# Modularization Modeling for Real-Time Simulation of Hydropower Plants

Chengming WU, Xianshan LI and Binqiao ZHANG

*Abstract*—**A modularization method has been proposed here for the full scope real-time simulation of a large-scale hydropower plant. In this method, the full scope dynamic simulation model can be decomposed into several subsystems that can be calculated independently in every time step, and each kind of subsystem model is developed to be a standard module. Using object-oriented modeling method for the simulation of hydropower plant protection systems, a general relaying module is developed to model a versatile protective relay, and a specific protective relay can be modeled through initialization of the general relaying module with different specific parameters and coordination settings. By doing these, the simulation time is reduced considerably, and the full scope simulation model of hydropower plant is convenient to develop, modify and maintain.**

*Index Terms*—**hydropower plant, decoupling method of large scale system, modularization, real-time simulation.**

## I. Introduction

For operator-training simulators of thermal power plants or nuclear power plants, the simulation modeling is generally one generating unit oriented because of the complexity of the electricity generation process in these kinds of power plants. The electricity generation process of a hydropower plant is relatively simple compared with that of a thermal power plant or a nuclear power plant. For a hydropower plant simulator (HPS), the simulation modeling should be whole plant, whole process and whole zone of plant oriented to develop a simulator with valuable functions for teaching, training, and research.

The simulation models of a hydropower plant simulator are developed mainly to meet the requirements of real-time simulation, calculation accuracy and the convenience of model maintenance and extension. At China Three Gorges University, a hydropower plant simulator has been developed and installed in the Hydropower Plant Simulation Laboratory (HPSL), which is the key laboratory of the State Power Corporation of China. To meet the functional requirements of HPS, the simulation mathematical model has been developed whole plant, whole process and whole zone of plant oriented. Whole plant oriented means that the simulation model of HPS must include all the generating units in a hydropower plant; whole process oriented indicates that the simulation model can reflect the complete energy conversion process of hydropower plant from hydraulic energy to mechanical energy and to electrical energy under any operating conditions; and whole zone of plant oriented means that the simulation model base should include not only all generating components which directly take part in the energy conversion process, but also such auxiliary systems which are related to the energy conversion process as the supervisory and control system, protection system, external equivalent system, etc.. As such, the simulation model of HPS must include all the primary systems, secondary systems, auxiliary systems, external equivalent systems, and computer supervisory and control systems of the simulated hydropower plant, and this modeling is called here the full scope modeling of a hydropower plant. To achieve the desired performances of the HPS in HPSL and reflect the actual dynamic process of hydropower plant, reasonably accurate models must be used and must be calculated in real time. The order of the developed mathematical model of the HPS in our laboratory is over 200. Precise simulation of such a large system in real time is too severe a load for the computer using the conventional method. The accuracy and speed requirements are generally contradictory. In different circumstances varying methods are proposed to achieve the tradeoff between accuracy and computation time [1-6].

In this paper, decoupling and partitioned method of large scale dynamic systems are used to decompose the dynamic system of a large-scale hydropower plant (LSHP) into several subsystems which can be calculated independently in every time step. Furthermore, the order of the iteration model of every subsystem is reduced to the lowest by using model compressing method, and the simulation time can be reduced considerably. The module base is developed to be composed of component and subsystem module base. Component module base is developed physical components oriented, and subsystem module base is developed for the subsystems of the large-scale dynamic system. A general protective relay module is developed through object-oriented modeling method for the hydropower plant protective system simulation, and a specific protective relay can be modeled through initialization of the general protective relaying module with the specific parameters and coordination settings.

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## II. Component Models of Hydropower Plant Simulator

The component models of LSHP include hydro generator units, transformers, buses, circuit breakers, transmission lines, loads, control systems, protection systems, automatic re-closers, and auxiliary systems. Based on modularization method, each kind of physical components is abstracted into a component module, such as transformer module, circuit breaker module, bus module, transmission line module, etc.. A subsystem module, which will be described in the next part, is developed composed of several component modules.

