Multicriterion Techniques For Control-Room Security Economy Decision-Making

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Abstract: We propose a decision-support aid for control room security economy decision-making that considers probabilistic characteristics of contingencies and load conditions of power systems. The approach is based on use of risk-based security assessment to enable treatment of security level as an objective within multi-criterion decision making (MCDM) techniques. The approach is illustrated using the IEEE RTS 96 system.

Keywords: security assessment, risk, variance, MCDM, preventive action, low voltage, overload

I. Introduction

Electric power system control center operators more frequently encounter complex decision-making situations requiring assessment of multiple criteria. The following describes a situation recently witnessed in a major US utility control center. Bus names are fictitious. *Thursday,2pm: Outside temperature is 102° F. Every available generator is on-line, and all reactive resources for voltage support are in use. The system is stressed, and discussion in the control room among the engineers and operators reflects their concern. Yet they know the company's shareholders will be pleased with the day's large profits, assuming they avoid major outages and the associated financial and political costs. The day's security desk operator has been watching the Smythville 500/ 230 transformer bank loading throughout the day, and it is now at 110% of capacity; loss of that bank will result in violations of reliability criteria. It is not an old bank and should survive at this loading…. But maybe not at 115%, nor at 105° F. There are some options. He could call for interruptible loads to disconnect, but it would make the papers the next day, and the company would eventually hear about it from the regulators. Or he could make a TLR request– transmission loading relief – for the more than 1000 MW of transmission service presently being utilized across the system. This would have a direct effect on the bank loading, but the company would pay for cutting firm contracts. There was another option: he could switch out the Belinda-Smythville 500 kV circuit, sending its 200 MW down the Belinda 500/230 kV bank. Simulations using his EMS software indicated it would in fact off-load the Smythville bank to 102%, but at the same time, it would push the Belinda bank from 91% to 98%, area voltages would drop, and an underlying 115 kV circuit would load to 103%. So it's a tradeoff between decreased overload risk on the Smythville bank to increased overload risk on the Belinda bank and on the 115 kV circuit plus increased voltage risk in the entire area….*

In this situation, and in many others like it, the control room staff are faced with the task of assessing risk associated with the engineering system, and, if the risk is significant, identifying alternatives, and then deciding whether to take action, or not, and if so, which one to take and to what extent. Typically, the objectives in this decision-making problem include an engineering one (risk to the physical system) and an economic one (cost, price, profits). We refer to it as control room security-economy decision-making (CR/SE/DM). The decision-making can be performed systematically if information regarding the probability and consequence of outcomes under the various alternatives are available. In practice, the decision-making process is quite subjective. One reason for this is that existing control room tools, within the energy management system (EMS), provide only deterministic information, requiring subjective weighing of one alternative against another. Perhaps the most advanced decision-aid tool in use today is the security-constrained optimal power flow (SCOPF) [1-5]. Yet, implementations of this tool do not easily admit variations on objectives, outcomes, alternatives, and problem scope and size but rather tend to provide global, system solutions that are optimal only insofar as the entire solution is actuated. There is a strong need for tools that are more flexible, that can conform to the problem-specific attributes according to the desire of the decision-maker (DM), the operator, and that can provide a multiplicity of *good* solutions from which the operator may probe, refine, and select.

In this paper, we use a risk-based approach to assess the security of the power system, which not only considers the impacts but also the probabilities of different contingencies. Use of risk in assessing security level is essential to treating security level as an objective to be achieved, rather than as a hard constraint to be satisfied. The decision problem is treated as a multi-criteria decision-making (MCDM) problem in an effort to aid the operator to make a good decision.

In Section II, we introduce the probabilistic method used to assess the power system security -- risk based security assessment. In Section III, some MCDM decision techniques are summarized. Section IV gives an overview of CR/SE/DM problem. Section V describes an approach that utilizes both the risk based security assessment and MCDM techniques to select the preventive action, and section VI illustrates through an example. Conclusions are drawn in Section VII.

