International Journal of Control and Automation
Vol.7, No.3 (2014), pp.317-326
http://dx.doi.org/10.14257/ijca.2014.7.3.30

Condition based Maintenance Optimization for the Hydro Generating Unit with Dynamic Economic Dependence

Xinbo Qian and Yonggang Wu

School of Hydropower and Information Engineering,
Huazhong University of Science and Technology
1037 Luoyu Road, China, 430074

simble777@163.com, ygangwu@163.com

Abstract

This paper considers a condition-based maintenance (i.e. CBM) model for the hydro generating unit in the deregulated power system. As the downtime cost of the generating unit varies according to the time-varying electricity price, the economic dependence among the critical component of the generating unit is dynamic. In this paper, the proposed Dynamic-Economic-Dependence and proportional hazards model based CBM policy considers the dynamic economic dependence among components as well as the reliability and the monitoring information of different critical components. An example for the hydro generating unit is presented to verify the effectiveness of the proposed condition based maintenance policy.

Keywords: *Condition based maintenance, Optimization solution, Multi-component system, Proportional hazards model, Economic dependence*

1. Introduction

Generating units are important units of the power system. The reliability of generating units is of course essential for the power system with high reliability [1-3]. Maintenance has been introduced as an efficient way to improve the reliability and extend the lifetime of the units. Consequently, the maintenance scheduling problem of generating units has been studied extensively in the last decades.

The development of maintenance scheduling environment for generating units has been developed from the traditional centralized power system to the deregulated power systems. In a traditional centralized power system, the independent system operator (ISO) [4] schedules maintenance time for all generating units in a corresponding area, aiming to keep the reliability level of the whole power system, meanwhile reducing the total maintenance cost. A great number of papers have been published for the solution of such a problem, such as [5, 6]. However, in the aforementioned maintenance models, the generating unit was simplified as a single-component system; actually it is multi-component system in practice. The maintenance policy of a multi-component system differs from that of a single-unit system because dependencies exist among components, including economic dependence, structural dependence and stochastic dependence [7]. In this paper, we only focus on the economic dependence. Economic dependence means that performing maintenance on several subsystems jointly costs less money and/or time than on each subsystem separately [8]. Therefore, there is often a great potential for cost savings by implementing an opportunistic maintenance policy [9-11]. Opportunistic maintenance basically refers to the situation in

ISSN: 2005-4297 IJCA

which preventive maintenance is carried out at opportunities, either by choice or by restriction. For example, it is possible to do preventive maintenance for non-failed subsystems at a reduced additional cost while failed subsystems are being repaired. According to different criterions, the opportunistic maintenance for the multi-component system can be divided into three categories: traditional reliability approaches, condition data-based maintenance and integrated approaches.

Traditional reliability approaches can be referred to as event data based maintenance models, which can be divided into two main categories: time-based opportunity maintenance and failure rate-based opportunity maintenance. For time-based opportunity maintenance policy, upon a component failure the other component as well as the failed one is performed maintenance if its age exceeds a pre-determined control limit. More studies on time-based maintenance of multi-component systems have been reported in literature [10, 12]. Zheng *et al.* [11] examined an opportunistic maintenance policy based on failure rate tolerance for a system with multi-type units. A component is replaced either when the hazard rate reaches the threshold L or when the failure rate is in a predetermined interval, and L and u are policy decision variables. Attention is restricted to policies which take actions based on the actual condition of all components. The 'age' of a component or the failure rate is usually used as the condition variable. However, the aforementioned maintenance models did not consider the condition monitoring information, such as vibration data, acoustic emission data, oil analysis data and temperature data.

However, although condition monitoring data are a rich source of information for fault/failure perdition, it should be noted that current condition state can support the short-term maintenance strategy, instead of providing the indication of failure time or probability of failure [13]. To utilize the available information fully for a long-range maintenance strategy, the integrated approaches, which are based on both event and condition data, can be promising research challenges [13]. A kind of PHM (*i.e.*, proportional hazard model) based CBM policy for multi-component systems was proposed in [14], for which economic dependence exists among different components. Upon a component failure the other component as well as the failed one is performed maintenance if its hazard risk exceeds a pre-determined control limit. While for cases with time-dependent economic dependences, there may exist the potential profit if assign different thresholds to the different downtime costs.

