

# A Multi-Agent Computing Approach for Power System Production Simulation

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**Abstract:** Along with the development of smart grid, demand response becomes the key character of it. Traditional method is unable to simulate the effect of the demand response to the power system operation. Intelligent engineering theory provides us a useful tool to address such difficulty. Based on the intelligent engineering, kinds of demand response resource are integrated and treated as efficiency power plant (EPP), an power system production simulation method with the multi agent computing approach is presented to simulate the EPP, among which generation agent (GA), efficiency power plant (EPPA), as well as the coordination agent (CA) is established. CA make the generation scheduling according to the bidding price of the power plant aiming to balance the power demand and supply, GA and EPPA adjust its bidding strategies on the basis of clear price and the profits received. Comparison with equivalent energy function and sequence operation method, as well as analysis and calculation of the reliability indicator of EPP has been carried out based on the IEEE RTS 79 system demonstrate the validity of the proposed approach.

**Keywords:** Intelligent Engineering, Demand Response, Efficiency Power Plant, Probabilistic Production Simulation

## 1 Introduction

In order to meet the challenges of energy shortage and resources limitation, smart grid will become the development trend of the electricity sector in the near future. Consumer can interact with grid according to their objectives and the amounts of shiftable load [1]. In the smart grid, power planning takes into account both the conventional plants and the resources in demand side, which can be integrated into Efficiency Power Plant (EPP). Obviously, EPP can reduce the demand for electricity so as to optimize the resource allocation and improve the efficiency of electricity use at the same time [2].

With the gradual development of smart grid, it is necessary to take into account EPP's effect in terms of power source optimization and power system operation analysis. Therefore, we have done some research on power system production simulation considering EPP resource.

Traditionally, Equivalent Energy Function Method and Monte Carlo Sampling Method are used to analyze power system operation. Paper [3, 4, 5] introduced the principle and calculation processes of Equivalent Energy Function Method, and estimated the reliability of power

system with power plants have energy constraints. Paper [6] made an introduction of principles and characteristics of three basic Monte Carlo Simulation algorithms, Sequential Simulation, Non-sequential Simulation and Pseudo-sequential Simulation, expounded the idea and procedure of Monte Carlo method in reliability calculation of power system and analyzed the convergence of this approach. However, equivalent load duration curve used in the Equivalent Energy Function Method is an approximate method, and it fails to separate load of different reliability requirements. Moreover, large scale of computation in the Monte Carlo Method will cost a lot of time, thus accuracy of the result will be difficult to achieve.

Considering the drawbacks of above traditional methods, Paper [7] and [8] proposed Sequence Operation Method that are suit for Integrated Resource Planning and Probabilistic Production Simulation in power market based on sequence operation theory. This method takes resources in supply and demand sides, as well as loads of different reliability requirements into account, and treats production simulation as the matching process between supply and demand. During the supply-demand balance process, sequence operation method sort different

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resources in supply and demand sides according to their economic index, and terminate the process when it reaches equilibrium. Then economic and reliability indicators can be calculated consequently. However, based on the fixed order of the supply resource and the load, the sequence operation method ignore the ability of the resource in the supply side and some load could adjust its output during operation.

With the development of Artificial Intelligence (AI) and Agent simulation technology, Intelligent Engineering, which is based on Neural Network, Fuzzy system and AI, can reflect the behaviors of individuals and the way they adjust their behaviors, as well as how the whole system evolve to the optimal state, it has been utilized widely in power development strategy[9]and power grid planning [10].

Based on Intelligent Engineering theory, this paper proposes a multi agent computing approach to carry out the simulation of both conventional units and EPPs considering forced outage of units. Then, economic indicators and reliability indicators of the system can be calculated. Finally, comparison of agent simulation method with Equivalent Power Function Method and Serialization Method, as well as the case study of RTS-79 considering EPPs verifies the validity of the proposed method.