II. Risk Based Security Assessment

Risk-based security assessment (RBSA) measures the power system security level in terms of probabilistic indices [6,7]. Here we define two kinds of risks: precontingency risk and contingency-related risk as the expected severity of the power system with and without consideration of contingencies, respectively. Assessment of precontingency risk provides information essential for determining whether or not to take corrective actions. Assessment of contingency-related risk provides information essential for determining whether or not to take preventive actions.

The precontingency risk of a component can be used to measure the security condition of the component. For the i^{th} component, the risk can be calculated as:

$$Risk(Sev_i \mid X_{t,f}, C_0) = E(Sev_i \mid X_{t,f}, C_0) = \sum_j \Pr(X_{t,j} \mid X_{t,f}) \times Sev_i(C_0, X_{t,j}) \qquad (1)$$

where: $X_{t,f}$ is the forecasted condition at time t, $X_{t,j}$ is the j^{th} possible loading condition, $\Pr(X_{t,j}|X_{t,f})$ provides the probability of this condition, $Sev_i(C_0,X_{t,j})$ quantifies the severity of i^{th} component under j^{th} possible operating condition. We use a short notation $Risk_{i,0}$ to represent this, where "i" represents the i^{th} component and 0 represents that assessment is being performed only under the conditions associated with a single network configuration, i.e., no contingencies are included in the assessment. The precontingency risk of a component is a good index that indicates the security level associated with a particular component. The precontingency risk of the entire system is used to measure the security condition of the power system under only the conditions associated with a single network configuration. It is computed as:

$$Risk(Sev \mid X_{t,f}, C_0) = E(Sev \mid X_{t,f}, C_0) = \sum_j (\Pr(X_{t,j} \mid X_{t,f}) \times \sum_i Sev_i(C_0, X_{t,j})) \qquad (2)$$

We use a short notation $Risk_{T0}$, where "T" represents "total," and "0" represents precontingency conditions, as the summation of the risk of each component. It represents the condition of the power system without contingencies.

Similarly, the risk of the i^{th} component under k^{th} ($k>0$) contingency can be calculated as

$$Risk_{i,k} = E(Sev_i \mid X_{t,f}, C_k) = \sum_j \Pr(X_{t,j} \mid X_{t,f}) \times Sev_i(C_k, X_{t,j}) \qquad (3)$$

where C_k is the k^{th} contingency, and C_0 represents the condition that no contingency occurs. The risk of the k^{th} contingency for the whole power system is

$$Risk_{T,k} = E(Sev \mid X_{t,f}, C_k) = \sum_i Risk_{i,k} \qquad (4)$$

The postcontingency risk measures the expected security condition of the power system under possible contingencies, and is calculated as:

$$Risk_{T,C} = E(Sev \mid X_{t,f}, \overline{C_0}) = \sum_{k \neq 0} \left(\Pr(C_k \mid \overline{C_0}) \cdot Risk_{T,k}\right) = \sum_{k \neq 0} \left(p'_k \cdot Risk_{T,k}\right) \qquad (5)$$

where $\overline{C_0}$ represents the condition that one of contingencies will happen, and p'_k is the probability that k^{th} contingency will happen in the next time interval.

Another important index that represents effects of contingencies are variance of contingencies, which measures the variabliability of the impacts of contingencies. The calculation of variance is as follows:

$$Variance_{TC} = Var(Sev \mid \overline{C_0}) = \sum_{k>0} p'_k \cdot (Risk_{T,k})^2 - \left(Risk_{T,C}\right)^2 \qquad (6)$$

In all of the above, the severity functions are continuous.

III. MCDM Techniques

In electric power systems, economic objectives typically conflict with security-related objectives, and as a result, the decision problem faced by control center operators is essentially a MCDM problem. MCDM problems are more difficult than single-criterion decision-making problems in that an optimal tradeoff needs to be reached for two or more conflicting criteria. Thus, for MCDM problems, extra effort is required to establish the DM's preference structure for different criteria. Table 1 summarizes many MCDM techniques and their attributes.

Mathematically, a MCDM-problem is a vector optimization problem that can be defined as follows:

Maximize $\{f(x)|x\in X\}$ where $f(x)=(f_1(x),\ldots,f_k(x))$, $x=(x_1, x_2,\ldots,x_n)$. The function $f_i(x)$ measures how desirable the i^{th} criterion is; X is the decision space. In this vector optimization problem, x^* is an efficient solution if and only if there does not exist any other solution x that can outperform x^* in all criteria, i.e., there is no such x that $f_i(x) \geq f_i(x^*)$ for all i.