For the problem multi-component system, we propose a time-dependent control-limit strategy for the CBM policy. In this paper, we propose a Dynamic-Economic-Dependence and Proportional hazard model based CBM (DED&PHM based CBM) policy for the generating unit as a multi-component system. Time-dependent economic dependence exists among different components for the time-dependent downtime cost. Comparative numerical examples for a hydro generating unit are presented to verify the effectiveness of the proposed CBM policy.

The rest of the paper is organized as follows. In Section 2, time-dependent control-limit CBM policy is proposed. Simulation studies are presented in Section 3. Finally, some conclusion remarks are given in Section 4.

2. Dynamic-economic Dependent PHM based CBM Policy

2.1. PHM based CBM policy

The valuable statistical procedure for estimating the risk of equipment failure when it is subjected to condition monitoring is the proportional hazard model (PHM) [15]. The forms of PHM combine the based hazard function h0 along with a component that takes into account covariates which are used to improve the prediction of failure. The particular form used in this study is known as a Weibull PHM which is a PHM with a Weibull baseline, and it is given by

$$h(t,z_t)=h_0(t)\exp(\gamma z_t)=\frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1}\exp(\gamma z_t) \quad (1)$$

where β and η are parameter of the proportional hazards model, t is the age of the component, z_t is the covariate value of the component at time t and γ is the corresponding coefficient of the covariate. The covariates, which can be considered as the key condition monitoring measurements reflecting the health condition of the equipment, can be obtained by the software EXAKT [16, 17]. The CBM optimization approach for the multi-component system based on proportional hazards model, and the method for calculating the cost and reliability objective function, were developed in Ref. [14]. For the PHM based CBM policy, two-level risk thresholds $\{d_1, d_2\}$ were introduced to determine which component should be performed preventive maintenance (PM) or opportunistic maintenance (OM) at a certain inspection point. The objective of the CBM optimization is to find the optimal d_1 and d_2 to minimize the total maintenance cost.

2.2. Dynamic-economic dependent & PHM based CBM policy

Since the outage cost of the generating unit varies according to the time-dependent electricity price, the economic dependence among the critical components of the generating unit is dynamic. So some extended model should be studied for the dynamic cost structure [18]. In this section, we propose the dynamic-economic dependent (DED) & PHM based CBM policy for the generating unit, considering the dynamic economic dependence among the components, as well as the reliability and the monitoring condition of different critical components. The following assumptions are made in this paper regarding the multi-component systems under discussion:

(1) The generating unit is on operation continuously, unless it is shut down for maintenance.

(2) The components are repairable, and they are independent in their degradations and failure processes.

(3) The components are economically dependent. Specially, a time-dependent downtime cost, denoted by $C_d(t)$, is incurred if the multi-component system is shut down for any maintenance performed on any component. If maintenance is performed on multiple components simultaneously, the downtime cost is incurred only once.

(4) We focus on the maintenance optimization in this study, and the inspection interval is not a design variable in the optimization problem. So the inspections are assumed to be performed for constant interval.

(5) The effect of maintenance is as good as new for simplification.

In this work, we extend the PHM based CBM policy for multi-component systems from time-independent downtime cost to time-dependent downtime cost. So the time-dependent downtime cost can be referred to as the dynamic economic dependence among components. The proposed policy takes the dynamic economic dependence among components into consideration. The time-dependent two-level risk thresholds are introduced to determine which components should be preventively or opportunistically maintained. First, the time-dependent two-level risk thresholds $\{d_1(t), d_2(t)\}$ are characterized as follows:

$$d_1(t)=C_d(t)\cdot d_{k1} \quad (2)$$

$$d_2(t)=C_{\mathrm{d}}(t)\cdot d_{\mathrm{k}2} \tag{3}$$

where d_{k1} and d_{k2} are the risk threshold scaling factors of the time-dependent downtime cost. The time-dependent two-level risk thresholds are determined once the two risk threshold scaling factors $\{dk_1, dk_2\}$ are given. So the DED&PHM based CBM policy extended from the PHM based CBM policy is proposed as follows:

(1) Perform failure corrective maintenance if a failure occurs on component *i*.

(2) For component *i*, preventive maintenance is performed if $Kh_i>d_1(t)$ where K is the difference between the corrective maintenance and preventive maintenance.

(3) If preventive or corrective maintenance is performed on any other component of the system, perform opportunistic maintenance on component *i* if $Kh_i>d_2(t)$, where $d_1(t)> d_2(t)$.

