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Congestion Adaptability Management in Power Market

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Abstract

This paper presents a novel method of congestion adaptability management in electricity power markets based on risk theory. Probability distribution of ambient conditions around transmission line is taken into account. Impact of overload of transmission line is also included. Instead of the traditional deterministic current or power constraint, the risk constraint is used for transmission line thermal security. An optimal power flow model is built based on the risk constraint. Primal-Dual Interior Point Method is adopted to solve the problem. The results provide a useful decision-making assistance for the independent system operator to relief transmission congestion. A test power system is used to illustrate the efficiency of the proposed method.

Keywords: *Power system, Congestion adaptability management, risk, Primal-Dual Interior Point Method*

1. Introduction

The electricity power system has been shifting from a regulated system to a competitive and uncertain market environment. The organizational unbundling of supply, transmission, and system operation has resulted in more highly stressed and unpredictable operating conditions. Transmission congestion occurs when demand for power transmission exceeds a system's capability. Transmission congestion may render power system instability. Many countries have already reported cases of system collapse with losses of millions of dollars. Congestion adaptability management consists in enforcing transmission capacity limits to ensure stability condition for a secure operation. ISO should determine the changes in the congestion adaptability management that ensure a secure operation [1-3].

Generally, the operation of congestion adaptability management aims at the adjustment cost minimization. As a result, OPF has been widely used in congestion adaptability management of power systems for power dispatch. The purpose of OPF is to schedule power system controls to optimize an objective function while satisfying a set of nonlinear equality and inequality constraints. Some researchers have been undertaken on the congestion adaptability management based on different OPF models. Reference [4-8] proposes a basic OPF model on transmission congestion. Reference [9] proposes a modified OPF model constrained by voltage stability on congestion adaptability management. Reference [10] proposes a multi-objective OPF method on congestion adaptability management with special emphasis on voltage stability. Up to now, almost all the relative researches on OPF for congestion adaptability management are based on deterministic method. The deterministic method optimizes economy within hard constraints of the secure operational region. However, with the emphasis on economic competition and the associated increased network vulnerability, there is a growing recognition that the deterministic method cannot tradeoff between the economy and security. Especially, the deterministic thermal constraint of transmission line in traditional OPF model is typically conservative and results in under-utilization of the conductors.

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This fact is of particular importance in a competitive electricity power market. Risk theory is introduced to power system studying recently. Risk index can quantitatively capture the factors that determine security level: probability and impact of events. And risk based method is a good solution for tradeoff between the economy and security.

To find an efficient solution to this problem, a new risk based method of congestion adaptability management is presented in this paper. The risk constraint is used for transmission line thermal security instead of the traditional deterministic current or power constraint. Under the risk constraint, not only the probability distribution of ambient conditions around transmission line but also the impact of overload of transmission line can be taken into account. A RBOPF model is built based on the risk constraint, whose objective is to minimize the adjustment cost. The PDIPM is adopted to solve the RBOPF problem. The results provide a useful decision-making assistance for the ISO to relief transmission congestion.

This paper is organized as follows. Section II introduces the deterministic OPF model and its conservative character. The basic risk theory and its applications are introduced in section III. Section IV presents the detailed results of applying the method to the test system. Finally, section V describes the main contributions of the paper and discusses some possible future research directions.

2. Deterministic OPF Model

The following is a typical deterministic OPF model

$$\begin{aligned}
&\min \sum f(P_{gi}, P_{lj}) \\
&s.t. \\
&P_i - V_i \sum_{j \in N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \\
&Q_i - V_i \sum_{j \in N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \\
&\underline{P}_{gi} \le P_{gi} \le \overline{P}_{gi} \\
&\underline{Q}_{ri} \le Q_{ri} \le \overline{Q}_{ri} \\
&\underline{V}_i \le V_i \le \overline{V}_i \\
&\left| I_{ij} \right| \le \overline{I}_{ij}
\end{aligned} \tag{1}$$

The first two equality constraints are power flow constraints. The third and the fourth are active and reactive power generation constraints respectively. The fifth is the bus voltage constraints. The last one is the transmission line thermal constraints. These constraints represent deterministic constraints, which provide a straightforward approach to operational decision-making. The deterministic OPF method optimizes economy within hard constraints of the secure operational region. However, with the emphasis on economic competition and the associated increased network vulnerability, there is a growing recognition that the deterministic OPF method cannot tradeoff of the economy and security. As the deterministic thermal constraint of transmission line of traditional OPF model is typically conservative and results in under-utilization of the conductors, we will put our emphases on this constraint.

