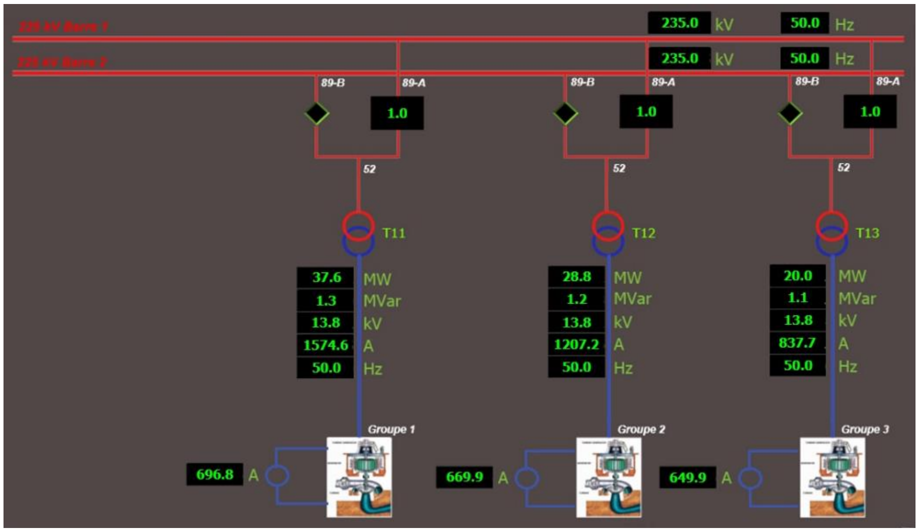


Figure 2: State of the hydroelectric power plant visualized with SCADA synoptic diagrams in MyHPP Simulator user interface.

During the simulation, each user action is inserted in chronological order in an event table which the user can consult from the simulator. Some of the user -actions can be defined as a sequence of sub-actions which are displayed as well in the event table. The display of sub-actions is performed when its state is validated according to the state of the simulation. The *Table **2*** illustrates the sub-actions related to the start-up and synchronization user action.

Table 2: Sequence of sub-actions related to the start-up and synchronization user action

	Sub-action	**State**
1	Open intake valve	Intake valve open
2	Start refrigeration pump	Flow rate detected
3	Apply brakes	Brakes applied
4	Start regulation pump	Isolation valve open
5		Isolation valve open
6		Valve closed
7		Pump pressure present
8	Release the lock	Lock released
9	Release brakes	Brakes released
10	Open guide vanes	Guide vane control engaged
11		Rotational speed >80%
12	Engage the excitation	Excitation engaged
13		Rotational speed >95%
14	Closing the group circuit breaker	Synchronisation in progress
15		Circuit breaker closed

In addition to the user actions and their related sub-actions, alarms are indicated in the event table if electrical protections are raised. Indeed, if the user has enabled the electrical protections from the user actions panel, then some protections may trip during simulation depending on the faults simulated. For instance, when simulating a short circuit, the stator current may exceed a permissible limit and trips the unit. In this case, if the protection is activated, an alarm is raised and will be displayed in the event table. A protection is defined from a monitored variable, a threshold and a duration. If the quantity exceeds the threshold for a time greater than the specified duration, the alarm is raised and displayed in the event table.

2. Custom Hydroelectric Simulator for CIE company

2.1. Taabo and Ayamé-I Hydroelectric Power Plant Simulators

CIE, Compagnie Ivoirienne d'Electricité, is a private company in charge of producing, transporting, exporting and importing, distributing and marketing electrical energy throughout Ivoiry Coast. It operates six hydroelectric power plants with a total installed capacity of 604 MW. CIE acquired MyHPP Simulator software to replicate the Taabo and Ayamé-I power plants. The Taabo hydropower plant is equipped with three Francis turbines, with a total capacity of 230MW, operating at a nominal head of 59m. Each unit is fed by its own penstock of 200 meters long with a diameter of 6.6m. Regarding the Ayamé-I hydropower plant, it is equipped with two Kaplan turbines, with a total capacity of 20MW, operating at a nominal head of 19m. Each unit is fed by its own penstock of 42 meters long with a diameter of 4.6m. The *Table **3*** shows pictures and drawings of the two hydroelectric power plants replicated in MyHPP Simulator and *Table **4*** shows the related hydraulic and electrical data.