For the proposed policy, two levels of time-dependent risk thresholds are used to deal with the time-varying economic dependence among different components, while time-dependent two-level risk thresholds are used to determine whether preventive maintenance or opportunistic maintenance should be performed on a component.

For the time-dependent downtime cost, it is cost effective to utilize the time-dependent risk threshold instead of the constant risk threshold. Qualitatively, for lower thresholds preventive maintenance can be performed with higher frequency. Conversely, for higher maintenance thresholds, preventive maintenance can be performed with lower frequency. Then for this proposed policy, it can be a result that the higher the price the higher the thresholds. So for higher downtime costs, the thresholds are higher; and the thresholds are lower for lower downtime costs. So it can be cost-effective to perform PM with lower (respectively, higher) possibility during periods of higher (respectively, lower) downtime costs. As shown in **Error! Reference source not found.**, for high downtime cost $C_d(t)$, the dynamic risk threshold $d(t)$ should be relatively high so as to make the possibility of performing preventive maintenance be lower (and vice versa).

The cost measure can be evaluated for DED&PHM based CBM policy using an algorithm to be presented in the next section. Thus the objective of the proposed policy is to find the optimal risk threshold scaling factor values $\{d_{k1}, d_{k2}\}$ to minimize the expected maintenance cost per unit time during the planning horizon. The optimization model can be formulated as follows:

$$\begin{aligned} &\min C(d_{k1}, d_{k2}) \\ &\text{s.t. } d_{k1} > d_{k2} > 0\,. \end{aligned} \tag{4}$$

A numerical algorithm was developed for the cost evaluation of a PHM based CBM with respect to determined risk thresholds, more detail can be seen in the Ref. [14]. However, this kind of cost evaluation method is time-consuming as the component number and covariate number increase. To balance the computation time and computational accuracy, the cost evaluation method based on Monte Carlo simulation [19] method is applied to calculate the expected maintenance cost during the planning horizon, and then the optimal thresholds can be obtained by minimizing the expected maintenance cost.

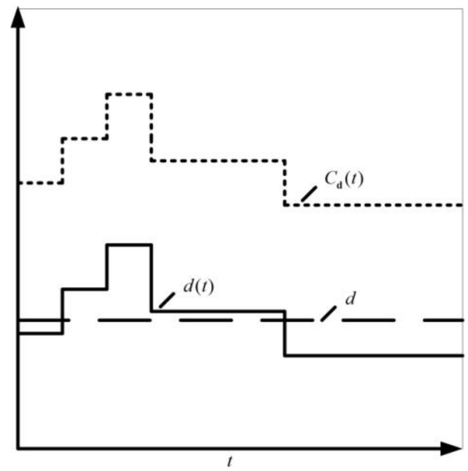

Figure 1. Sketch map of time-dependent risk threshold

3. Example

In this section, we would like to consider a real case of a hydro generating unit of 100MW to illustrate the proposed DED&PHM based CBM policy. If the critical components are considered, the hydro generating unit can be treated as a series system connected by hydro turbine, generator and transformer, etc., as shown in Figure 2. A failure of any component will lead to system malfunction, so there is economic dependence among the components.

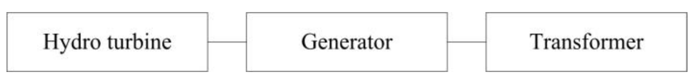

Figure 2. Block diagram of critical components for a hydro generating unit

In this case, we choose condition indicator as covariate. Condition indicator (CI) is quantitative rating given after assessment of equipment thoroughly [20]. The condition indicator varies from 0 to 100, and scoring is done with respect to the present physical state of the component. Based on the failure, maintenance events and concomitant condition indicators of the three critical components of a hydro generating unit, the PHM parameters can be thus estimated [21], and the parameters for the components are given in Table 2.

