Risk Assessment for Special Protection Systems

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***Abstract*—Special protection systems (SPS) have been widely used to increase the transfer capability of the network by assisting system operators in administering fast corrective actions. Compared with constructing new transmission facilities, SPS can be placed in service relatively quickly and inexpensively. However, increased reliance on SPS results in additional risks to system security. In this paper, based on existing reliability evaluation methods, a generic procedure for risk-based assessment of SPS is proposed. The procedure can help the system operator to identify the risk brought by SPS and to make SPS-related decisions. An illustrative example which uses a generator rejection scheme (GRS) for transient instability is provided.**

***Index Terms*—Generator rejection scheme, impact, probability, reliability, risk, special protection systems.**

I. Introduction

SPECIAL protection systems (SPS) (also called remedial action schemes, or RAS) are designed to detect abnormal system conditions, typically contingency-related and initiate pre-planned, corrective action to mitigate the consequence of the abnormal condition and provide acceptable system performance [1]. SPS can provide rapid corrective actions and are often used to increase the transfer capability of the network. These systems are sometimes perceived as attractive alternatives to constructing new transmission facilities because they can be placed in service relatively quickly and inexpensively [2], [3] and they provide that the system may be securely operated at a higher level of stress, assuming the SPS works properly. However, excessive reliance on SPS can result in increased risk. Because SPS are normally armed only under stressed conditions, when their failure would result in very severe consequences, this risk can be significant. In addition to the risk caused by failure to operate when required, SPS also contributes risk via unintended operation and unplanned interaction with other SPS. The latter risk becomes of significant concern as the utilization of SPS grows [2].

In this study, a generic procedure for risk-based assessment of SPS is developed. The failure mode and effect analysis (FMEA) and Markov modeling modeling techniques are suggested for SPS reliability assessment. An illustrative example of risk based assessment of generator rejection scheme (GRS), the most commonly used type of SPS in industry [4], [5], for transient stability is presented in detail. The problem of when to arm the GRS is analyzed as an sample of SPS-related decision-making problem based on risk calculation results. It shows that the traditional worst-case scenario method to determine the arming point sometimes can unnecessarily increase system risk.

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II. Reliability of SPS

An SPS event can be classified into one of the following three categories which are

1) desirable operation;
2) undesirable operation;
3) failure to operate.

An SPS operation may be desirable or undesirable, depending on the consequence of the operation relative to the consequence had the SPS not operated. If the consequence of the operation is less severe than the consequence had the SPS not operated, the operation is desirable. If the consequence of the operation is more severe than the consequence had the SPS not operated, the operation is undesirable. Undesirable operation may either be unintended, due to a hardware, software, or human error, or it can be intended (according to the design), but still undesirable due to a fault in the design logic. A nuisance operation, when an SPS takes unnecessary action when there is no disturbance in the system, is an example of this form. An SPS failure to operate occurs when the SPS fails to respond as designed to conditions for which the SPS is supposed to operate. An SPS may fail to operate as expected for several reasons, among which are

1) hardware failure;
2) faulty design logic;
3) software failure;
4) human error.

Hardware failure occurs when some physical stress exceeds the capability of one or more installed components. Faulty design logic may occur as a result of inappropriate or incomplete study procedure during the design. Software failure results from errors in vendor written and user written embedded, application, and utility software. The vendor software typically includes the operating system, I/O routines, diagnostics, application-oriented functions and programming languages. User written software failure results from errors in the application program, diagnostics and user interface routines. Human errors can be classified according to whether they are associated with construction, operating, or maintenance [6].

When correctly operating, SPS significantly improve system response following a contingency. However, the failure of SPS to accurately detect the defined conditions, or the failure to carry out the required preplanned remedial action, can lead to serious and costly consequences. The survey by IEEE-CIGRE [4] in 1992 suggests that the cost of SPS failure can be very high as most of the respondents selected the highest cost category when asked to estimate the cost of an operational failure of SPS. Some examples of SPS failure from the U.S. NERC System Disturbance Reports from 1986–1997 [7] have been summarized in [3].

III. Generic Procedure for SPS Risk Assessment

The calculation of the risk is accomplished through quantitatively assessing the probability and impact. In this section, a generic procedure of the transformer risk assessment is suggested. The adopted procedure consists of seven main steps as shown in Fig. 1.