The optimal compromise solution can be achieved in two steps: the determination of efficient solutions and the determination of an optimal compromise solution. Two methods are commonly used to determine the efficient solutions [8]. They are the weighting method and the ε-constraint method. For a relatively simple problem, one may solve analytically for the set of efficient non-inferior solutions x*. But an analytical approach is only practical for a rather limited class of problems. Alternatively, a decision-maker

Table 1: Some MCDM Methods and their Characteristics

	Weighting method (Including AHP)	**Value or utility–based approaches**	**ELECTRE IV**	**Evidential Theory**	**Goal programming**	**Lexicographic Method**	**Interactive method (Geoffrion's method, STEM, etc)**
Preference Structure	Using weights to represent the preference.	Preference for levels of an attribute, attitudes toward risk, weights	Indifference, preference, veto and discrimination thresholds	Basic probability number (degree of support)	Distance to target, weights	Existence an order of importance of the criteria	Can be utility or distance to target.
Technique used	Holistic	Holistic	Heuristic	Holistic	Holistic	Holistic	Holistic
Automatic or semiautomatic	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic	Semi-automatic
Decision Space	Continuous, Infinite alternatives	Continuous, Infinite alternatives	Discrete, Limited alternatives	Discrete, Limited alternatives	Continuous, Infinite alternatives	Continuous, Infinite alternatives	Continuous, Infinite alternatives

(DM) may apply different MCDM methods to a problem. Such an approach typically results in identification of different alternatives, none of which are entirely optimal, but all of which are "good," since quantification of human preference, typically required by MCDM methods, is highly subjective. In the process of examining and resolving the conflicts between the various "good" alternatives, the DM will gain more insight into the problem and his preferences. The DM can then choose a method that is appropriate and make the decision with more confidence. Thus, in regards to the CR/SE/DM problem, we propose the creation of a decision-making "toolbox" with which the DM can easily try different methods so as to identify and compare various possible alternatives.

IV. CR/SE/DM Problem

In traditional deterministic methods, the objective of corrective actions is to make the power system operate well under the current condition, while the objective of preventive action is to make the power system operate well under contingencies. These objectives do not change when using the risk-based method. What does change is the way the objectives are formulated.

In the risk-based corrective action method, we replace deterministic operating limits by component risk limits. Also, it may be that many components are near component risk limits but not in excess of them, which indicates that the system is highly stressed. This condition is not desirable. To avoid such a condition, we pose another limit on the total risk of the no-outage state. For prevention actions, the total risk of all contingencies is a good index to measure the security level of power systems. We define an appropriate bound on the total risk of contingencies. When the total risk of contingencies is below the limit, we believe the power system is secure enough; no preventive action is needed to reduce the risk. When the total risk of contingencies is beyond the limit, the security of the power system needs to be enhanced. We express the scheme of corrective, preventive action in Fig. 1.

We describe the preventive action selection approach, as it requires the consideration of contingencies. The corrective action selection can be similarly addressed.

V. MCDM for Preventive Actions

The preventive action selection problem is treated as a MCDM problem with criteria being security and cost and is handled in three stages. In the first stage, effective controls are selected. In the second stage, we treat the problem as a vector optimization problem to find a set of representative efficient solutions. These solutions are potentially good alternatives to be further investigated. In the third stage, given the alternatives, we employ different MCDM methods to evaluate the alternatives, resulting in a ranking of the alternatives, information that is helpful for the operator. By studying the information, the operator can investigate the alternatives from different views, obtain insight into his real preferences and make the decision with more confidence.