Table 3: Taabo and Ayamé-I power plant pictures and drawings

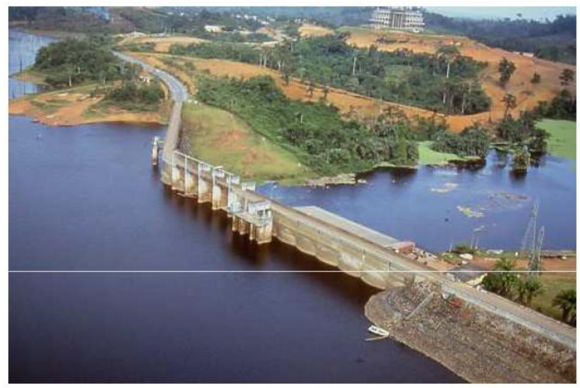
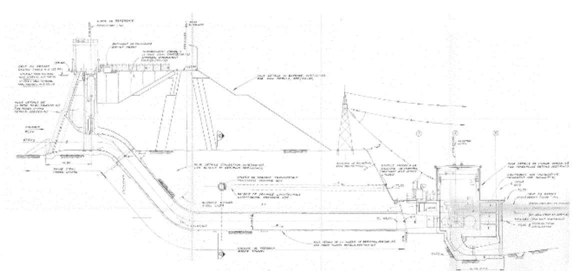
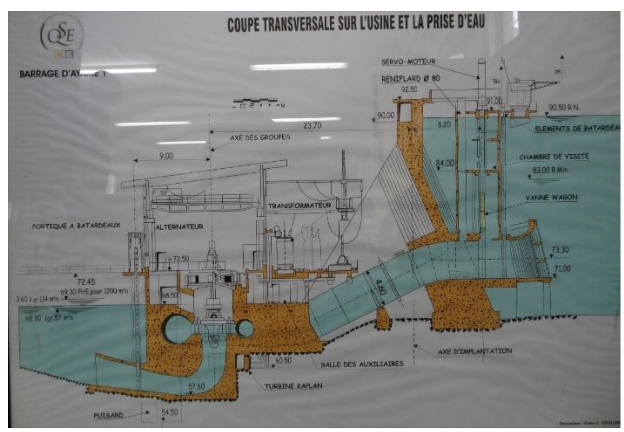
Taabo HPP	Ayamé-I HPP
	
	

Table 4: Hydraulic and electrical data of Taabo and Ayamé-I power plants

	My Hydraulic Power Plant		**Taabo**	**Ayamé-I**
Hydraulic data	Type of machinery	-	Francis	Kaplan
	Number of groups	-	3	2
	Unitary power	MW	80.6	9.6
	Head	mWC	59	19
	Flow rate	m^3/s	154	57
	Rotational speed	rpm	150	214
	Reference diameter	m	4.21	2.9
	Inertia	$kg.m^2$	3'000'000	241'280
Electrical data	Apparent power	MVA	82.5	15
	RMS line voltage at primary side	kV	225	90
	RMS line voltage at secondary side	kV	13.8	5.665
	Frequency	Hz	50	50

2.2. Hydraulic modeling of power plants

Figure 3 shows the modelling of hydraulic and mechanical components for the two hydroelectric power plants which allows to take into account:

- transient water hammer phenomena in the pipes, considering the inertia of the water, the compressibility of the fluid, and the deformation of the pipes under the effect of the pressure;
- transient behavior of turbines depending on guide vane opening, flow rate and rotational speed;
- the rotating masses and the torsional behavior of the shaft line;
- the influence of the PID turbine controller whose input error is computed from combination of a power setpoint error multiplied by the permanent droop parameter and a rotational speed setpoint error.