In the following subsections some guidelines about these steps are provided.

A. Collect Information

A overall knowledge of the physical layout of the SPS, operating logic, functions of each physical part, location, success criteria, embedded software information, as well as maintenance and test procedures, is necessary to begin the SPS reliability evaluation. The information about system operating conditions, human interaction procedure and human reliability should also be collected. This is a crucial step for SPS risk assessment and it is often repeated in the future steps whenever necessary.

B. Identify the Initiating Events

An initiating event is usually a disturbance such as line outage, generator tripping, load dropping, etc. In this step, a set of initiating events needs to be identified. If the main objective is to compare the system risk with SPS and the system risk without SPS, only the initiating events which activate SPS need to be included. If the objective is to compute the system total risk with SPS, then all possible system disturbances must be considered.

C. Identify the Risk Sources

SPS is designed to mitigate the consequence of the abnormal condition after large disturbances. The risk from SPS mainly comes from the following four sources:

1) hardware failure;
2) faulty design logic;
3) software failure;
4) human error;

as they are described in Section II. Any of these sources may cause the following risks to the system:

- SPS fails to respond correctly to disturbance conditions for which the SPS is planned to operate;
- SPS operates during steady state conditions or in response to disturbance conditions for which the SPS should not operate.

D. Perform SPS Reliability Assessment

In order to know availability of SPS in the future, which is critical for SPS risk assessment, some methods for SPS reliability assessment must be adopted. It is suggested that Markov

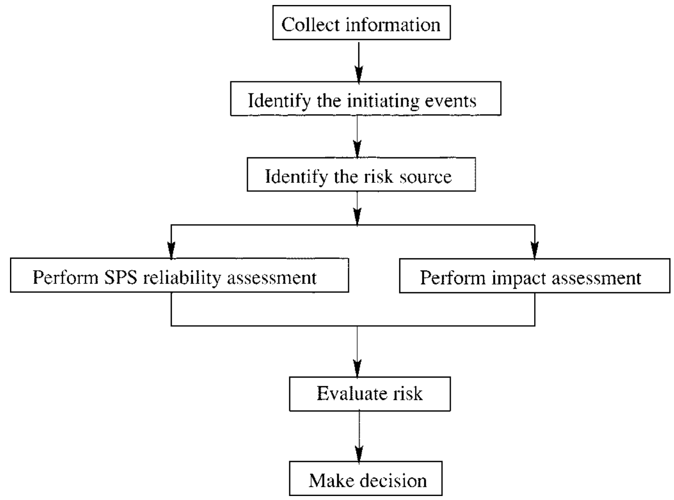

Fig. 1. Procedure for SPS risk assessment.

modeling is well suited for SPS reliability assessment because its flexibility provides that it can account for the variety of features which are common in SPS [3]. Specifically, Markov modeling can incorporate independent and common cause failures, partial and full repairs, maintenance and diagnostic coverage. Most importantly, it provides that all of these features can be modeled as a function of time. This is in contrast to probability methods which provide steady state results and are accurate only for short repair times and low failure rates [3]. The failure mode and effect analysis (FMEA) can be used as an initial step to identify failure modes for Markov modeling. The following steps should be followed for SPS reliability evaluation if the FMEA and Markov modeling are used.

Describe the System: Based on the information collected in step 1, a logic diagram is usually developed to describe the system. This diagram can help to conduct the FMEA in the next step.

Complete a System-Level FMEA: In this step, all the SPS components are identified and listed. In order to simplify the calculation, each component can include one or several physical parts. For each component, all failure modes and system effects should be identified. A component failure is usually defined when it cannot perform its predefined functions.

Develop the Markov Model: First, the system states need to be defined. They are represented by the combinations of states of all system components. Markov model construction begins from a state in which all components are successful. This state is normally numbered state 0. When building the Markov model, the rule is "For any successful state, list all failure rates for all successful components" [8].

Simplify the Markov Model: In order to ease the calculation, some states in Markov model can be merged [8]. The simple rule is "When two states have transition rates that are identical to common states, those two states can be merged into one, entry rates are added, exit rates remain the same."

Calculate the State Probabilities: The Markov model can be represented by showing its probabilities in matrix form which is often called "transition matrix." By manipulating the transition matrix, the state probabilities can be obtained.