A. Selection of efficient controls

In practice, the number of available control actions is

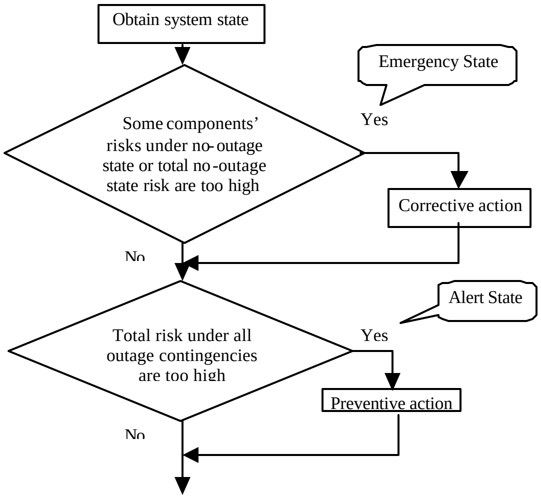

Fig. 1 Flow chart for preventive/corrective action

limited. The selected controls should be capable of reducing the post-contingency risk. Thus, the effectiveness of reducing the post-contingency risk can be used to rank the controls. In this paper, we use risk sensitivities to evaluate the total post-contingency risk reduction achievable by each control. Calculation of risk sensitivities is described in the appendix.

For a given control x, the sign of the post-contingency risk sensitivity with respect to the control indicates how to operate the control to reduce the total risk of all contingencies. If the sensitivity is positive, then we need to decrease x, otherwise, we need to increase x. The operating reserve of the control is obtained from the upper and lower bounds of x. Then the amount of total risk that can be reduced by the control x can be roughly computed as the product of total risk sensitivity and operating reserve. On the other hand, as risk cannot be a negative value, the maximum risk reduction is the present risk value. So the amount of total risk that can be reduced by control x is:

$$\Delta Risk_{TC} = \sum_{k} p_k' \left(\sum_{i} \min\left(\frac{\partial Risk_{i,k}}{\partial x} \Delta x, Risk_{i,k} \right) \right) \quad (7)$$

where inner summation is overall possible control actions i.

By ranking the controls according to their effectiveness in reducing the total contingency risk, we identify a number of potentially good controls. Another issue is that operation of the identified controls should not cause other operating limits to be violated. The operation of a particular control may reduce the total contingency risk and increase the pre-contingency risk of some components at the same time, and new violations of operating limits may accompany the reduction of total contingency risk. So it is necessary to recheck the controls chosen through the rankings of efficiencies and eliminate those controls that may cause new violations. This rechecking is described below.

Without loss of generality, we consider a control x with a positive sensitivity of total risk of all contingencies. Then we need to decrease x to reduce the risk of contingencies. Let's assume that the operating reserve is Δx. We can calculate components' pre-contingency risks when the control is operated fully to its limit.

$$Risk_{i0}(x+\Delta x) = Risk_{i0}(x) + \frac{\partial Risk_{i0}}{\partial x} \cdot \Delta x \qquad (8)$$

Checking the risks of components after the change of the selected control, if there exist a component risk that is out of the predefined component risk limit, then the control is not good for preventive action and is eliminated.

B. Generating efficient solutions

The desirability of a course of preventive action is measured by four attributes: operation costs, total post-contingency risk, total pre-contingency risk, and variance of contingencies. In this step, we provide some alternatives from which operators are to choose. It is a vector optimization problem with the following form.

Minimize (Cost, $Risk_{T0}$, $Risk_{TC}$, $Variance_{TC}$)

Subject to: $Risk_{i0} < LR$ (for all components) (9)

Here Cost denotes the operation costs of the preventive action, $Risk_{T0}$ denotes the total risk under current condition, $Risk_{TC}$ denotes the total risk of contingencies and $Variance_{TC}$ denotes the variance of contingencies, $Risk_{i0}$ is the precontingency risk of the ith component. As stated before, $Risk_{i0}$ reflects the current condition of the ith component. It is necessary that all the components are working normally. LR is a predefined limit of risk to ensure this.