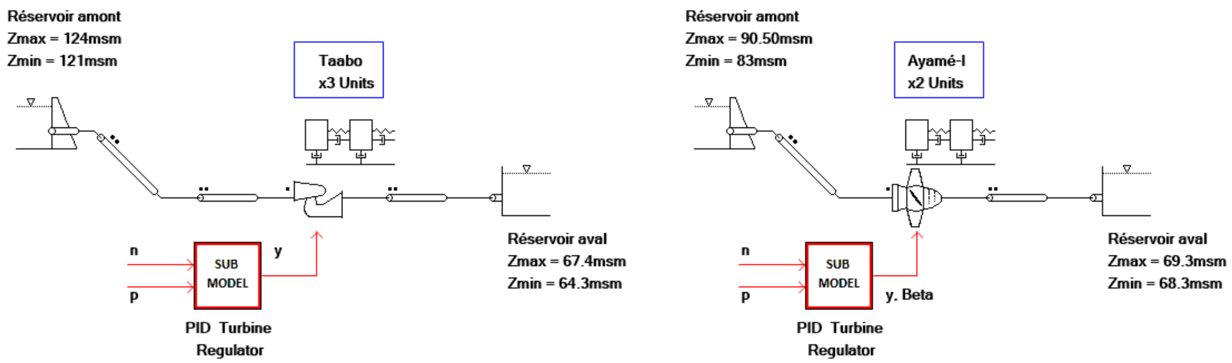


Figure 3:SIMSEN modeling of hydro-mechanical components.

2.3. Validation of hydraulic modeling

The modelling of the two hydroelectric powerplants replicated in the simulator was subjected to a validation phase by comparing simulation results with measurements. In January 1979, tests were carried out on the Taabo power plant [2]. These measurements have been used to qualitatively validate the dynamic behavior of the model. *Figure 4* compares the time evolution of the guide vane opening and the pressure in the spiral case between the measurement and the simulation during an load rejection from 50MW. The maximum pressure and rotational speed computed are in good agreement with measurements. This test allowed to validate the maneuvering time of guide vanes, the inertia of the unit, the adduction system and the dynamic behavior of the turbine controller.