E. Perform Impact Assessment

In this step, the consequence due to SPS failure needs to be estimated in terms of financial losses, i.e., the total cost associated with the SPS failure. The impact can be equipment damage, equipment outage, load interruption and penalties [9]. The estimation can be obtained from historical data, survey, or expert opinion.

F. Evaluate Risk

In this step, the system risk which incorporates the information of reliability of SPS is computed. In order to compare, the system risk without SPS should also be computed.

G. Make Decision

Based on the risk calculation results, the system operator can make SPS-related decisions to improve system security for both operation planning and online assessment purpose. One of such kind of decision is when to arm the SPS. In present industry practice, the SPS arming point is obtained deterministically based on worst-case scenario regardless of arming time.[1] Sometimes, it is possible that the probability of the worst case is so low that the system risk with SPS is higher than risk without SPS. In this study, risk is used to determine the arming point.

Since risk is only the expected value of impact, the variance of risk might also affect the decision made by the system operator. For example, it is possible that two situations, one is corresponding to with SPS and the other is without SPS, have the same risk, but they have different variances of risk. The system operator, who is usually a risk-averse person, will determine whether to arm the SPS or not by choosing the situation with lower variance of risk.

IV. Numerical Illustration

In this section, the previous procedure will be applied to a GRS, which is the most popular type of SPS currently used in power industry [10] for transient stability [11].

A. Collect Information

The typical power plant in which a GRS is installed features high generation capacity and multiple generation units, interconnected to the system by two or more transmission lines. Without GRS, disturbances resulting in decreased transmission capacity may cause an out of step condition at the plant during high loading conditions. Any circuit that initiates GRS action during a forced outage condition is defined as a critical circuit. A properly designed GRS, activated by outage of any critical circuit, will trip a limited amount of generation at the plant in order to avoid out of step conditions for the remaining units [12]. Fig. 2 shows a portion of the IEEE Reliability Test System [13] together with an illustration of the GRS logic. Line 12–13 and line 13–23 are critical lines. Without GRS, outage of either of these two outlet transmission lines may result in a plant-out-of-step condition. To improve the transient

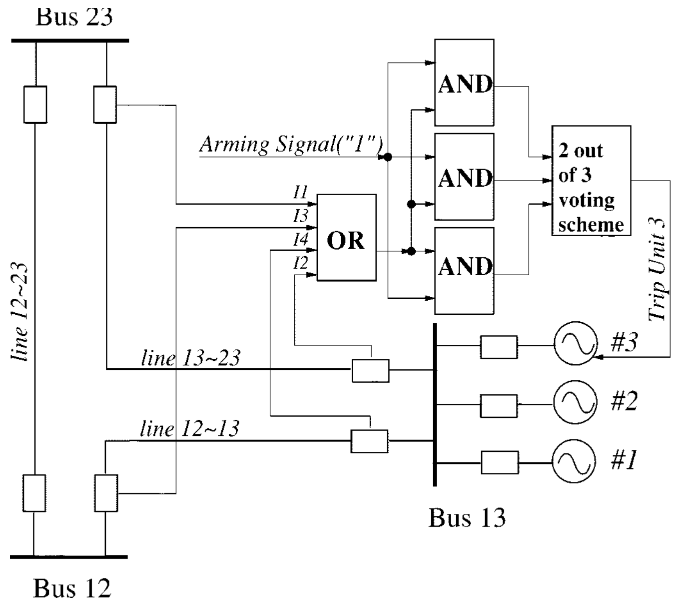

Fig. 2. GRS logic circuit and voting scheme.

stability performance of this plant, a GRS is installed. When the GRS detects a line outage on either of these two lines, it trips promptly only one generator to keep the other two generators in service. The GRS logic is simple: when there is a fault on a critical line, the breakers on this line open; an "open" signal (high-level signal) from any breaker energizes the output of the OR gate. The high-level signal from the OR gate output, together with the high-level arming signal, sets the AND gate output in high level, which is input to the two out of three voting scheme. When two or more of the voting scheme input signals are high signals, the voting scheme output signal is high; otherwise, it is low. The high-level signal from the voting scheme will trip the selected generator. Here, breakers and the voting scheme are assumed fully reliable. Breakers are external to GRS; so assuming they are 100% reliable helps to isolate the GRS influence. Their failure potential can be included in this analysis if desired. The voting scheme is assumed fully reliable to simplify the illustration process.