The relationship of these criteria with the control variables is complex and as a result, it is not possible to obtain the efficient solutions using an analytical approach. Instead, we choose a weighting method to obtain a set of representative efficient solutions. After choosing a set of weighting (w_0, w_1, w_2, w_3), which satisfies $0 \le w_i \le 1$ i=0,1,2,3, and $\sum_{i=0}^{3} w_i = 1$, optimization problem (9) changes to:

$$\text{Minimize} \quad w_0 Cost + w_1 Risk_{T0} + w_2 Risk_{T0} + w_3 Variance_{TC} \qquad (10)$$

$$\text{Subject to: } Risk_{i0} < LR \text{ (for all components)}$$

Then the single objective problem is solved numerically for each set of (w_0, w_1, w_2, w_3). It is not practical to generate the entire set of efficient solutions by try all weighting sets, but we can choose a representative subset of weighting sets which reflect the preference of operators. A final choice can be selected from this subset. The weighting method converts the vector optimization problem into a series of single objective optimization problems where each solution of a single objective optimization problem is an efficient solution. Because this method is attractively simple (the weights chosen can roughly represent the preferences), we can easily obtain efficient solutions.

C. Evaluation of efficient solutions

After obtaining different efficient solutions, various MCDM methods can be used to evaluate them. Here we use the goal programming method and the value based method.

VI. Simulation Results

To test the approach, we use a modified version of IEEE 96 Reliability Test System. The system differs from the system reported in [5] in the following ways:

- Line 11-13 is removed
- Shift 480 MW of load from buses 14, 15, 19, 20 to bus 13
- Change the rating branches A22 and A23 from 500MVA to 400MVA.

We increase the reactive power at bus 6 (PQ bus) by 0.257 p.u, voltage at bus 5 (PV bus) by 0.0247 p.u, decrease real power output at bus 16 and 18 by 1.007 and 0.407p.u. respectively (the real power output at slack bus will increase accordingly). The contingency set includes the following N-1 contingencies:

- Outage of line A21, which is from bus 12 to bus 23, with an outage rate of 1.142×10^{-5} per hour.
- Outage of line A22, which is from bus 13 to bus 23, with an outage rate of 5.594×10^{-5} per hour.
- Outage of line A20, which is from bus 12 to bus 13, with an outage rate of 4.242×10^{-5} per hour.

A. Selection of efficient controls

After selecting controls based on method described in section V.A, we identify ten efficient control variables (in descending order of effectiveness): real power output of generator at buses 21, 18 and 23, VAR source at PQ buses 24, 4, 12, 9 and 3, real power output of generator at bus 15 and generator voltage at bus 14.

B. Generating efficient solutions

All the selected controls are employed to solve the optimization problem formulated in section V.B. To calculate the operation costs, we define the cost coefficients of generator voltages, VAR sources and real power outputs of generators are 1, 2 and 3 respectively. To get the non-inferior solutions of the vector optimization problem, we choose the following sets of weights: (w_0, w_1, w_2, w_3)∈ {$\mathbf{w^0}$, $\mathbf{w^1}$, $\mathbf{w^2}$, $\mathbf{w^3}$, $\mathbf{w^4}$}={(0.3, 0.2, 0.45, 0.05), (0.4, 0.15, 0.4, 0.05), (0.5, 0.15, 0.3, 0.05), (0.1, 0.3, 0.5, 0.1), (0.2, 0.3, 0.45, 0.05)}.

By applying weights to the different objectives and utilizing the gradient search method, we identify representative preventive actions alternatives. Table 2 gives the solutions corresponding to the above sets of weights. In the table, each value indicates by how much the corresponding control variable should be increased. For example, ? P_{15} = -0.3245

Table 2: Preventive actions corresponding to representative sets of weights

Pre-ventive actions	Vector of weights				
	$\mathbf{w^0}$	$\mathbf{w^1}$	$\mathbf{w^2}$	$\mathbf{w^3}$	$\mathbf{w^4}$
? V_{14}	0.05299	0.05299	0.05299	0.05299	0.05298
? P_{15}	-0.3245	0.04608	0	-0.6940	0.6926
? Q_3	0.7300	0.6731	0.7300	0.4656	0.7300
? Q_9	0.1995	0.02725	0	0.2301	0.3660
? Q_{12}	0	0	0	0	0
? Q_4	0.6317	0.3404	0	0.3643	0.6133
? Q_{24}	0	0	0	0.07693	0
? P_{23}	-0.2173	0.03143	0	-0.6900	0.6002
? P_{18}	-0.3141	0.01984	0	-0.6858	0.6808
? P_{21}	-0.2861	0	0	-0.6797	0.6714

means to decrease the real power output at generator bus 15 by 0.3245 p.u. Table 3 gives the values of different objectives achieved for each preventive action alternative.