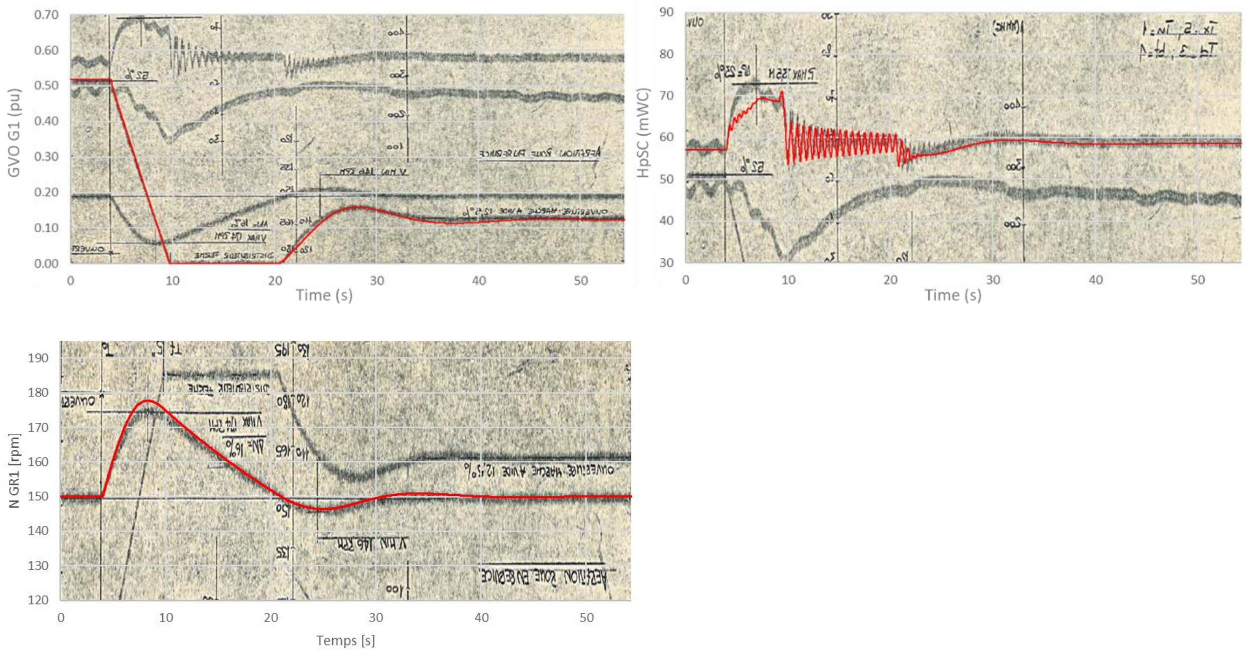


Figure 4: Taabo HPP. Hydraulic transient of guide vane opening (top left), pressure in spiral case (top right) and rotational speed (bottom) of group1 induced by load rejection event at 50MW. Comparison between measurements from the commissioning performed in 1979 and MyHPP Simulator results.

In 1994, tests were carried out on the Ayamé I power plant. *Figure 5* compares between measurement and simulation, the extreme values of spiral case pressure and rotational speed of the generator induced by load rejection at different output power values. The obtained results are in good agreement with measurements validating the implemented model of the Ayamé-I power plant.

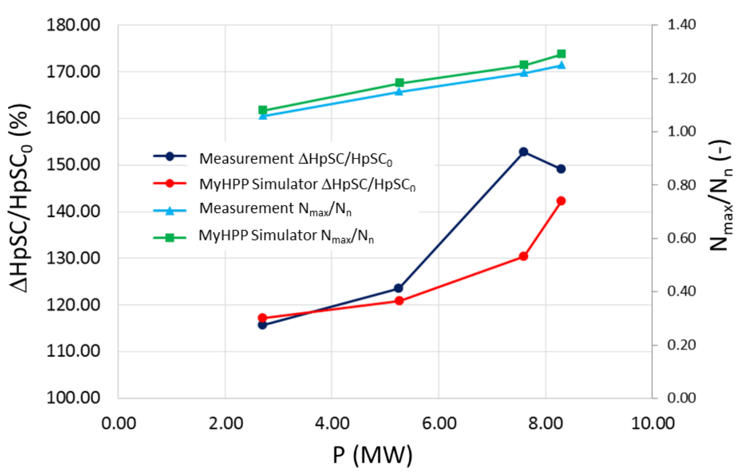


Figure 5: Ayamé-I HPP. Maximum rotational speed and pressure in spiral case as function of output power induced by load rejection. Comparison between measurements performed in 1994 and MyHPP Simulator results.

2.4. Modeling of electrical components of the hydroelectric power plants

Figure 6 shows the modelling of the electrical components which allows to take into account:

- the sub-sub-transient behavior of synchronous generators, transformer, transmission line and power network;
- the influence of the voltage regulator on the behavior of the generators;
- the electrical protections of the unit.

Regarding the electrical topology, each unit is connected to a transformer and then connected in parallel to the grid via a common transmission line. For the reader's convenience, only one group has been represented in *Figure 6*. The electrical power system (EPS) maybe quite big and complex in the reality, with many different interconnections, sub systems and components (e.g., local distribution system, transport system). Hence, in MyHPP Simulator, the model of the EPS must be simplified to a level which still represents the main grid behavior while keeping the focus on the units of the power plant under study. In that purpose, MyHPP Simulator offers three different models of the EPS, each of them represents a different configuration of the EPS, namely (i) infinite grid, (ii) islanded grid, (iii) isolated grid. With these three configurations, different phenomenon can be explored.