## 2 Intelligent Engineering Hybrid Model

Intelligent Engineering extends traditional mathematical model and uses generalized model to depict mapping relationship in the complex systems. Moreover, in the generalized model, mapping  $f$  is used to reflect a certain relationship between any set  $X$  and  $Y$ :

$$f : x \rightarrow y \quad x \in X, y \in Y \quad (1)$$

Generalized model is consisted of the following five kinds of models: mathematical model, rule model, fuzzy reasoning model, neural network model and hybrid model.

### 2.1 Agent model

Agent model combines two different models above and creates an intelligent space, which can be regarded as a hybrid model[11].In the agent model, agent can be described as:

$$a_{gti} = \langle S, A, u, p \rangle \quad (2)$$

where  $a_{gti}$  is agent  $i$ ;  $S$  refers to the intelligent space,  $A$  refers to the action space;  $u : S \times A \rightarrow R$  refers to the utility matrix that Agent received,  $p : S \times A \rightarrow \Delta$  represents the transformation function matrix.

The utility of agent can be described as

$$U_i = U_i(c_{i1}, c_{i2} \dots c_{im})$$

$$1) \frac{\partial U_i}{\partial c_i} > 0 (i = 1 \dots n)$$

$U_i$  increase with the increment of the good consumption  $c_i$

$$2) \frac{\partial^2 U_i}{\partial c_i^2} > 0 (i = 1 \dots n)$$

marginal utility decrease progressively.

### 2.2 Decision making process

Agent aims to maximize its payoff and the decision making process can be described as follows:

$$v(s, \pi) = \sum \beta^t E(u_t | \pi, s_0 = s) \quad \beta \in [0, 1] \quad (3)$$

where  $s_0$  is the initial state,  $u_t$  is the payoff received at hour  $t$ ;  $\beta$  is the coefficient; agent will adjust its production in response to the change in the external environment and reach a new state  $v(s', \pi')$  after adopting strategy  $\pi'$ .

At the same time, other agent in the system will adjust strategy  $A_i$  according to its state  $S_i$   $r_{S_i} = A_1, A_2, \dots A_n | S_i$   $R = r_{S_0}, r_{S_1}, \dots r_{S_n}$  Therefore, utility of the whole system can be described as follows:

$$U = u(U_1) + u(U_2) + u(U_3) + \dots + u(U_n) = \sum_{1 \leq i} U_i = \sum_{1 \leq i \leq j} C_{im} \quad (4)$$

After every agent choose its strategy  $\pi$ , all the agent set  $A_{gti} = a_{gt1}, a_{gt2}, \dots a_{gtn}$  will come into the state of the whole system  $s = (s_1, s_2, \dots s_n)$ , among which  $s_i \in \mathbb{S}_i (i = 1, 2, \dots n)$ . State of the whole system as hour  $t$  can be described as  $s^t$ .

#### Assumption:

Generally, relations of the agent are non-cooperative, if agent  $a_{gti}$  change its strategy from  $\pi_i$  to  $f_i$ , just as follows:

$$\forall S_0, \pi \quad \text{and} \quad v(s, \pi) = v_0(s_0, \pi_0) \quad (5)$$

then

$$S \parallel f_i \quad \text{and} \quad S \parallel f_i = (s_1, s_2, \dots s_n) \quad (6)$$

and

$$v(s, \pi) = u(s, a_\pi) + \beta \Sigma (s' | s, a_\pi) v(s', \pi) \quad (7)$$

$$u'_i(s', \pi') \leftarrow u_i(s, \pi) \quad (8)$$

if

$$u'_i s'^{(t)} \parallel f_i \leq u'_i(s'^{(t)}) \quad (9)$$

then

$$s'^{(t)} = s(t) \quad (10)$$

where  $s'^{(t)}$  is the dynamic equilibrium state arrived after interaction between agents at hour  $t$ .