Table 1. Parameters of proportional hazards model for critical components

Component	Shape Parameter β	Scaling Parameter η	Coefficient parameter γ
Hydro turbine	3	3000	0.061
Generator	2	3750	0.044
Transformer	3	2400	0.026

Table 2. Transition probability matrix of condition indictor of Hydro turbine

Bands	[0, 35)	[35,60)	[60,85)	[85,100)
[0, 35)	0.72350	0.25340	0.02258	0.00052
[35,60)	0.03301	0.85120	0.11490	0.00089
[60,85)	0.01800	0.19220	0.78710	0.00270
[85,100)	0.00000	0.00000	0.00000	1.00000

Table 3. Transition probability matrix of condition indictor of Generator

Bands	[0, 35)	[35,60)	[60,85)	[85,100)
[0, 35)	0.79850	0.18180	0.01921	0.00049
[35,60)	0.02815	0.83270	0.13840	0.00075
[60,85)	0.02110	0.12250	0.74320	0.11320
[85,100)	0.00000	0.00000	0.00000	1.00000

Table 4. Transition probability matrix of condition indictor of Transformer

Bands	[0, 35)	[35,60)	[60,85)	[85,100)
[0, 35)	0.73590	0.23310	0.03038	0.00062
[35,60)	0.00926	0.82920	0.16070	0.00084
[60,85)	0.00794	0.09850	0.81030	0.08326
[85,100)	0.00000	0.00000	0.00000	1.00000

The transition probability matrix is required to calculate the cost evaluation of the DED&PHM based CBM policy. The transition probability matrix gives the possibilities of a covariate going from current range to the range at the next inspection time. Assume the inspection interval is 30 days. The transition probability matrix can be estimated by the history information for condition indicators of different components. The estimated matrix for critical components is shown in Table 2, 3 and 4. Covariate ranges are defined for four levels, such as between 0 and 35, between 35 and 60, between 60 and 85, between 85 and 100. They are selected by combining practical experience and covariate distribution histograms. These four ranges are referred to as four states: state 1, 2, 3 and 4. Thus the highest possible component state is J=4, and a component is in state 1 if the condition indictor falls into range [0, 35) and so on. The corrective maintenance cost, preventive maintenance cost for critical components of the hydro generating unit is presented in Table 5.

The electricity price history profiles are from the Monthly Locational Marginal Pricing of PJM power market from 1999 to 2012 [20].The forecasting electricity price for next year can be obtained the SARIMA model [23, 24]. For simplification, the forecasting electricity for the next four years is identical since the history data is not enough. According to the forecasting electricity price, the forecasting time-dependent of downtime cost is shown in Figure 3. In this research the forecasting price is determined instead of stochastic. The case with stochastic outage cost will be discussed in future work. The downtime cost is time dependent since the monthly electricity price is varying. The planning horizon T_{tal} is 48 months in this case.

We perform a comparative study between the PHM based CBM policy and DED&PHM based CBM policy for the hydro generating unit as a multi-component system. Then the cost of the PHM based CBM policy can be evaluated through certain risk threshold values d1 and d2. Meanwhile the cost of a certain DED&PHM based CBM policy can also be evaluated through certain risk threshold scaling factor values dk1 and dk2. With respect to the two kinds of CBM policy, the optimal cost values and the optimal CBM policies are listed in Table 6. We can see that the optimal cost of DED&PHM based CBM policy is about 10% lower than that of PHM based CBM policy.

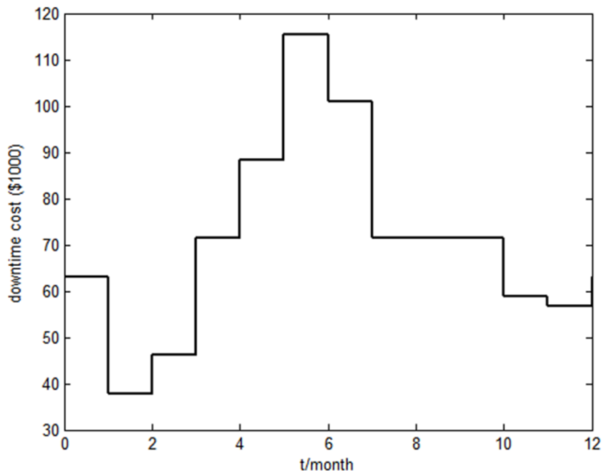

Figure 3. The time-dependent downtime cost

Table 5. Corrective and preventive maintenance cost for major components

Component	Corrective maintenance cost ($1000)	Preventive maintenance cost ($1000)
Hydro turbine	71	12
Generator	50	10
Transformer	70	12

Table 6. Comparative result of optimal cost for hydro generating unit as multi-component system

	d_1 or d_{k1} ($\log_{10}$)	d_2 or d_{k2} ($\log_{10}$)	Cost($/day)	Cost-saving
PHM based CBM policy	-1	-3	207	
DED&PHM based CBM policy	-2.8	-5	187	10%