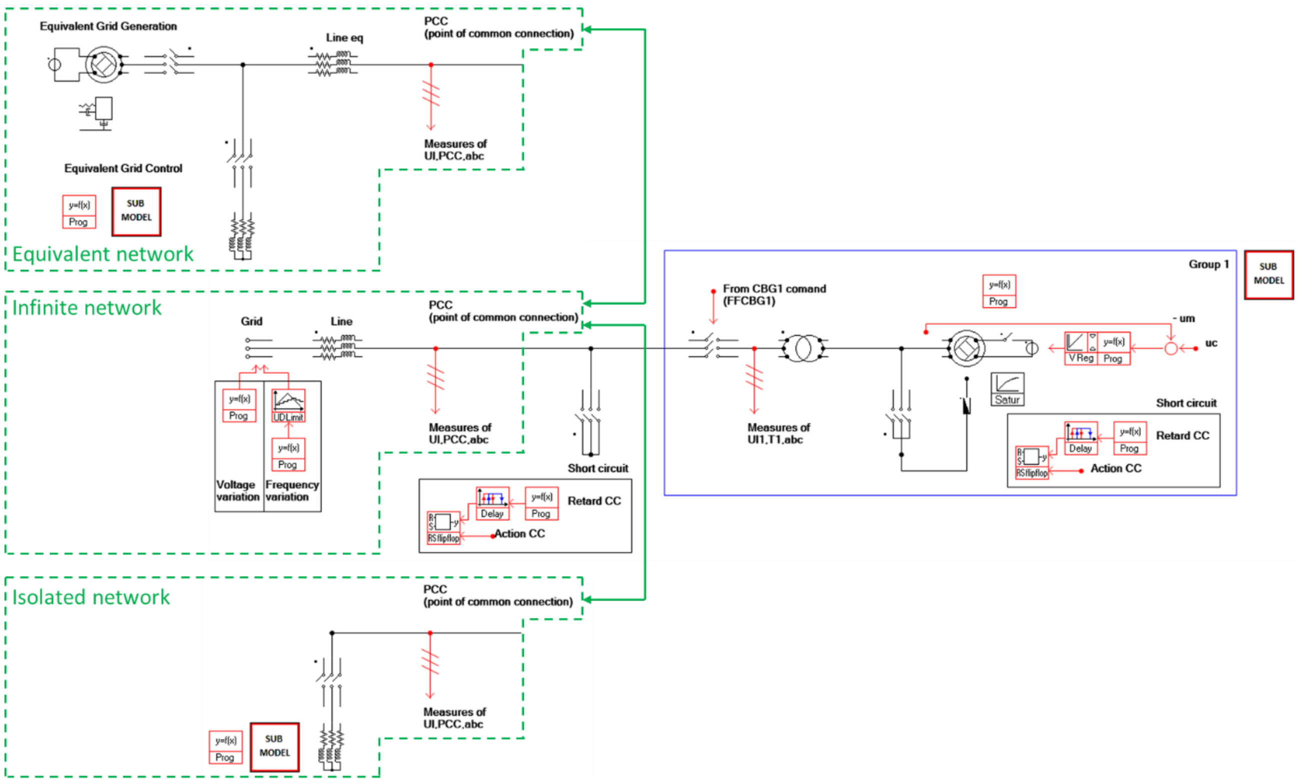


Figure 6:SIMSEN modeling of electrical components.

The first configuration by default is the **infinite power network**. In such case, the power grid model consists in an ideal voltage source, with constant voltage and frequency. This voltage source is in series with an impedance that represents the short-circuit impedance of the grid at the point of common connection (PCC) between the power plant and the grid. This configuration allows to have realistic voltages level for given active and reactive power operating point of the plant. Users are free to adjust the voltage level and frequency to simulate different grid conditions or grid fast transient phenomenon. The reaction of the units after an imposed change of voltage will depend on the settings of the voltage regulator and on eth generator's parameter. The reaction of the units after an imposed change of grid frequency will depend on the inertia and settings of the speed governor, in particular the primary control. However, because the grid is infinite, reactions of the power plant units to the imposed changes in grid condition have no counter action on the grid itself, because it is an infinite grid.