## III. THE SIMULATION ALGORITHMS AND SUBSYSTEM MODULE

### A. Concept of Large-Scale Dynamic Systems s

Equation (1) shows a large-scale dynamic system composed of n subsystems, and ε is the coupling coefficient. According to the decoupling theories of large-scale dynamic systems, the system can be decoupled into n subsystems when ε meets the decoupling conditions. Apparently, when ε=0, the system can be decoupled into n subsystems which can be analyzed independently.

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \vdots\\ \dot{X}_n\end{bmatrix}=\begin{bmatrix}A_{11} & \varepsilon A_{12} & \cdots & \varepsilon A_{1n}\\ \varepsilon A_{21} & A_{22} & \cdots & \varepsilon A_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ \varepsilon A_{n1} & \varepsilon A_{n2} & \cdots & A_{nn}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\\ \vdots\\ X_n\end{bmatrix}+\begin{bmatrix}B_{11} & \varepsilon B_{12} & \cdots & \varepsilon B_{1n}\\ \varepsilon B_{21} & B_{22} & \cdots & \varepsilon B_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ \varepsilon B_{n1} & \varepsilon B_{n2} & \cdots & B_{nn}\end{bmatrix}\begin{bmatrix}U_1\\ U_2\\ \vdots\\ U_n\end{bmatrix} \quad (1)$$

### B. The Main Simulation Models of Hydropower Plant and Algorithms

The dynamics of hydropower plant can be described by a set of algebraic and differential equations representing the dynamic behavior of hydro-generators and their controllers, including the electric network in the substations and external equivalent systems. These equations are described as follows:

$$\frac{dX}{dt}=F(X,Y) \quad (2)$$

$$Y=G(X,Y)) \quad (3)$$

$$x_{n+1}=x_n+\frac{h}{2}(f(x_{n+1},y_{n+1})+f(x_n,y_n)) \quad (4)$$

Where X is the state vector of all the hydro-generator units and their control systems, including the external equivalent systems; Y is the vector of generator terminal voltages and the electric network node voltages; h is the time step.

Equation (2) is solved using the trapezoidal rule shown as (4), because this method is stable in numerical calculation procedure, even if the system includes time constants shorter than the time step h. That is good for achieving real time simulation. After differentiated, (2) is connected with (3) to formulate the hydropower plant simulation mathematical model. There are two methods to solve these equations, a simultaneous solution and a partitioned solution. Although the simultaneous solution offers good accuracy, it takes a long time because a set of nonlinear equations must be solved and its Jacobian matrix changes at every iteration step. So, it is very difficult to achieve real time simulation using simultaneous solution in calculating large-scale hydropower plant mathematical model whose order of differential equations is over 200. Here partitioned method is used to reduce the calculation time. According to the structural characteristics and the actual physical procedures of hydropower plant, decoupling method of large scale dynamic system is used to decompose the mathematical model of LSHP into several subsystems which can be calculated independently in every time step, thus the calculation time is reduced considerably.

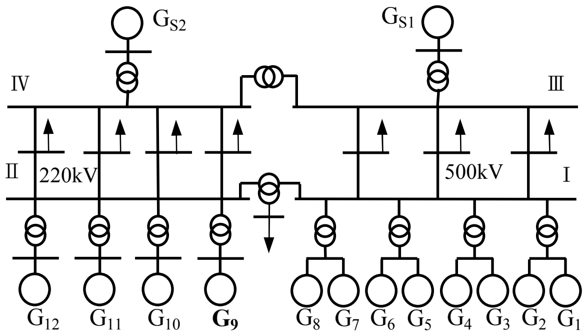



Fig. 1. The model of hydropower plant for HPS

Fig. 1 is the model hydropower plant used in HPSL, which models the Gezhouba Hydropower Plant with a reasonable reduction in the number of generator units and transmission lines. This hydropower plant simulation model consists of two power stations with 8 generator units ($G_1$ ~ $G_8$) with capacity of 1250 MW installed in the Grand Channel Power Station and 4 generator units ($G_9$ ~ $G_{12}$) with capacity of 1250 MW installed in the Second Channel Power Station; 2 sub-stations, one is 500 kV AC switchyard and the other is 220 kV AC switchyard represented by bus Ⅰ and bus Ⅱ, respectively; 7 transmission lines connected with the external equivalent systems $G_{S1}$ and $G_{S2}$ represented by two typical generator models and their controllers. A generator unit is composed of water system, hydraulic turbine, speed governor, generator, excitation system, Automatic Voltage Regulator (AVR), and Automatic Generation Control (AGC) system. The electric network, the protective systems, the supervisory and control systems, and auxiliary systems are also included in the simulation models.