Thus, evolution of complex systems can be expressed by intelligent path set  $PB$  which link initial state set  $S_0$  and target state set  $D$ :

$$(S_0, D) \rightarrow PB \quad (11)$$

Therefore, the approach then becomes to solve  $B = \langle S_0, D, PB \rangle$ , and  $m-1$  intermediate states between  $S_0$  and  $D$  form an ordered sequence  $S_0, D_1, D_2, \dots, D$  and  $PB_1, PB_2, \dots, PB_m$ . Then we can get  $m$  states in the solving process, as shown in Fig.1:

$$B_{11} = \langle S_0, D_1, PB_1 \rangle \quad (12)$$

$$B_{12} = \langle D_1, D_2, PB_2 \rangle \quad (13)$$

$$B_{1m} = \langle D_{m-1}, D, PB_m \rangle \quad (14)$$

$$B = B_{11} \cap B_{11} \cap \dots \cap B_{1m}, PB = PB_1, PB_2, \dots, PB_m \quad (15)$$

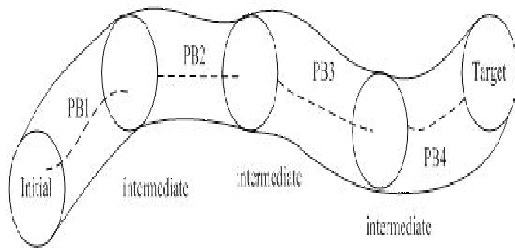


Fig. 1: Intelligent path and its solving mechanism

### 3 Agent-based Production Simulation Model considering EPPs

In smart grid, power companies and consumers adjust their strategies and behaviors in order to maximum their profits. Agent-based model can simulate individual's autonomous response behaviors ideally, so it can be used to simulate the autonomies of power companies, consumers, and the interactions between individuals and the grid. Also, further analysis on the reliability of grid in interactive mode can be carried out.

#### 3.1 Model Design

The proposed model is consisted of three kinds of entities: power generation enterprises, power consumers and grid. So the Agent-based production simulation model considering EPPs includes Generation Agent (GA), EPP Agent (EPPA) and Coordination Agent (CA).

#### 3.2 Generation Agent

Generation Agents represent various conventional generator units, such as thermal power, hydropower and

nuclear power, etc. Firstly, operating state of the conventional units is simulated by sampling method. Then the process is carried out repeatedly to simulate the stochastic forced outage of the units approximately. GAs select bidding strategies aiming to maximize their payoffs and its objective function is:

$$Max f_i = \lambda P_{GAi} T_{GAi} X_{i,t} - C_i P_{GAi} T_{GAi} X_{i,t} \quad (16)$$

$$s.t. P_{GAi min} \leq P_{GAi} \leq P_{GAi max} \quad (17)$$

$$Q_{GAi min} \leq Q_{GAi} \leq Q_{GAi max} \quad (18)$$

$$(t_{up}(i) - T_i^{up})(X_{i,t-1} - X_{i,t}) \geq 0 \quad (19)$$

$$(t_{down}(i) - T_i^{down})(X_{i,t-1} - X_{i,t}) \geq 0 \quad (20)$$

$$B = B_{11} \cap B_{11} \cap \dots \cap B_{1m}, PB = PB_1, PB_2, \dots, PB_m \quad (21)$$

where  $\lambda$  is the clear price in the market;  $P_{GAi}$  is the power generation of generator agent  $i$ ;  $T_{GAi}$  is the total operation time of generator agent  $i$ ;  $X_{i,t}$  is the status of generator  $i$  at hour  $t$ , and generator  $i$  is on ( $X_{i,t} = 1$ ) at hour  $t$ ;  $t_{up}(i)$  and  $t_{down}(i)$  refer to the duration during which unit  $i$  is continuously ON/OFF;  $T_i^{up}$  and  $T_i^{down}$  refer to the minimum up/down time of generator  $i$ ;  $C_i P_{GAi}$  is the cost function of generator  $i$ ;  $Q_{GAi}$  is the reactive power of the generator  $i$ ;  $P_{GAi min}$ ,  $P_{GAi max}$  and  $Q_{GAi min}$ ,  $Q_{GAi max}$  refer to the minimum and maximum output of the active and reactive power of generator  $i$ . According to paper [12], cost function of generator  $i$  can be described as follows:

$$C_i(P_{GAi}) = \alpha_i P_{GAi}^2 + \beta_i P_{GAi} + \gamma_i \quad (22)$$

where  $\alpha_i, \beta_i, \gamma_i$  refers to the coefficient of the cost function.