In reality, voltage change at the PCC and grid frequency deviation are due to changes in the grid configuration (load insertion or removal, power generation connection or disconnection, line insertion, etc.). In order to simulate such phenomenon, a second configuration of the EPS is available in MyHPP Simulator and denoted as **islanded grid**. In this configuration, the power grid is represented by a synchronous generator together with an inertia and equivalent voltage and speed/power regulators. This equivalent synchronous unit represents the whole power generation of the grid that user wants to represent, e.g. Ivory coast's power generation capabilities. In addition, there is a load (passive) connected in parallel to the equivalent unit. This load represents the actual load of the grid, concentrated in one consumption point. With this configuration, any load imbalance phenomenon will induce realistic frequency deviations and voltage deviations, to which all connected units will respond and contribute to stabilize the grid frequency and voltage again. User can configure and plan the load unbalance to be simulated as shown in *Figure 7* for the case of Taabo HPP operated in islanded grid under load changes. The models are prepared for different initial load flow in order to study influences of initial conditions.

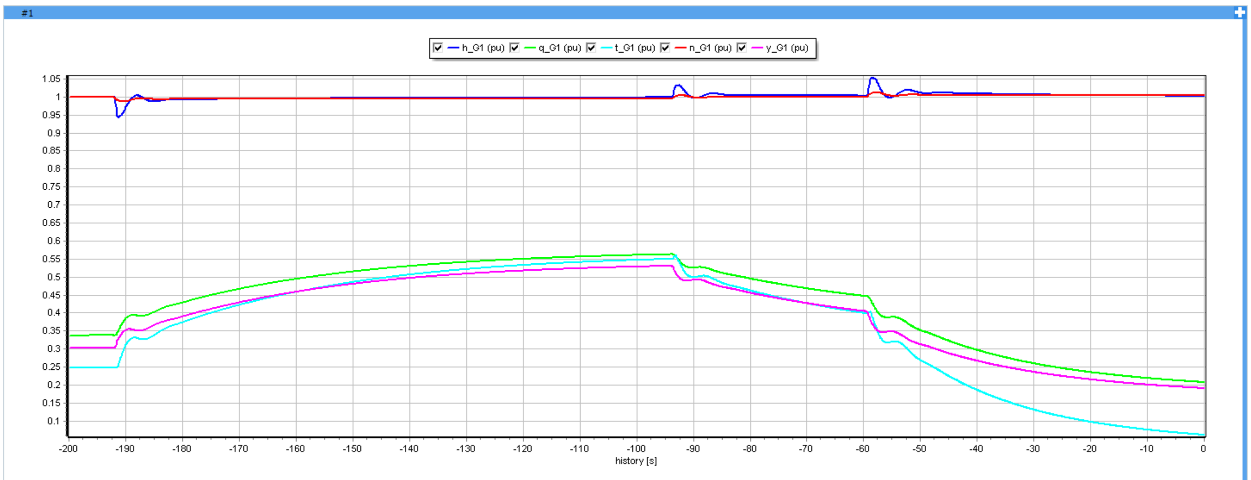


Figure 7:Example of simulation results of 1 Taabo unit response to active power load variation in islanded grid configuration (with h: net head (blue), q: discharge (green), t: torque (cyan), n: rotational speed (red) and y: guide vane opening (pink) (all in per unit (pu))).

The last configuration of the EPS is the **isolated grid** configuration where the power plant is isolated from any other power generation units of the grid and must supply alone all the local loads connected to it. The challenge for the units is to maintain alone the voltage and frequency stability, which largely depends on the inertia and settings of the turbine governors and voltage regulators. In that configuration, user can vary the local load and see to what extend the units can maintain the local grid stability. In this configuration, the units are initialized in a stable operating point, at rated speed. Based on this isolated network configuration, the black start capability of the power plant can be simulated. The initial operating point corresponds to a stopped unit (zero speed) and no load are connected. It is the starting sequence and the reconstruction of a local grid that is the focus here: starting of the unit, energizing transformers and then reconnecting the local loads with the necessary maximum load increment to guarantee grid stability, as illustrated in *Figure 8* for the case of black-start of the unit 1 of Taabo HPP and then subject to load changes in isolated grid operation.