Table 7. Comparative result of cost analysis

Policy	Cost($/day)	ACCM	ACPM	ACD	PNCM	PNPM	MTBM
PHM based CBM policy	207	51	32	124	45%	55%	554 days
DED&PHM based CBM policy	187	46	32	108	42%	58%	532 days

For detailed cost analysis, as shown in Table 7, we can compare the two CBM policies with: (1) the expected maintenance cost per day, (2) the average cost of corrective maintenance cost per day (*i.e.*, ACCM, the unit is $/day), (3) the average cost of preventive maintenance per day (*i.e.*, ACPM, , the unit is $/day), (4) the average downtime cost per day, (5) the proportion of expected number of corrective maintenance (*i.e.*, PNCM), (6) the proportion of expected number of preventive maintenance (i.e. PNPM) and (7) the average time between maintenance (*i.e.*, MTBM, the unit is day). It can be seen that the proportion of expected number of failures (corrective maintenance) was reduced from 45% to 42% and the proportion of expected number of preventive maintenance increases from 55% to 58%. And the average time between maintenance decreases from 554 days to 532 days. According to the cost analysis, the proposed DED&PHM based CBM policy is more reasonable and cost effective.

The reason is that preventive maintenance is inclined to be performed during the periods of low downtime costs by the proposed policy. The reason for the cost-saving of the proposed DED&PHM based CBM policy is that, the preventive maintenance is inclined to be performed during the periods of low downtime costs. Meanwhile, for the PHM based CBM policy, the preventive maintenance thresholds are constant, so preventive maintenance can be performed with nearly equal possibilities during different periods. While preventive maintenance can be performed with much lower possibilities during the periods with higher downtime costs by the proposed policy.

4. Conclusion

In this research, we have proposed the Dynamic-Economic-Dependence and PHM based CBM policy for the multi-component system considering the dynamic economic dependence among components. For the proposed CBM policy, the risk threshold is dependent on the time-varying downtime cost instead of being constant value. So the dynamic risk threshold is represented by the product of the time-dependent downtime cost and the risk threshold scaling factors for the proposed CBM policy. However, the cost evaluation for DED&PHM based CBM policy becomes much more complex when the number of components becomes large and the types of the components are different, so a simulation method is developed for the proposed policy to efficiently reduce the computation time. For the simulation cases, it shows that simulation method in this paper can efficiently reduce calculation of cost evaluation without affecting the accuracy of the optimal risk thresholds. Future research topics will be to develop CBM policies for the multi-component system with stochastic economy dependence, and how to determine the optimal risk thresholds within reasonable computing time.

References

[1] M. Munasinghe, W. G. Scott and M. Gellerson, “Economics of power system reliability and planning”, Theory and case study, International Bank for Reconstruction and Development, Washington, DC (USA), **(1979)**.
[2] P. K. Koner and G. Ledwich, “Distribution Network Optimisation for Enhanced Reliability”, Journal of Electrical & Electronics Engineering, Australia, vol. 21, no. 3, **(2002)**, pp. 199-208.
[3] R. Billinton, M. Fotuhi-Firuzabad, and L. Bertling, “Bibliography on the application of probability methods in power system reliability evaluation 1996-1999”. Power Systems, IEEE Transactions on, vol. 16, no. 4, **(2001)**, pp. 595-602.
[4] H. Singh and A. Papalexopoulos, “Competitive procurement of ancillary services by an independent system operator”, Power Systems, IEEE Transactions on, vol. 14, no. 2, **(1999)**, pp. 498-504.
[5] R. Mukerji, H. M. Merrill, B. W. Erickson, J. H. Parker and R. E. Friedman, “Power plant maintenance scheduling: optimizing economics and reliability”, Power Systems, IEEE Transactions on, vol. 6, no. 2, **(1991)**, pp. 476-483.
[6] H. Kim, Y. Hayashi and K. Nara, “An algorithm for thermal unit maintenance scheduling through combined use of GA, SA and TS”, Power Systems, IEEE Transactions on, vol. 12, no. 1, **(1997)**, pp. 329-335.
[7] L. Thomas, “A survey of maintenance and replacement models for maintainability and reliability of multi-item systems”, Reliability Engineering, vol. 16, no. 4, **(1986)**, pp. 297-309.
[8] H. Wang, “A survey of maintenance policies of deteriorating systems”, European Journal of Operational Research”, vol. 139, no. 3, **(2002)**, pp. 469-489.
[9] M. Berg and B. Epstein, “Comparison of age, block, and failure replacement policies”, Reliability, IEEE Transactions on, vol. 27, no. 1, **(1978)**, pp. 25-29.
[10] D. Cho and M. Parlar, “A survey of maintenance models for multi-unit systems”, European Journal of Operational Research, vol. 51, no. 1, **(1991)**, pp. 1-23.
[11] X. Zheng and N. Fard, “A maintenance policy for repairable systems based on opportunistic failure-rate tolerance”, Reliability, IEEE Transactions on, vol. 40, no. 2, **(1991)**, pp. 237-244.