Every transmission line used in power system has an associated current limit, which is called the thermal limit corresponding to the thermal constraint in OPF model. This thermal limit is determined by the maximum of design temperature of the transmission line, which is associated with both the sag of the transmission line and the rate of annealing. Generally, the thermal limit is deterministically calculated by assuming specific values of ambient conditions. Ambient temperature, wind speed and solar radiation are the three major factors of ambient condition. It is obviously that these factors are random and not always so severe. Hence the deterministic result is typically conservative and renders under-utilization of the conductors as Figure 1. Even when the transmission line caries its deterministic limiting current $\overline{I}$, its temperature is typically below its maximum design value θ_M . Only for very high air temperature, very serious solar radiation and very low wind speed, does the conductor temperature exceed θ_M

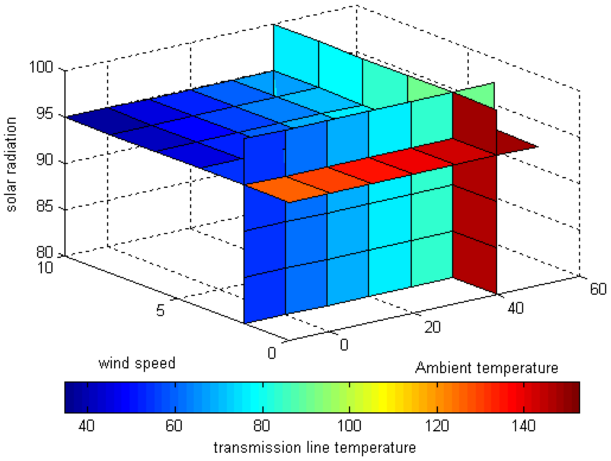

Figure 1. Conductor Temperature under Various Ambient Conditions
($\overline{I} = 992A, \theta_M = 100°C$ **)**

3. Risk Theory and its Applications

Risk is defined as a condition under which there is a possibility of an adverse deviation from a desired outcome that is expected or hoped for. Risk index can quantitatively capture the factors that determine security level: probability and impact of events. The value of risk can be obtained by summing over the multiplying products of the probability and the impact of all possible outcomes.

3.1. Impact of Thermal Overload

The overload through the transmission line results in an elevation of conductor temperature, which may render sag and annealing of the transmission line. Sag may cause flashover to the ground or another line, resulting transmission line fault, even system cascading collapse. Annealing may cause the replacement of the transmission line. The impact of thermal overload provides a quantitative evaluation of the economy loss to the power system when sag and annealing take place. Reference [11] studied these problems and gave some formulations. The impact of sag $I_s[\theta]$ at conductor temperature θ is as follows

$$I_s[\theta] = \begin{cases} C_s[Fault], \theta > \theta_L \\ 0, otherwise \end{cases} \tag{2}$$

where $C_s[Fault]$ is the cost of an outage of the transmission line caused by sag, θ_L is the threshold value of sag.

The impact of annealing $I_a[\theta]$ at conductor temperature θ is proportional to the decrease of expected transmission line life and is given as follows

$$I_a[\theta] = \begin{cases} \dfrac{\Delta t}{t_0} \times C_a, \theta > \theta_M \\ 0, otherwise \end{cases} \tag{3}$$

where Δt is the decrease in expected transmission line life, t_0 is the expected remaining transmission line life. θ_M is the permissible value of current.

The impact of thermal overload $I_c[\theta]$ is the combination of the impact of sag $I_s[\theta]$ and the impact of annealing $I_a[\theta]$ as follows

$$I_c[\theta] = I_s[\theta] + I_a[\theta] \tag{4}$$

3.2. Probability of Transmission Line Temperature Distribution

Transmission line temperature is determined by both the current through it and ambient conditions. At a given current, the probability of transmission line temperature is governed by the ambient conditions. Ambient temperature θ_a, wind speed V_w and solar radiation S_r are the three major factors of ambient conditions. Hence, the probability density $P[\theta \mid I]$ of conductor temperature θ at a given current I is calculated by the joint probability function of the three major factors of ambient condition as follows

$$P[\theta \mid I] = \sum_z P[z], \forall z \in \{z : \theta(z, I) = \theta\} \tag{5}$$

where z is the set of ambient conditions that determine θ under the given current I by the thermal balance equation $\theta(z, I) = \theta$. $P[z]$ is the joint probability function of ambient conditions z. If the correlation between the factors of ambient conditions is negligible, then $P[z]$ is calculated as follows

$$P[z] = P[\theta_a] \times P[V_w] \times P[S_r] \tag{6}$$

where $P[\theta_a]$, $P[V_w]$ and $P[S_r]$ the probability functions of θ_a, V_w and S_r respectively, which can be obtained by statistics method from historical data.