Table 3: Objectives achieved for different preventive actions

Objective	Vector of weights				
	$\mathbf{w}^0$	$\mathbf{w}^1$	$\mathbf{w}^2$	$\mathbf{w}^3$	$\mathbf{w}^4$
Cost	5.093	1.439	0.8360	9.491	9.750
$\text{Risk}_{T,0}$	0.6417	1.508	2.059	0.3095	0.1249
$\text{Risk}_{T,C}$	2.589	4.824	5.656	1.430	1.069
Var_c	2.249	4.082	4.112	0.1839	0.3127

C. Ranking the alternatives

Two MCDM methods are used to rank the alternatives.

1) Value Method: A value function is required for each criterion that represents the DM's preference for different levels of the criterion. For DMs that are not risk neutral, the value functions are non-linear. There are different forms of value functions; we use exponential value functions. For an attribute A with value of x, the value function can be expressed as $V_A(x) = a+be^{cx}$. The coefficients a, b, c can be determined by three points. Consider first a risk-averse DM. For the attribute of operation cost, suppose that the DM considers the value of cost to be 1, 0.5 and 0 when cost is 0, 3 and 10, respectively. The coefficients are then computed to yield $V_{cost}(x)=-0.1978+ 1.1978e^{-0.1801x}$. Similarly, suppose the DM's attitude towards total precontingency risk under is $V_{riskT0}(0.5)=1$, $V_{riskT0}(1.5)=0.5$ and $V_{riskT0}(4)=0$. The value function for total precontingency risk is $V_{riskT0}(y)=-0.1624+ 1.5398e^{-0.5624y}$. Assuming $V_{riskTC}(1)=1$, $V_{riskTC}(3)=0.5$ and $V_{riskTC}(6) =0$, we get the value function for total contingency as $V_{riskTC}(z) = -0.7840+ 2.1029e^{-0.1644z}$. Assuming $V_{varc}(0.1)=1$,$V_{varc}(1)=0.5$ and $V_{varc}(4.5)=0$, we obtain the value function for variance of contingencies as $V_{varc}(u)= -0.04286+ 1.1213e^{-0.7254u}$. The value functions for risk-averse preferences towards different attribute are shown as lower curves in Fig. 1 to 4. Likewise, for the risk-seeking DM, these four value functions are:

$V_{cost}(x)= 1.1978-0.1977e^{0.1801x}$; $V_{riskT0}(y)= 1.1624-0.1226e^{0.5624y}$; $V_{riskTC}(z)= 1.7841-0.6652e^{0.1644z}$; $V_{varc}(u)= 1.0657 -0.06164e^{0.6333u}$

The value functions for the risk-seeking DM are shown as the upper curves in Fig. 1 to 4. These single-attribute value functions capture the DM preferences in terms of different attribute levels. Multi-attribute value functions consider the effects of all value functions. Two kinds of widely applied multi-attribute value functions are multiplicative and additive value functions. We choose the following additive value function to evaluate the alternatives:

$$TV_i = w_0V_{cost}(x_i)+w_1V_{riskT0}(y_i)+w_2V_{riskTC}(z_i)+w_3V_{var2}(u_i)$$

The weights lie between 0 and 1 and the sum of the weights is 1. The weights of the additive function can be chosen by a combination of gamble and indifference tradeoff methods. Here, we assume an additive function of

$$TV= 0.35V_{cost}(x)+0.15V_{riskT0}(x)+0.4V_{riskTC}(x)+0.1V_{var2}(x)$$

The results of the value method for each of the two DMs are shown in Table 4.