The dynamic model of this hydropower plant can be described as (5) as follows:

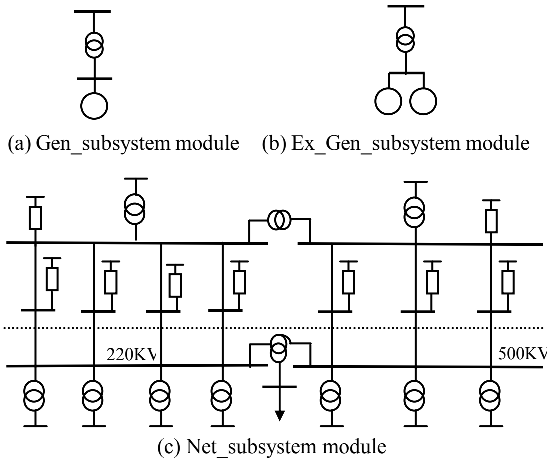
$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \vdots\\ \dot{X}_{14}\end{bmatrix}=\begin{bmatrix}A_1 & & \mathbf{0} & \\ & A_2 & & \\ \mathbf{0} & & \ddots & \\ & & & A_{14}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\\ \vdots\\ X_{14}\end{bmatrix}+\begin{bmatrix}B_1 & & \mathbf{0} & \vdots & B_{1W}\\ & B_2 & & \vdots & B_{2W}\\ \mathbf{0} & & \ddots & \vdots & \vdots\\ & & B_{14} & \vdots & B_{14W}\end{bmatrix}\begin{bmatrix}U_1\\ \vdots\\ U_{14}\\ U_W\end{bmatrix} \quad (5)$$

$$F_g(X_i, U_i, U_W)=0 \qquad (i=1,2,\cdots,10) \quad (6)$$

$$F_W(U_i, U_W)=0 \qquad (i=1,2,\cdots,10) \quad (7)$$

Where $X_i$ is the state vector of the hydro-generator units and their control systems, including generators $G_1$~$G_{12}$ in the hydropower plant and the external equivalent systems $G_{S1}$~$G_{S2}$, the dimension of $X_i$ equals to the number of all the state variables of hydro-generator unit $G_i$ and its control systems. $U_i$ is the non-state vector of the hydro-generator $G_i$ including the terminal voltage and current, the dimension of $U_i$ equals to the number of all the non-state variables of $G_i$. $U_w$ is the electric network node voltage vector including the voltages of bus Ⅰ、Ⅱ、Ⅲ and Ⅳ.

It is shown in (5) that the coupling among generators is all through bus nodes, there are no direct connections among generators. Each generator unit is connected to the electric network through a transformer. Whether the system can be decoupled or not is decided by the method coping with the bus node voltage vector $U_w$. Here, the hydropower plant mathematical models are calculated using partitioned method. The dynamic system expressed by (5) is decomposed into several subsystems at the bus nodes, the generator subsystems and the electric network subsystem. $U_w$ are predicted when solving the generator subsystem equations.