3.3. Risk Analysis

When the transmission line carries a given current, its temperature varies due to the random of the ambient conditions around it. It is possible that the temperature of transmission line is greater than the permissible value and cause financial loss, which is risk. Given the current I, its value of risk $R[I]$ is obtained by summing over the multiplying products of probability of the temperature being greater than permissible value θ_M and its corresponding impacts as follows

$$R[I] = \int_{\theta > \theta_M} (P[\theta \mid I] \times I_c[\theta \mid I]) d\theta \tag{7}$$

Combining the distribution of temperature with its potential impacts, the risk curve for various current levels is obtained as follows

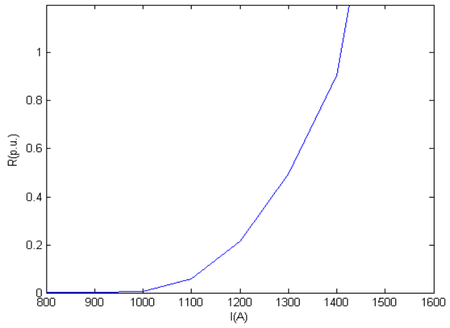

Figure 2. Risk Curve for Various Current Levels

3.4. Risk based OPF Model

Based on transmission line thermal risk function developed in the previous sections, the RBOPF model is formulated. Transmission line thermal risk limit is set on each transmission line in the system. The objective of the RBOPF is to minimize the total congestion adaptability management cost while keeping the risk of each transmission line below a predefined limit as follows

$$
\begin{aligned}
& \min \sum_{j \in Ng} (r_{Gj}^{up} \Delta P_{Gj}^{up} + r_{Gj}^{down} \Delta P_{Gj}^{down}) + \sum_{i \in Nd} (r_{Di}^{up} \Delta P_{Di}^{up} + r_{Di}^{down} \Delta P_{Di}^{down}) \\
& s.t. \\
& P_i - V_i \sum_{j \in N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \\
& Q_i - V_i \sum_{j \in N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \\
& \underline{P}_{gi} \le P_{gi} \le \overline{P}_{gi} \\
& \underline{Q}_{ri} \le Q_{ri} \le \overline{Q}_{ri} \\
& \underline{V}_i \le V_i \le \overline{V}_i \\
& \left| R(I_{ij}) \right| \le \overline{R}_{ij}
\end{aligned}
\tag{8}
$$

PDIPM is used to solve the OPF problem. It has become popular for solving this problem, given their computational advantages when dealing with large systems that include a variety of operational and control limits. The results give ISO assistance for congestion adaptability management.

4. Case Study

A 5-bus test system is used to demonstrate the proposed framework of congestion adaptability management. The network structure and parameters are shown in Figure 3. In this system there are two generators which are G1 at bus 4 and G2 at bus 5 and three 3 consumers which are L1 at bus 1, L2 at bus2 and L3 at bus 3. The transmission capacity limits are listed in Table 1. Generator active power, reactive power and redispatch cost parameters are listed in Table 2. The base power is assumed as 250MW. 0.9 and 1.1 are the lower and upper limit of bus voltage respectively. The behavior of air temperature, wind speed and solar radiation are modeled as Normal distribution. The mean and standard deviation of air temperature, wind speed and solar radiation are listed in Table 3. As detailed analysis of the thermal mechanics is beyond the scope of this paper, for simple illustration purposes, we set $C_s = 1$, C_a =0.01, and $\Delta t / t_0 \approx (\theta - \theta_M) / \theta_M$.