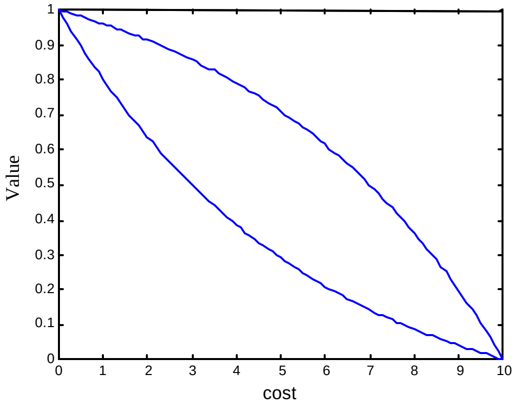

Fig. 1 Value function for operation cost

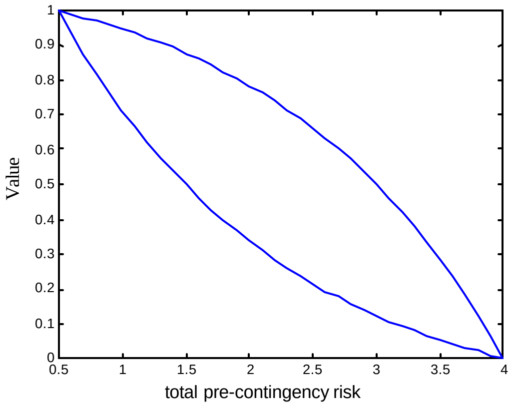

Fig. 2 Value function for total pre-contingency risk

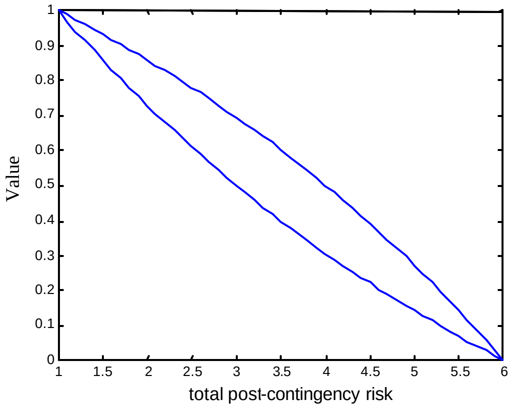

Fig. 3 Value function for total post-contingency risk

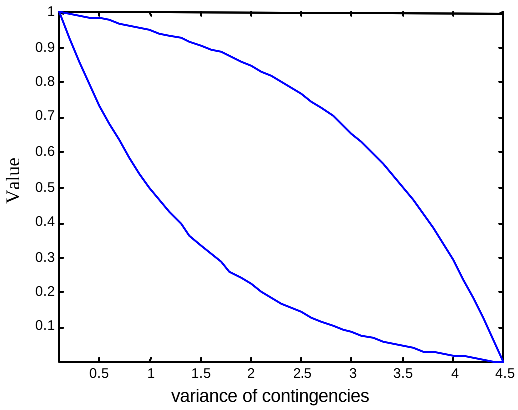

Fig. 4 Value function for variance of contingencies

2) Goal programming method: In this method, a goal or a target value G_i for each one of the criteria is specified. The alternatives are ranked according to their distance to the goal, given as $\left\{\sum_{i=1}^{I}\left[w_i\left|G_i - V_i(A)\right|\right]^p\right\}^{1/p}$. This method usually assumes linear value functions, which we do here:

Operation cost: $V_1(x)= 1-0.1x$
Total risk under current condition: $V_2(y)=1.0714-0.1428y$
Total risk of contingencies: $V_3(z)= 1.2 - 0.2z$
Variance of contingencies: $V_4(u)= 1.0465- 0.2326u$

Suppose the operator sets goals of 1 for operating cost, 1.5 for total risk under current condition, 2 for the total risk of contingencies and 0.5 for the variance of contingencies. Then we have $G_1= 0.9$, $G_2= 0.8571$, $G_3= 0.8$ and $G_4= 0.9302$. Also, suppose that the operator considers the total risk of contingencies to be 4 times as important as variance, 2 times as important as total risk under current condition, and 1.3 times as important as the operating costs. The corresponding set of normalized weights for the four attributes, cost, precontingency risk, contingency risk, and variance, are 0.3, 0.2, 0.4 and 0.1, respectively. Here, we calculate the distance for p=1 and 2. The results are shown in Table 4.