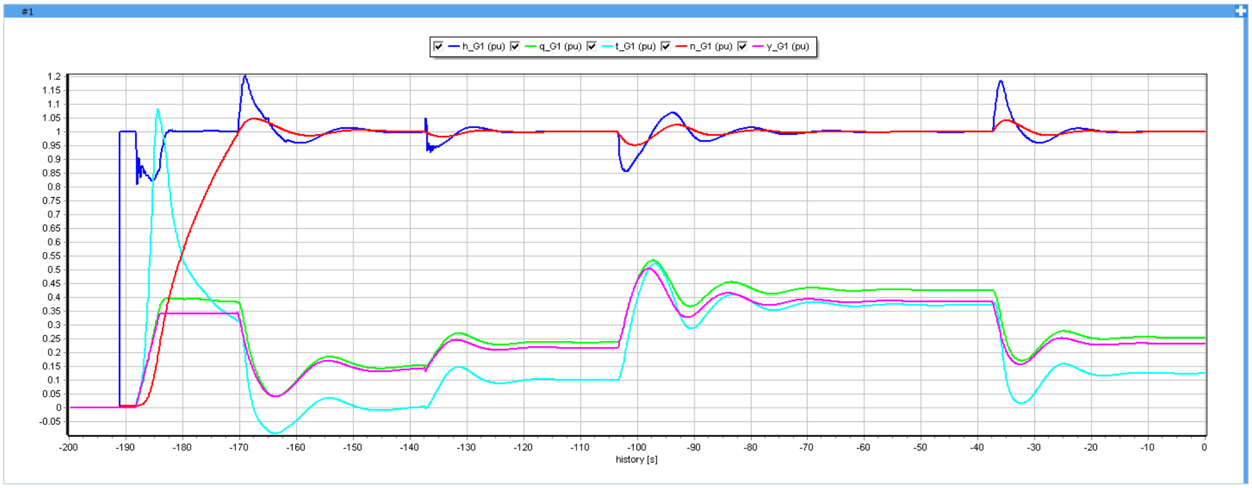


Figure 8: Black-start of 1 unit of Taabo HPP, with connection of local load consumption and variation of its active power (with h: net head (blue), q: discharge (green), t: torque (cyan), n: rotational speed (red) and y: guide vane opening (pink) (all in per unit (pu))).

3. Training of CIE's collaborators

3.1. Overview of training process

The training process of CIE's collaborators is divided in two steps as illustrated in *Figure 9*. First, Power Vision Engineering Sàrl company which is in charge of MyHPP Simulator development has trained 8 CIE's instructors through 3 training levels: "Basic", "Advanced" and "Expert" levels. The content of each level is described more in details in Section 3.2. Then, these 8 CIE's instructors have trained internally CIE's collaborators with a training rate of 250 collaborators per year accord to 3 training levels: "Basic", "Advanced" and "Confirmed". The content of each level is described more in details in Section 0.

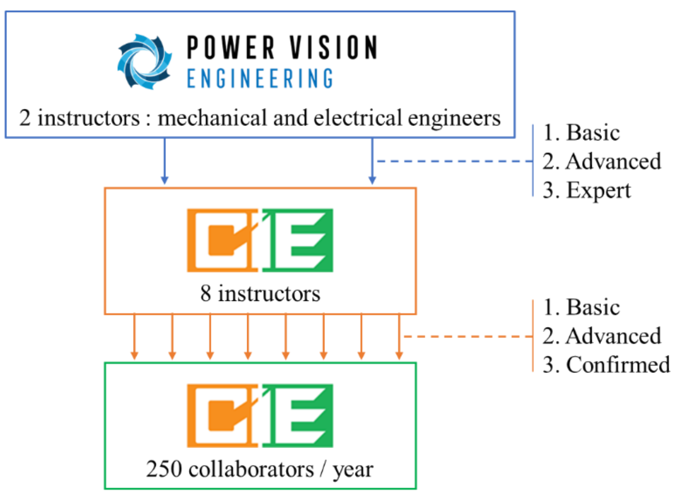


Figure 9:2 steps training process of CIE's collaborators.