In the remaining part of this section, the following nomenclature is used:

- F_i event that there is a fault on circuit i;
- A fault type random variable. In this paper, one phase to ground, two phase to ground, three phase to ground and phase to phase fault are represented by 1, 2, 3, 4, respectively, for all possible values of A;
- N_c number of critical circuits;
- N_T total number of events considered in the study;
- $\cap, \cup$ the AND and OR operators, respectively;
- E_i initiating events.

The first N_c outage events correspond to "$N-1$" outages, i.e.,

$$E_i = \overline{F}_1 \cap \overline{F}_2 \cdots \overline{F}_{i-1} \cap F_i \cap \overline{F}_{i+1} \cdots \overline{F}_{N_c} \quad i = 1, \ldots, N_c$$

and the $N_c + 1$ outage event is no fault, i.e.,

$$E_{N_c+1} = \overline{F}_1 \cap \overline{F}_2 \cap \cdots \cap \overline{F}_{N_c}.$$

[1]Arming time is the time duration for which GRS is expected to be armed.

Outage events $E_i, i > N_c+1$ correspond to simultaneous outage of two or more circuits. Note that normally, $N_T \leq N_C+1$.

K	transient instability event;
X	precontingency operating point; it is a vector of critical precontingency controllable parameters which significantly influence the post-contingency system performance. In this example, generation level is the most critical precontingency parameter and, thus, it is used to represent system operating condition.
T	GRS tripping event;
$Risk(\cdot)$, $Im(\cdot)$, $\Pr(\cdot)$	risk, impact, and probability, respectively, of an event.

B. Identify the Initiating Events

There are two basic events: F_1, loss of line 12–13 and F_2, loss of line 23–13. So there are total four initiating events: E_1, loss of line 12–13; E_2, loss of line 23–13; E_3, no outage; E_4, loss of both lines. E_i may occur in any of four different ways, $n = 1,2,3,4$, corresponding to the four basic fault types: one phase-to-ground faults, two phase-to-ground faults, three phase-to-ground faults, and phase-to-phase faults.

C. Identify the Risk Sources

A GRS is designed to trip some preselected generating unit(s) at a plant in order to prevent blackout of the entire plant. This action instantaneously reduces the electrical power input to the transmission system following the occurrence of specified contingencies. In this example, the risk for a system with a GRS comes from three sources:

1) if a GRS fails to take corrective measures when armed and initiated, the plant may or may not experience an out of step condition, depending on the pre-fault operating condition and the fault type and location;
2) if a GRS takes action promptly and correctly as designed, system stability will be maintained, but nonzero impact will occur via a controlled trip of a block of generation capacity;
3) if a GRS takes an unnecessary action when there is no outage for a critical line, then nonzero impact occurs via a controlled trip of a block of generation capacity. This is a nuisance trip.

The risk of an event E_i, $i = 1, 2, \ldots$, which causes either GRS trip T or instability K, is $Risk((K \cup T)/X)$. For simplicity, we drop the dependence on X, leaving the reader to be cognizant of it in what follows. Thus, the risk is

$$\begin{aligned} Risk(K \cup T) &= \sum_{i=1}^{N_T} Risk\left(E_i\right) \\ &= \sum_{i=1}^{N_T} \Pr\left(K \cap \bar{T} \cap E_i\right) Im\left(K \cap \bar{T} \cap E_i\right) \\ &\quad + \sum_{i=1}^{N_T} \Pr\left(T \cap E_i\right) Im\left(T \cap E_i\right). \end{aligned} \tag{1}$$

Here, the first term expresses the risk from source 1 and the second term expresses the risk from source 2 and 3.

The probability of the GRS failure to trip, T, resulting in instability K, is denoted as $\Pr(K \cap \bar{T} \cap E_i)$. Since E_i occurs in any of four different ways, probability term can be expanded as follows:

$$\begin{aligned} \Pr\left(K \cap \bar{T} \cap E_i\right) &= \sum_{n=1}^{4} \Pr\left(K \cap \bar{T} \cap E_i \cap (A=n)\right) \\ &= \sum_{n=1}^{4} \Pr\left(\bar{T} \cap E_i \cap (A=n)\right) \\ &\quad \times \Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A=n)}\right) \\ &= \sum_{n=1}^{4} \Pr\left(\bar{T} \cap E_i\right) \times \Pr\left(\frac{A=n}{\bar{T} \cap E_i}\right) \\ &\quad \times \Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A=n)}\right). \end{aligned} \tag{2}$$