Generator  $i$  bids according to their marginal cost as follows:

$$\lambda_i P_{GAi} = \frac{dC_i(P_{GAi})}{dP_{GAi}} = 2\alpha_i P_{GAi} + \beta_i \quad (23)$$

Generator evaluates its profit and adjusts its bidding strategy, as shown in Equation(24)

$$\lambda_i(t+1) = \phi_{GAi}(\lambda_i(t), f_i, P_{GAi}) \quad (24)$$

where  $\phi_{GAi}$  is the adjusting coefficient of the generator  $i$ ;  $t$  refers to the operation time.

#### 3.3 Efficiency Power Plant Agent

In the smart grid, consumers can interact with the grid so as to reduce their cost. Therefore, the efficiency power plant can be characterized by the way consumer responses to the price change in the market, and it can be described as follows:

### 3.3.1 Energy Saving EPP

Energy can be saved by replacing the high energy consumption equipment with energy saving equipment to save energy, for example, high efficiency motor, high efficiency appliance, and the saved energy can be treated as energy resources, thus output of this kind of EPP is the difference between these two kinds of equipment[13], as illustrated in Equation(25)

$$P_{EPPi}(t) = P_c(t) - P_{saving}(t) \quad (25)$$

where  $P_{EPPi}(t)$  is the output of the energy saving EPP;  $P_c(t)$  and  $P_{saving}(t)$  refer to the output of the traditional and replaced equipment respectively.

So, cost of energy saving EPP can be calculated as follows:

$$C_i(P_{EPPi}) = C_i(P_{saving}) - C_i(P_c) \quad (26)$$

where  $C_i(P_{EPPi})$  is the cost function of energy saving EPP;  $C_i(P_{saving})$  and  $C_i(P_c)$  is the cost of buying high efficiency and traditional equipment respectively.

Given that energy saving EPP is a reduction of the load curve, so, energy saving EPP chooses the fixed bidding strategy, and the profit can be calculated as follows:

$$f_i = T_{EPPi} \sum \lambda P_{EPPi} - C_i(P_{EPPi} T_{EPPi}) \quad (27)$$

$$s.t. P_{EPPimin} \leq P_{EPPi} \leq P_{EPPimax} \quad (28)$$

$$Q_{EPPimin} \leq Q_{EPPi} \leq Q_{EPPimax} \quad (29)$$

where  $P_{EPPimin}$ ,  $P_{EPPimax}$ ,  $Q_{EPPimin}$ ,  $Q_{EPPimax}$  refer to the minimum and maximum of the active power and reactive power of the energy saving EPP respectively.

### 3.3.2 Transferable and Interruptable EPP

Transferable and Interruptable EPP modifies the load in response to the system condition, for example, shifting them to off-peak periods or trimming the peak loads. Assuming that output of these two EPPs varies with the clear price in the market, and it is described as follows:

$$P_{EPPj}(t) = b_{EPPj} \lambda \quad (30)$$

where  $P_{EPPj1}(t)$  and  $P_{EPPj2}(t)$  refer to the output of the transferable and interruptable EPP respectively;  $b_{EPPj}$  is the coefficient of the output-price function.

EPPs bidding according to their cost, as illustrated below:

$$\lambda_j(P_{EPPj}) = b_{EPPj} + c_{EPPj} P_{EPPj} \quad (31)$$

where  $b_{EPPj}$  and  $c_{EPPj}$  is the coefficient of its bidding price and output.