3.2. Description of trainings levels proposed by Power Vision Engineering

The three training levels proposed by Power Vision Engineering are described in *Table* ***5***. The "Basic" level is the handling of MyHPP Simulator software with the presentation of the main functionalities. Then the "Advanced" level is focused on physical phenomena which can be observed in a hydroelectric power plant and which can be simulated with the simulator. After the second level, the CIE's instructor is able to start the internal training process of the CIE's collaborators. Finally, the "Expert" level allows to the CIE's instructors to parametrize the simulator and to create user models for specific training topics of interest for CIE's collaborators. The two first training levels have been performed in Ivory Coast, whereas the last one was held in Switzerland, see *Figure 10*. During this training process, the simulator was constantly improved according to the various feedbacks of the instructors in order to get a simulator adapted to their needs.

Table 5: Description of the 3 levels of training on MyHPP Simulator for CIE's instructors

Level	Objectives	Duration	Location
1-Basic	• Handling of the user interface • Introduction to the operation of a hydroelectric power plant and its components • Description and simulation of operating sequences (start-up, shutdown, faults, frequency and voltage control, etc) • Interpretation of simulation results	5 days	Ivory Coast
2-Advanced	• Transient phenomena in hydroelectric power plants • Interpretation of simulation results	5 days	Ivory Coast
3-Expert	• Introduction to SIMSEN software • Creation and parameterization of user models based on the simulator models • Analysis and interpretation of simulation results and study of the influence of the physical parameters of the model	10 days	Switzerland

Figure 10:Training of CIE's instructors in Ivory Coast at *Taabo CIE training center*.

3.3. Description of training levels proposed by CIE's instructors

The training proposed by CIE to their employees on MyHPP Simulator is divided into three levels which content is described in *Table **6***. The "Basic" level is related to the handling of the simulator with simulations of normal operating sequences. The "Advanced" level is focused on simulations of defaults and the "Confirmed" level is related to the electrical protections. Each of this training level takes place over five days.

Table 6: Description of the 3 levels of training on MyHPP Simulator for CIE's collaborators

Level	Objectives	Duration
1-Basic	• Handling of the user interface • Introduction to the operation of a hydroelectric power plant and its components • Description and simulation of normal operating sequences such as start-up, active and reactive power variation, normal stop, voltage and frequency network variation. • Interpretation of simulation results	5 days
2-Advanced	• Revision of basic level • Description and simulation of defaults inducing emergency shut down, quick shut-down or load rejection • Interpretation of simulation results	5 days
3-Confirmed	• Revision of advanced level • Description and simulation of electrical protections • Interpretation of simulation results	5 days

3.4. Benefits

The CIE has acquired the hydraulic simulator MyHPP Simulator and launched a training program with the goals of increasing the knowledge and skills of the operators and increasing the awareness of operation risks, which already lead to operational improvements such as :

- Reduction in failed start-ups;
- Reduction in the number of emergency shutdowns, quick shutdowns or load rejection per year increasing the availability of the groups on the network;
- Reduction of training time for new collaborators;
- Change in collaborator behavior in the operation of the power plant.

Conclusions

This paper presents the didactic tool "MyHPP Simulator" configured for two different hydroelectric power plants of the CIE: the Taabo and Ayamé-I power plants with an installed capacity of respectively 230MW for three Francis turbines and 22MW for two Kaplan turbines. This real-time simulator emulates the operation and dynamics of a specific hydroelectric power plant during normal, abnormal and emergency conditions. It is used as a didactic tool by CIE to train collaborators to (i) gain confidence and expertise, (ii) improve awareness of operation risks and (iii) increase knowledge and skills about hydroelectric transient phenomena. The 1D simulator is a physically based SIMSEN software solution taking into account the key components of hydroelectric power plants from water to wire and related dynamics including the corresponding control system considering interconnect, islanded and isolated grid operation.

References

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