The term $\Pr((A=n)/(\bar{T} \cap E_i))$ is the probability that, given a fault, it is of type n. This probability is obtained from historical data. The term $\Pr(K/(\bar{T} \cap E_i \cap (A=n)))$ is the probability of instability given a fault of type n, outage E_i and GRS failure to trip at an operating condition X. This term depends on the probability function used to model the distribution of fault location along the circuit associated with E_i. The remaining terms $\Pr(T \cap E_i)$ in (1) and $\Pr(\bar{T} \cap E_i)$ in (2) are the probabilities of GRS success and failure, respectively and will be addressed in Step 5.

D. Perform SPS Reliability Evaluation

Describe the System: The logic diagram has been already developed as Fig. 2. Corresponding to the four initiating events, there are four GRS input events as shown in Table I.

Complete a System Level FMEA: System states are represented by the combinations of states of all system components. Given defined modes, e.g.,

— 0: normal mode l;
— 1: failure mode 1;
— 2: failure mode 2.

The AND and OR gates have the following two failure modes:

— 1: the output of the component is "stuck" to 1;
— 2: the output of the component is "stuck" to 0.

Thus, the FMEA list, as shown in Table II, which also shows the assumed failure rates, is created.

Develop the Markov Model: Four digits $d_1d_2d_3d_4$ are used to code the state of system. The digit d_1 represents the state of component OR (0: normal, 1: failure mode 1, 2:failure mode 2). Digit d_2, d_3, d_4 represent the state of the three component AND's (0: normal, 1: failure mode 1, 2: failure mode 2). By this definition, the following 81 states are obtained as shown in the matrix at the bottom of the next page.

In order to reduce the dimension of the transition matrix, the number of system states can be reduced by merging some states as the three AND's play the same role in the system. The criterion is: states that have identical d_1 and the same combinations of d_2, d_3 and d_4 are considered to be the same state and merged.

TABLE I
EVENT INPUT MAPPING TABLE

Event	Signals to GRS Logic I_1	I_2	I_3	I_4	Probability
E_1	1	1	0	0	$\mathcal{P}(E_1) = \mathcal{P}(F_1)\mathcal{P}(\bar{F}_2)$
E_2	0	0	1	1	$\mathcal{P}(E_2) = \mathcal{P}(\bar{F}_1)\mathcal{P}(F_2)$
E_3	0	0	0	0	$\mathcal{P}(E_3) = \mathcal{P}(\bar{F}_1)\mathcal{P}(\bar{F}_2)$
E_4	1	1	1	1	$\mathcal{P}(E_4) = \mathcal{P}(F_1)\mathcal{P}(F_2)$

TABLE II
FMEA LIST FOR THE ILLUSTRATIVE SYSTEM

Failure Mode and Effect Analysis(FMEA)			
component	failure mode	failure effect	failure rate(per day)
OR	1	constant 1	$\lambda_1 = 0.0003/365$
OR	2	constant 0	$\lambda_2 = 0.02/365$
AND	1	constant 1	$\lambda_3 = 0.0003/365$
AND	2	constant 0	$\lambda_4 = 0.02/365$

As a result, the number of states is reduced to 30, according to the equation shown at the bottom of the page.

Here, $S = S0, S1, \ldots, Sn$ represent a state space of the GRS, where Sj is a set of mutually exclusive and exhaustive states. Further, each of the above states can be classified into one of the following C_1, C_2, C_3 and C_4 categories based on the response of each system state to system input events

C_1 If the input is an active signal, then the GRS trips successfully; if the input is an inactive signal; then the GRS has a nuisance trip.

C_2 If the input is an active signal, then the GRS trips successfully; if the input is an inactive signal, then the GRS does not trip.

C_3 If the input is an active signal, then the GRS fails to trip; if the input is an inactive signal; then the GRS has a nuisance trip.

C_4 If the input is an active signal, then the GRS fails to trip; if the input is an inactive signal, then the GRS does not trip.

For example, $S3$ and $S5$ are both in C_1 because when the GRS is in state $S3$ or $S5$, the GRS trips successfully if the input is an active signal and it has a nuisance trip if the input is an inactive signal. Similar thinking leads to the following.