Moreover, these two EPPs aim to maximize their payoffs in response to the price changes in the market, their target and constraint can be described as follows:

$$Max f_j = \sum \lambda P_{EPPj} T_{EPPj} - C_j(P_{EPPj} T_{EPPj}) \quad (32)$$

$$s.t. 0 \leq P_{EPPj}(t) \leq P_{load}(t) \quad (33)$$

$$Q_{EPPjmin} \leq Q_{EPPj} \leq Q_{EPPjmax} \quad (34)$$

$$\sum P_{EPPj}(kt) \leq P_{load}(k) \quad (35)$$

where  $C_j(P_{EPPj} T_{EPPj})$  is the cost of the transferable and interruptable EPP;  $T_{EPPj}$  is the operation period of the EPP;  $P_{EPPjmin}$  is the minimum output of the EPP, for interruptable EPP,  $P_{EPPjmin} = 0$ ;  $P_{EPPjmax}$  the maximum output of the EPP;  $\sum P_{EPPj}(kt)$  is the load that shifted from hour  $k$  to hour  $t$ .

Also, EPP adjust its bidding strategy at hour  $t$  according to its output and profit received at hour  $t - 1$ , as shown in Equation(36)

$$\lambda_j(t+1) \rightarrow \lambda_j(t) + \xi(\lambda, \lambda_j(P_{EPPj}), f_j) \quad (36)$$

where  $\xi$  the adjustment coefficient;  $f_j$  is the profit received.

## 3.4 Coordination Agent

Aiming to minimize the operation cost, coordination agent take decisions for committing generators depend on the bidding price and output of the power plant and the power demand under the network constraint. Then, Loss of Load Probability and Expected Energy Not Served during the time interval T can be calculated, CA aims to minimize the operation cost of the system:

$$Min f = \sum V_i(P_{GAi}) + \sum V_j(P_{EPPj}) \quad (37)$$

$$s.t. \sum_{i \in G} P_{GAi} + \sum_{j \in EPP} P_{EPPj} - P_{load} - P_{loss}(P_{GAi}, P_{load}) = 0 \quad (38)$$

$$P_{Tran}(P_{GAi}, P_{load}) \leq P_{Tran,max} \quad (39)$$

where  $V_i$  and  $V_j$  refers to the operation cost of the traditional generator and EPP;  $P_{loss}(P_{GAi}, P_{load})$  is the line loss;  $P_{Tran}(P_{GAi}, P_{load})$  is the power transmitted in line  $i$ ;  $P_{Tran,max}$  is the maximum transmission capability.

Coordination agent calculates the market clear price according the bidding price and the power demand and supply, and then makes the scheduling plan, as shown in Equation(40) and Equation(41)

$$B(t) = (\lambda_1(t), P_{GA1}(T)), \dots, (\lambda_n(t), P_{GAN}(T)), \dots, (\lambda_{EPPi}(t), P_{EPPi}(T)) \quad (40)$$

$$\lambda_1(t) \leq \lambda_1(t), \dots, \lambda_n(t) \tag{41}$$

if

$$P(t) \geq P_{Load} \tag{42}$$

then

$$\sum_{1 \leq i} P_{GAI}(t) = P_{Load}, \lambda(t) = \lambda_m(t) \tag{43}$$

else

$$P(t) \leq P_{Load} \tag{44}$$

$$\lambda(t) = \lambda_n(t) \tag{45}$$

$$P_{loss} = P_{Load} - P_t \tag{46}$$

where  $P_{loss}$  refers to loss of energy.

Finally, LOLP and EENS can be calculated as follows:

$$LOLP = \frac{\sum t_{loss}}{T} \tag{47}$$

$$EENS = \frac{8760 \sum P_{loss} t_{loss}}{T} \tag{48}$$

where  $t_{loss}$  refers to the duration during when power supply can not meet the demand;  $P_{loss} t_{loss}$  is the loss of energy.