(a) Gen_subsystem module (b) Ex_Gen_subsystem module

(c) Net_subsystem module

Fig. 2 Subsystems of hydropower plant simulation mathematical model: (a) Generator subsystem module; (b) extended generator subsystem module; (c) Electric network subsystem module

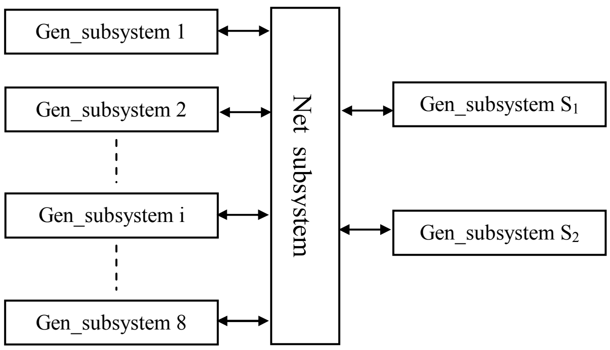



Fig. 3 Subsystems connection of hydropower plant simulation model

Considering the primary system connection characteristics of hydropower plant shown in Fig.1, the main transformers connecting generators to buses are included both in the generator subsystems and the electric network subsystem. This overlap is good for the numerical calculation convergence. As such, the dynamic system in (5) is decomposed into 10 generator subsystems and one electric network subsystem as shown in Fig. 2. Fig. 2(a) shows the one generator subsystem module (subsystems 5-8, shown as Gen_subsystem module) that includes one hydro-generator unit and its control systems and a transformer; this subsystem module represents generator units $G_9 \sim G_{12}$. Fig. 2(b) shows the two generator subsystem module (subsystems 1-4, shown as Ex_Gen_subsystem module) that includes two hydro-generator unit and their control systems and a transformer; this subsystem module represents generator units $G_1 \sim G_8$, and Fig. (2) (c) is the electric network subsystem module. As such, (5) can be decomposed into 8 dynamic subsystems of hydro-generators, 1 electric network subsystem and 2 external equivalent generator subsystems.

It is shown in Fig. 3 that all the generator subsystems are connected to the electric network subsystem. In the electric network subsystem, the variables are the bus voltages and the generator terminal voltages. The transformers are included both in generator subsystems and network subsystem,

The differential equations are differentiated and connected with the algebraic equations to formulate the subsystem simulation models. Actually, it is only necessary to predict the bus voltages $U_w$ in solving the Gen_subsystem and Ex_Gen_subsystem modules independently in every time step. Subsequently, Uw is obtained by solving the network subsystem. To get the best result, the subsystem models are compressed by deleting all the linear equations and the order of each subsystem model is lowered considerably, the calculation speed is promoted greatly.

Fig. 4 is the calculation procedure of the simulation program.

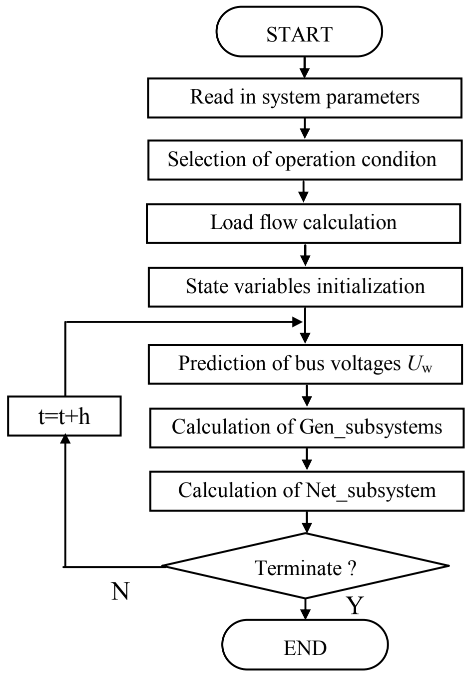



Fig. 4 Flowchart of the main simulation program

### C. *Relay Protection Systems Modeling*

First, the simulation models of the protection relaying system should include all the relaying devices of all equipments of a hydropower plant, such as protection systems of generators, transformers, buses, transmission lines, reactors, etc.. And secondly, the protection simulation models should be able to reflect all the principles of protection systems of a hydropower plant, such as over current protection, over voltage protection, impedance protection, differential protection, etc..