C_1: $S3$, $S5$, $S7$, $S10$, $S12$, $S13$, $S14$, $S15$, $S17$, $S22$, $S23$, $S24$, $S25$.

C_2: $S0$, $S1$, $S2$, $S6$.

C_3: None.

C_4: $S4$, $S8$, $S9$, $S11$, $S16$, $S18$, $S19$, $S20$, $S21$, $S26$, $S27$, $S28$, $S29$.

Fig. 3 shows the preliminary Markov model for our GRS.

0000	0001	0010	0100	0002	0020	0200	1000	2000
0011	0101	0110	0021	0201	0012	0102	0210	0120
1001	1010	1100	2001	2010	2100	0022	0202	0220
1002	1020	1200	2002	2020	2200	0111	0211	0121
0112	1011	1101	1110	2011	2101	2110	0221	0212
0122	1021	1201	1012	1102	1210	1120	2021	2201
2012	2102	2210	2120	0222	1022	1202	1220	2022
2202	2220	1111	2111	1211	1121	1112	2211	2121
2112	1221	1212	1122	2212	2122	2221	1222	2222

$S0--0000$
$S1--0001, 0010, 0100$
$S2--0002, 0020, 0200$
$S3--1000$
$S4--2000$
$S5--0011, 0101, 0110$
$S6--0021, 0201, 0012, 0102$
$0210, 0120$
$S7--1001, 1010, 1100$
$S8--2001, 2010, 2100$
$S9--0022, 0202, 0220$
$S10--1002, 1020, 1200$
$S11--2002, 2020, 2200$
$S12--0111$
$S13--0211, 0121, 0112$
$S14--1011, 1101, 1110$
$S15--2011, 2101, 2110$
$S16--0221, 0212, 0122$
$S17--1021, 1201, 1012, 1102$
$1210, 1120$
$S18--2021, 2201, 2012, 2102$
$2210, 2120$
$S19--0222$
$S20--1022, 1202, 1220$
$S21--2022, 2202, 2220$
$S22--1111$
$S23--2111$
$S24--1211, 1121, 1112$
$S25--2211, 2121, 2112\gamma$
$S26--1221, 1212, 1122$
$S27--2212, 2122, 2221$
$S28--1222$
$S29--2222$

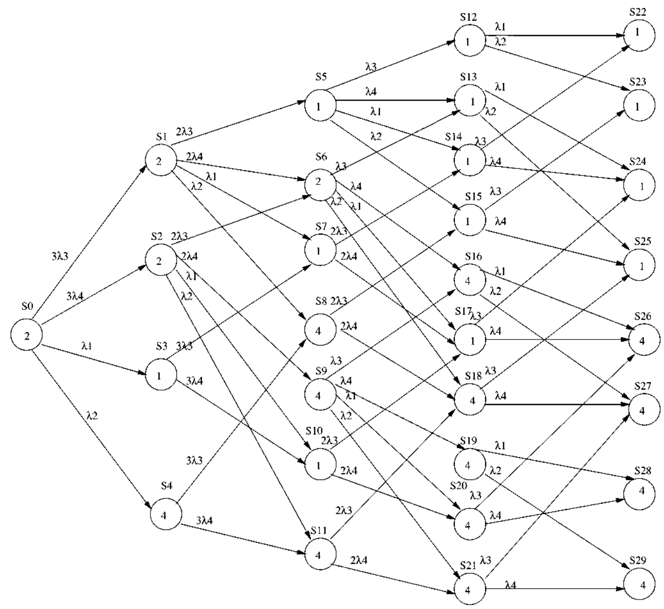

Fig. 3. Preliminary Markov model for the GRS.