### 3.5 Coordination Mechanism

Fig 2 shows a simplified architecture of the proposed multi-agent approach. For intelligent scheduling of generators, GA can communicate and share information with CA, and coordination between generators can be possible via CA. After GA and EPPA check their up and down output constraints, CA sorts the generator in ascending order of their bidding price, and then commits the generator. GA and EPPA adjust its bidding strategy at hour  $t$  based on the clear price delivered at hour  $t - 1$  by the CA. Finally, LOLP and EENS can be calculated when the CA terminates the proposed multi-agent approach at hour  $T$ .

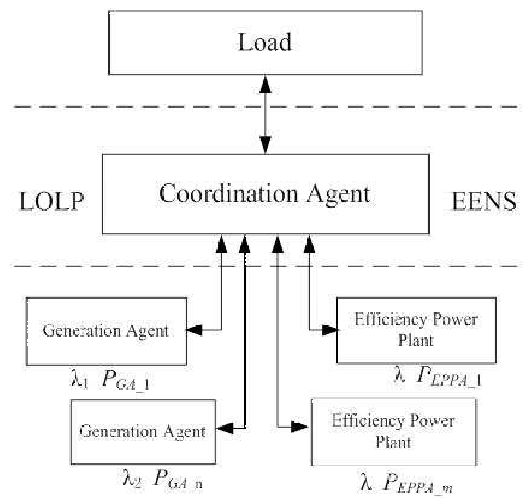


Fig. 2: Coordination mechanism of agent

### 3.6 Simulation flow chart

In this paper, communication and coordination between agents can be seen in the flow chart as shown in Fig 3.

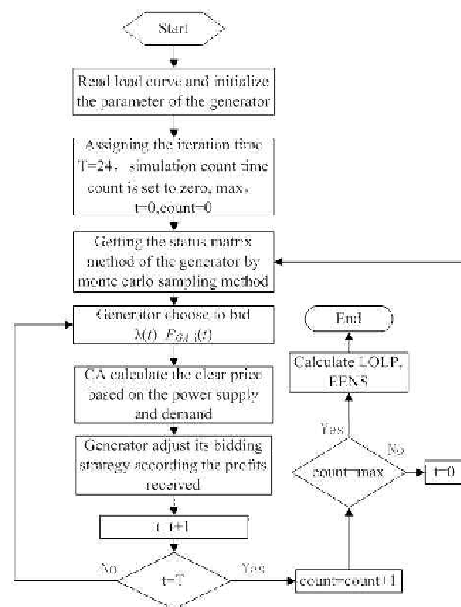


Fig. 3: Flow chart of the simulation

Step 1: This stage is designed to initialize parameters of the generators, as well as read the load curve.

Step 2: Assigning the iteration time  $T=24$ , and starting iteration time  $t=0$ . Similarly, simulation time



count is set to zero and its maximum value max is set to 100.

Step 3: According to the FOR of the generator, its operation status matrix can be got by monte carlo sampling method.

Step 4: GA choose to bid on the basis of (22), and sends its output and bidding price to the CA, so it is with the EPPA.

Step 5: CA sorts the generators in ascending order of their bidding price, and the market clear price can be calculated on the basis of the power supply and demand, and delivered to the GA and EPPA consequently.

Step 6: GA and EPPA evaluate its profit and adjust bidding strategy based on (23) and (35).

Step 7: The iteration time  $t$  increased by 1, if  $t$  is less than  $T$ , go to step 4; else, go to step 8.

Step 8: The simulation times count increased by 1, if count is less than max,  $t$  is set to zero and return to step 4; else go to step 9.

Step 9: EENS and LOLP can be calculated, terminate the iteration and output the result.

## 4 Validation

In this paper, validation analysis have been conducted by comparing the multi-agent approach and equivalent energy function and sequence operation method.

### 4.1 Comparing to the equivalent energy function

According to case 4-4 in paper[5], peak load of the system is 82MW, and the energy supply is consisted of three generators, whose capacity is 40MW, 40MW, 20MW respectively, with the coal consumption of 400g, 400g, 450g every kWh.