[12] R. Dekker, R. E. Wildeman and F. A. van der Duyn Schouten, " A review of multi-component maintenance models with economic dependence", Mathematical Methods of Operations Research, vol. 45, no. 3, **(1997)**, pp. 411-435.
[13] A. Heng, S. Zhang, A. C. C. Tan and J. Mathew, "Rotating machinery prognostics: State of the art, challenges and opportunities", Mechanical Systems and Signal Processing, vol. 23, no. 3, **(2009)**, pp. 724-739.
[14] Z. Tian and H. Liao, "Condition based maintenance optimization for multi-component systems using proportional hazards model", Reliability Engineering & System Safety, vol. 96, no. 5, **(2011)**, pp. 581-589.
[15] A. K. S. Jardine, D. M. Lin and D. Banjevic, "A review on machinery diagnostics and prognostics implementing condition-based maintenance", Mechanical Systems and Signal Processing, vol. 20, no. 7, **(2006)**, pp. 1483-1510.
[16] A. K. S. Jardine, V. Makis, D. Banjevic, D. Braticevic, and M. Ennis, "A decision optimization model for condition-based maintenance", Journal of Quality in Maintenance Engineering, vol. 4, no. 2, **(1998)**, pp. 115-121.
[17] A. K. S. Jardine, D. Banjevic, D. W. Wiseman, S. Buck and T. Joseph, "Optimizing a mine haul truck wheel motors' condition monitoring program Use of proportional hazards modeling", Journal of Quality in Maintenance Engineering, vol. 7, no. 4, **(2001)**, pp. 286-302.
[18] D. Banjevic, A. K. S. J. V. Makis and M. Ennis, "A control-limit policy and software for condition-based maintenance optimization", INFOR, vol. 39, no. 1, **(2001)**, pp. 32.
[19] M. Marseguerra, E. Zio and L. Podofillini, "Condition-based maintenance optimization by means of genetic algorithms and Monte Carlo simulation", Reliability Engineering & System Safety, vol. 77, no. 2, **(2002)**, pp. 151-165.
[20] Monthly Locational Marginal Pricing, http://www.pjm.com/markets-and-operations/energy/real-time/monthlylmp.aspx.
[21] S. R. Sharma, "Feasibility study of options for aging hydro-power generation facility", Master Thesis, The University of Texas at Arlington, **(2006)**.
[22] D. Percy and B. Alkali, "Generalized proportional intensities models for repairable systems", IMA Journal of Management Mathematics, vol. 17, no. 2, **(2006)**, pp. 171-185.
[23] J. D. Hamilton, "Time series analysis", Cambridge Univ Press, vol. 2, **(1994)**.
[24] G. E. Box, G. M. Jenkins and G. C. Reinsel, "Time series analysis: forecasting and control", A John Wiley & Sons, Inc., Publication, fourth edition, **(2008)**.

Authors

Xinbo Qian. She was born in Jiangsu province, China on January 10, 1986. She received her bachelor degree in Thermal and Power Engineering from Hohai University, Nanjing in 2008. Presently she is a PhD candidate from School of Hydropower and Information Engineering, Huazhong University of Science and Technology, Wuhan. Her current research is related to the condition-based maintenance of hydroelectric power plants in the context of electricity markets.

Yonggang Wu. He was born in Hunan province, China on October 27, 1963. He received his B.S. degree in automatic control engineering in 1984 and M.S. degree in electrical engineering in 1987, all from Huazhong University of Science and Technology (HUST). He received the degree of Ph.D. in power systems and automation in 1997, also from HUST. Since 1987, he has been researching in power system and plant optimization and control, hydro-thermal electrical planning. Now he is a full professor of the School of Hydropower and Information Engineering, HUST.