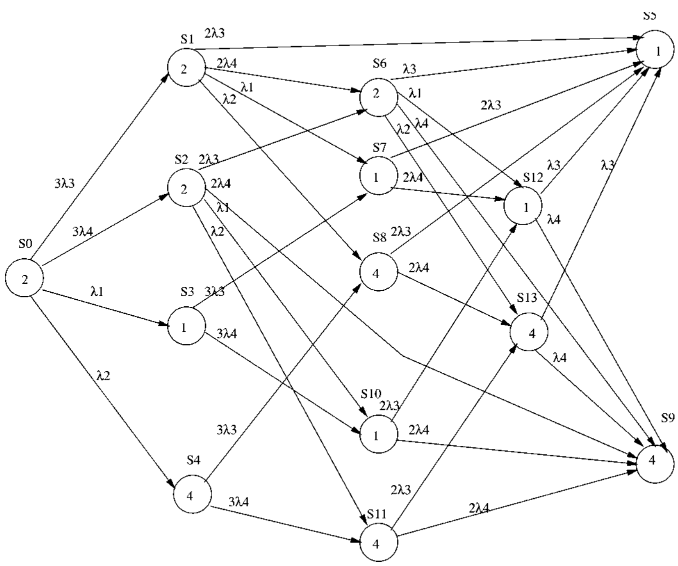

Fig. 4. Final simplification result.

Simplify the Markov Model: Following the rule described in Section III-D, the final reduction result of the previous Markov model is shown in Fig. 4.[2]

Calculate the State Probabilities: Assume that the failure of the GRS components has approximately an exponential distribution. Therefore, the pdf of component failure is $f(t) = \lambda e^{-\lambda t}$, where λ is the failure rate per unit time interval. Then the probability that the component fails before time t is

$$F(t) = \int_0^t \lambda e^{-\lambda t} dt = 1 - e^{-\lambda t} \approx \lambda t \tag{3}$$

where the approximation improves as λt gets small. With this model, a $n+1$ by $n+1$ transition matrix B can be formed, where $B_{ik} (i = 0, 1, \ldots, n, k = 0, 1, \ldots, n)$ indicates the probability that the system transfers from state Si to Sk and n stands for the number of states.

[2]Detailed description of these reduction procedures can be found in [9].

Assume the probability list at initial time $t = t_0$ is

$$Pr^{(0)} = (Pr\,(S0'\,(t_0)) \cdots Pr\,(Sn'\,(t_0))).$$

After m time intervals, the probability list is

$$Pr^{(m)} = (Pr\,(S0'\,(t_0)) \cdots Pr\,(Sn'\,(t_0))) = Pr^{(0)} \times B^m.$$

The elements in the probability list $Pr^{(i)}$ provide the probability that system is in state Sj' after m time intervals. Then, we get

$$\begin{aligned} Pr\,(C_1) &= \sum Pr\,(Si') \quad Si' \in C_1 \\ Pr\,(C_2) &= \sum Pr\,(Si') \quad Si' \in C_2 \\ Pr\,(C_3) &= \sum \mathrm{Pr}\,(Si') \quad Si' \in C_3 \\ Pr\,(C_4) &= \sum Pr\,(Si') \quad Si' \in C_4. \end{aligned}$$

By defining the following terms

$$\begin{aligned} p_1 &= 1 - \lambda_1 - \lambda_2 - 3\lambda_3 - 3\lambda_4 \\ p_2 &= 1 - \lambda_1 - \lambda_2 - 2\lambda_3 - 2\lambda_4 \\ p_3 &= 1 - 3\lambda_3 - 3\lambda_4 \\ p_4 &= 1 - \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4 \\ p_5 &= 1 - 2\lambda_3 - 2\lambda_4 \\ p_6 &= 1 - \lambda_3 - \lambda_4 \end{aligned}$$

the following state transition matrix is obtained, $B = (B_1 \quad B_2)$ where

$$B_1 = \begin{pmatrix} p_1 & 3\lambda_3 & 3\lambda_4 & \lambda_1 & \lambda_2 & 0 & 0 \\ 0 & p_2 & 0 & 0 & 0 & 2\lambda_3 & 2\lambda_4 \\ 0 & 0 & p_2 & 0 & 0 & 0 & 2\lambda_3 \\ 0 & 0 & 0 & p_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_3 & p_4 \\ 0 & 0 & 0 & 0 & 0 & 2\lambda_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2\lambda_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_3 & 0 \end{pmatrix}$$

and

$$B_2 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_1 & \lambda_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2\lambda_4 & \lambda_1 & \lambda_2 & 0 & 0 \\ 3\lambda_3 & 0 & 0 & 3\lambda_4 & 0 & 0 & 0 \\ 0 & 3\lambda_3 & 0 & 0 & 3\lambda_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_4 & 0 & 0 & \lambda_1 & \lambda_2 \\ p_5 & 0 & 0 & 0 & 0 & 2\lambda_4 & 0 \\ 0 & p_5 & 0 & 0 & 0 & 0 & 2\lambda_4 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2\lambda_4 & p_5 & 0 & 2\lambda_3 & 0 \\ 0 & 0 & 2\lambda_4 & 0 & p_5 & 0 & 2\lambda_6 \\ 0 & 0 & \lambda_4 & 0 & 0 & p_6 & 0 \\ 0 & 0 & \lambda_4 & 0 & 0 & 0 & p_6 \end{pmatrix}.$$