**Table 1:** Simulation results compared to EEF method

	EEF	Agent Method	Difference
EENS	52.21	50.43	-3.41%
LOLP	0.14	0.13	-6.80%

As shown in Table 1, the LOLP and EENS in the agent model is close to the results acquired in the EEF method, and difference between them are 3.41% and 6.8% respectively. The reason for this difference is because the load curve used in the EEF method is transformed to equivalent load duration curve, error will occur during the transformation process, while chronological load curve used in the agent method without the transformation may offer additional accuracy.

### 4.2 Comparing to the sequence operation method

**Table 2:** Results compared with the series methods

	Real	Sequence Operation	Agent
LOLE d/a	1.37	1.34	1.35
LOLP	0.00%	2.31%	-1.61%

Table 2 illustrates the difference of using sequence operation method[14] and agent method to calculate the reliability index of the IEEE RTS 79 system[15]. It can be seen that difference of these two methods are 2.31% and 1.61% comparing to the results in paper[16]. So, the results derived from the simulation by agent model are closed to the values acquired in reality, thus it can be used to simulate the power system operation considering the demand response resource, as well as the EPP resources.

## 5 Conclusion

In conclusion, based on the intelligent engineering theory, a multi agent computing approach is presented in this paper to carry out the production simulation of the power system, among which different rules and principles of the agents are established. Comparison to the traditional equivalent energy function and sequence operation method verifies the validation of the multi agent computing approach. Thus, agent simulation approach can be used to simulate production of the power system considering EPPs. Future research will be focused on the different initial state and its effect on: 1) the equilibrium state  $u_i^t, s_i^{(t)} \parallel f_i \leq u_i^t, s_i^{(t)}$  2) the intelligent path  $B = \langle S_0, D, PB \rangle$ .

## References

- [1] L.Z Ya, Electric Power and Energy in China, China Electric Power Press, Beijing, 2012.
- [2] Z.J Hong, H.Z Guang and T.J Wei, Automation of Electric Power Systems **18**, 27-31 (2012).
- [3] W.X Fan and W.X Li, Automation of Electric Power Systems **8**, 10-15 (2003).
- [4] C.H Yong and W.X Fan, Automation of Electric Power Systems **11**, 22-26 (2000).
- [5] W.X Fan, Power System Planning Fundamentals, China Electric Power Press, Beijing, 1994.
- [6] S.X Tong, Study on Reliability Evaluation of Power System based on Monte Carlo Simulation, Dissertation papers, Department of Electrical Engineering, Shandong University.
- [7] K.C Qing, B. L Chao, X Qing, Proceedings of the CSEE **9**, 6-11 (2002).
- [8] Z.Ning, K.C Qing, C.Z Ping, Proceedings of the CSEE **25**, 1-9 (2011).

- [9] H.Z Guang, F.Y Ping, Proceedings of the CSEE **3**, 45-49 (2000).
- [10] D.Wei, H.Z Guang, Proceedings of the CSEE **16**, 15-21 (2008).
- [11] H.Z Guang, S.B Guo, Power Supply and Demand Simulation: Soft Science Based on the Intelligent Engineering, China Electric Power Press, Beijing, 2009.
- [12] F.Jie, Y.L Bing, L.X Gang, Automation of Electric Power Systems **9**, 60-65 (2013).
- [13] Z.J hong, Research on Efficiency Power Plant Theory and Integrated Resource Strategic Planning Model Economic Record, Dissertation papers, Department of economic management, North China Electric Power University **32**, 334-361 (1956).
- [14] K.C Qing, X. Qing, X. N De, Sequence Operation Theory and Its Applications, Tsinghua University Press, Beijing, 2003.
- [15] A Report Prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee, IEEE Transactions on Power Apparatus and Systems **6**, 2047-2054 (1979).
- [16] R.N.Allan, R. Billinton, N.M.K. Abdel-Gawad, IEEE Transactions on Power Systems **4**, 1-7 (1996).



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