The full-scale-oriented protective relaying system of a hydropower plant is composed of all the protection devices of all the electric components of the hydropower plant, and all the protection devices is developed various protective relaying principle-based. The full scope protective system simulation modeling should reflect various principles of protection devices, and the coordination among all the protective relaying systems. As an important part of the whole simulation model of a hydropower plant, the simulation model of protection systems should be able to communicate with other parts of the simulation models, such as the connection of trip-signals of a protective relay with the dynamic simulation models. And furthermore, the simulation of the protection system should be in real-time.

The half logical modeling method is adopted here to achieve the compromise between simulation speed and accuracy, namely, the principles of instantaneous-time protection relay devices are expressed with logical equations, but the long-time delay devices or actions will be described by equations with reflected variables calculated by the dynamic or fault models. We propose an object-oriented simulation modeling method for the simulation of hydropower station protection systems, a general relaying model is developed to model a versatile protective relay, and a specific protective relay can be modeled through initialization of the general relaying model with different specific parameters and coordination settings.

The actual protective relaying system of a hydropower station can be modeled as composed of equipment protective systems, such as protective systems of generators, transformers, transmission lines, etc., and all these are called equipment protection models or EP-models, as shown in Fig. 5. Every EP-model is composed of several protection units called functional protection models or FP-models, generally, every EP-model has one or two FP-models. And every FP-model includes several protective relay models or PR-models, such as over current protective relays, over voltage protective relays, according to the specific protection of power generation equipment. From these, we can see that every EP-model is composed of PR-models. So, the protection system modeling is basically the protective relay modeling.

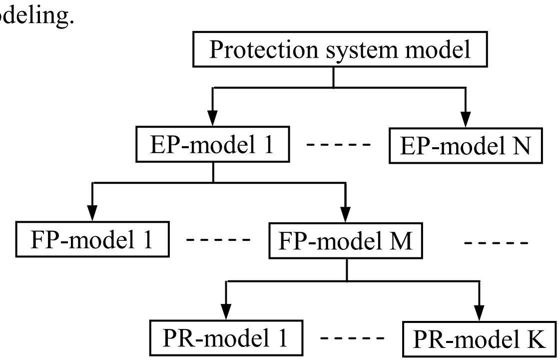



Fig. 5 Hierarchies of hydropower station protective relay system

Through abstraction, a general protective relay module (PR-model) is developed as shown in Fig. 6, and a FP-model is composed of several PR-models according to the actual equipment protection. A general PR-model can be abstracted as having the following attributes: Input Signal, Fault Signal, Emergency Signal, Tripping Signal, Generator Shut-Down Signal, Excitation Tripping Signal and Starting Circuit Breaker Failure Protection Signal. Started by inputs (fault variables), the PR-model compares the input variables with the setting values, and the time delay with the time setting. When the input variable and the time delay meet the action criteria, the protection model will output fault signal, emergency signal, and tripping signal etc. according to the initiation for a specific PR-model.

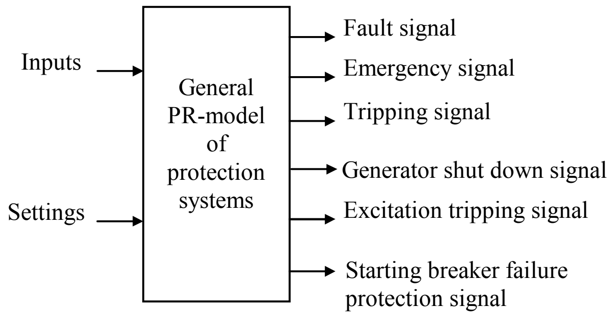



Fig. 6 General PR-model

## IV. Conclusion

In this paper, a modularization simulation modeling method for a hydropower plant and speed up mechanism for a real time dynamic simulation of large scale hydropower station are discussed. The module base is developed to be composed of component module base and subsystem module base. Component module base is developed physical components oriented, and subsystem module base is developed for the subsystems of the large-scale dynamic system of a hydropower plant. A general protective relay module is developed through object-oriented modeling method for a hydropower station, and a specific protective relay can be modeled through initialization of the general protective relaying module with different specific parameters and coordination settings. By doing these, the simulation modeling is much simple, and the computation time can be reduced enormously.

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