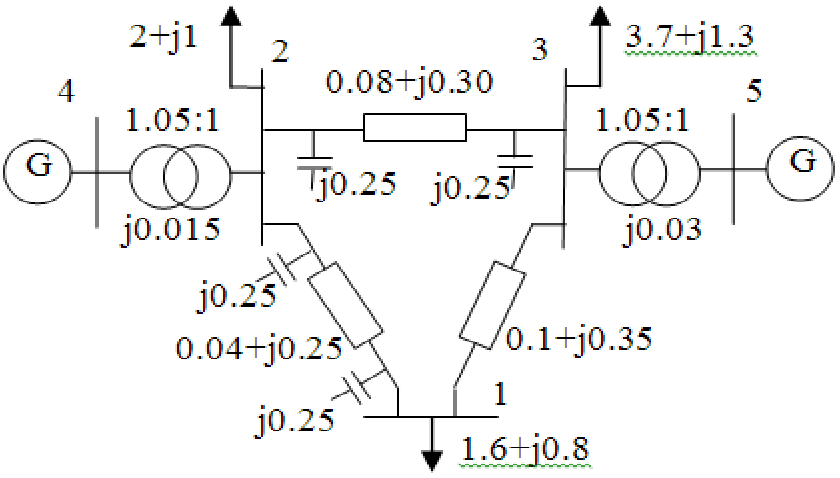

Figure 3. 5-bus Power System

Table 1. Limit of Line

Line No.	From bus	To bus	Maximum design temperature ($^{\circ}C$)	Deterministic limiting current (p.u.)	Limiting risk (p.u.)
			Ambient conditions: Air temperature 40 $^{\circ}C$, Wind velocity 2 ft/s, Solar radiation 95.2 w/ft^2		
1	1	2	100	4	0.03
2	1	3	100	4	0.03
3	2	3	100	4	0.03
4	2	4	100	4	0.03
5	3	5	100	4	0.03

Table 2. Generator Parameters

No.	Bus No.	Up limit (p.u.)		Down limit (p.u.)		Cost coefficience (p.u.)	
		Active	Reactive	Active	Reactive	r_G^{up}	r_G^{down}
G1	4	8	3	1	-3	200	100
G2	5	8	5	1	-2.1	500	400

Table 3. Distribution of Ambient Conditions

	mean	deviation
Air temperature ($^{\circ}C$)	15	6.3
Wind velocity (ft/s)	3.5	1.3
Solar radiation (w/ft^2)	95.2	38.1

A day-head electric energy market based on a pool considers is considered here. Within this pool, producers and consumers submit production and consumption bids to ISO. ISO clears the market using an appropriate market-clearing procedure. This procedure results the initial state of power system as follows

Table 4. Original Generate Planning

Generator	Bus i	Active power (p.u.)	Reactive power (p.u.)
G1	4	5.0	1.8131
G2	5	2.5794	2.2994

The transmission current $I_{24} = 4.7619$ on line L_{24} violates the upper limit $\overline{I}_{24} = 4$. ISO need to reschedule to mitigate this congestion. The results of traditional OPF and RBOPF are listed in Table 5.

Table 5. Results of Congestion Adaptability Management

		Congestion adaptability management(p.u.)	
		Traditional	Risk based
Generator	G1	4.0000	4.8790
	G2	3.4350	2.6622
Line No.	1	-1.4333	-1.5821
	2	-0.3043	-0.1682
	3	0.9048	1.2099
	4	-4.0000	-4.4355
	5	-2.8326	-2.4553
Management cost		527.8024	53.5032

Comparing with traditional OPF results, it is found that for RBOPF results although the current of L4 increase about 10.89%, the total congestion adaptability management cost is reduced about 89.86%. The results of traditional OPF are over conservative. This is mainly because the current limit in traditional OPF is determined by strict ambient conditions. However, the ambient conditions are not always so severe. Sometimes even when the line caries its deterministic limiting current, its temperature is typically below its maximum design value. Hence the results of RBOPF are more reasonable. It takes into account the random behavior of ambient conditions and gives ISO assistance for tradeoff between economy and security.

5. Conclusions

This paper presents a new congestion adaptability management method that takes into account the random behavior of ambient conditions. The RDOPF model is built based on risk constraints. PDIPM is used to obtain the results for congestion adaptability management. The main contributions of the paper are as follows

a) The model of transmission line thermal security is built. It takes into account the probability distribution of ambient conditions around transmission line and the impact of overload of transmission line.

b) The risk constraint is used for transmission line thermal security instead of the traditional deterministic current or power constraint. A risk based optimal power flow (RBOPF) model is built based on the risk constraint.

c) The risk theory is introduced to congestion adaptability management. A new framework of congestion adaptability management is built based on RBOPF. A single power system is used to illustrate the efficiency of the proposed method.

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