Table 4. Evaluating alternatives by value and goal programming methods

Ranking Methods Options	Value method (Additive Value)		Goal programming (Distance)	
	Risk-averse	Risk-seeking	p=1	p=2
1 ($w=w^0$)	0.489	0.781	0.221	0.138
2 ($w=w^1$)	0.397	0.611	0.337	0.242
3 ($w=w^2$)	0.359	0.517	0.412	0.306
4 ($w=w^3$)	0.621	0.666	0.327	0.260
5 ($w=w^3$)	0.671	0.669	0.366	0.274

From Table 4, we observe that for the value method, alternatives 5 and 1 have the highest additive value for risk-averse and risk-seeking DMs, respectively. For goal programming, alternative 1 ranked best for p=1 and p=2. Alternative 3 always ranks last. The operator may choose preventive actions from one of alternatives 1 and 5.

VII. Conclusions

In this paper, we propose a decision-support aid for control room security economy decision-making that considers probabilistic characteristics of contingencies and load conditions of power systems. This approach is based on the use of risk-based security assessment to enable treatment of security level as an objective within multi-criterion decision making (MCDM) techniques. It is very significant that this approach enables treatment of security level as an objective rather than a constraint. We believe "tool-box" decision aids comprised of methods such as those presented in this paper will ultimately result in much more effective control room, security-economy decision making.

Appendix. Calculation of Sensitivities

The sensitivity of pre-contingency risk is

$$\frac{\partial Risk_{T0}}{\partial x} = \sum_i \frac{\partial Risk_{i0}}{\partial x} \qquad \text{(A-0)}$$

The sensitivity of post-contingency risk is

$$\frac{\partial Risk_{TC}}{\partial x} = \sum_{k>0} \frac{\partial\left(Risk_{T,k}\cdot p'_k\right)}{\partial x} = \sum_{k>0} p'_k \cdot \frac{\partial Risk_{T,k}}{\partial x}$$
$$= \sum_{k>0} p'_k \cdot \left(\sum_i \frac{\partial Risk_{i,k}}{\partial x}\right) \qquad \text{(A-1)}$$

The sensitivity of variance of contingencies with respect to the control variable x can be calculated as:

$$\frac{\partial Variance_{TC}}{\partial x} = \frac{\partial}{\partial x}\left(\sum_{k>0} p'_k \cdot Risk_{T,k}^2 - \left(Risk_{T,C}\right)^2\right)$$
$$= \sum_{k>0} 2p'_k \cdot Risk_{T,k}\frac{\partial Risk_{T,k}}{\partial x} - 2Risk_{T,C}\cdot\frac{\partial\left(\sum_{k>0} p'_k \cdot Risk_{T,k}\right)}{\partial x}$$
$$= \sum_{k>0} 2p'_k \cdot Risk_{T,k}\frac{\partial Risk_{T,k}}{\partial x} - 2Risk_{T,C}\sum_{k>0} p'_k \frac{\partial Risk_{T,k}}{\partial x}$$
$$= \sum_{k>0} 2p'_k\left(Risk_{T,k} - Risk_{T,C}\right)\frac{\partial Risk_{T,k}}{\partial x}$$
$$= \sum_{k>0} 2p'_k\left(Risk_{T,k} - Risk_{T,C}\right)\left(\sum_i \frac{\partial Risk_{i,k}}{\partial x}\right) \qquad \text{(A-2)}$$

All of the above formulas contain $\frac{\partial Risk_{i,k}}{\partial x}$. Here we use low voltage risk as an example to show how to calculate it. For overload risk, the calculation is similar.

$$\frac{\partial Risk_{i,k}}{\partial x} = \frac{\partial Risk_{i,k}}{\partial \overline{V}_{i,k}} \cdot \frac{\partial \overline{V}_{i,k}}{\partial x}$$

If we use $V_{i,k}$ to donate $V_i|C_k$, which is the voltage (amplitude) of bus i under the kth contingency, then according to the result of [7], it follows normal distribution, we have

$$V_{i,k} \sim N(\overline{V}_{i,k}, s_{i,k}^2)$$

Here, $\overline{V}_{i,k}$ and $s_{i,k}^2$ are the mean and variance of V_i under the contingency k respectively.

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