$Pr(Si(t_0))$ provides the probability that the system is in state j at time $t = t_0$. It is assumed that at initial time $t = t_0$, every component is in perfect condition due to inspection or maintenance. Therefore

$$Pr^{(0)} = (Pr\,(S0\,(t_0)) \quad Pr\,(S1\,(t_0)) \quad \cdots \quad Pr\,(S13\,(t_0))) \\ = (1 \quad 0 \quad \cdots \quad 0).$$

After m time intervals from initial time $t = t_0$, the probability list is

$$Pr^{(m)} = (Pr\,(S0\,(t_m)) \cdot Pr\,(S1\,(t_m)) \quad \cdots \quad \Pr\,(S13\,(t_m))) \tag{4}$$

$$= Pr^{0} \times B^{m}. \tag{5}$$

Therefore, the elements in the probability list $Pr^{(365)}$ provide the probability that system is in state Sj after 365 time intervals, i.e., one year, since the time interval is chosen as one day. Substituting the FMEA data in Table II into (5) gives

$$\begin{aligned} Pr^{(365)} =& Pr^{(0)} \times B^{365} \\ =& (9.2200e-01 \quad 8.3845e-04 \quad 5.5896e-02 \\ & 2.7948e-04 \quad 1.8632e-02 \quad 2.6383e-07 \\ & 3.3792e-05 \quad 2.5344e-07 \quad 1.6896e-05 \\ & 1.1574e-03 \quad 1.6896e-05 \quad 1.1264e-03 \\ & 1.0186e-08 \quad 6.7907e-07). \end{aligned}$$

Since $S3$, $S5$, $S7$, $S10$, $S12$ constitute C_1, $S0$, $S1$, $S2$, $S6$ constitute category C_2 and $S4$, $S8$, $S9$, $S11$, $S13$ constitute C_4, we have

$$\begin{aligned} Pr(C_1) =& Pr(S3)+Pr(S5)+Pr(S7)+Pr(S10)+Pr(S12) \\ =& 2.9691e-04 \\ Pr(C_2) =& Pr(S0)+Pr(S1)+Pr(S2)+Pr(S6) \\ =& 9.7877e-01 \\ Pr(C_3) =& 0 \\ Pr(C_4) =& Pr(S4)+Pr(S8)+Pr(S9)+Pr(S11)+Pr(S13) \\ =& 2.0933e-02. \end{aligned}$$

E. Perform Impact Assessment

The impact associated with GRS failure to trip, $\bar{T}$, possibly resulting in instability K, is denoted as $Im(K \cap \bar{T} \cap E_i)$. This includes redispatch costs and startup costs. The impact associated with GRS trip, T, is denoted by $Im(T \cap E_i)$. This impact, although it does not include an instability event, is nonetheless nonzero because a unit does in fact trip. However, whereas instability causes loss of an entire plant, a controlled trip typically includes only one unit. Therefore, the impact of a controlled trip is usually much less than the impact of an instability.

In this study, it is assumed that three 350 MW units at Bus 13 would be out of service for 10 h in the event of transient instability; but when a unit trips due to successful GRS operation, it is estimated that the unit is out of services for 3 h. The costs of system redispatching and generator startup are estimated in Table III,[3] in which the impact costs are assumed following normal distribution. It is also assumed that there is no cost related to transient voltage dip and frequency dip.

[3]The cost data here are only for illustration purpose. For real application, they should be obtained from industry. More detailed discussions about how to estimate these data could be found in [16]

F. Evaluate Risk

First, an approach needs to be developed for computing $Pr(T \cap E_i)$ and $Pr(\bar{T} \cap E_i)$ for use in (1) and (2).

Since $S = S0, S1, \ldots, Sn$ represent a state space of the GRS, where Sj is a set of mutually exclusive and exhaustive states, we have

$$\begin{aligned} Pr\,(E_i \cap T) =& Pr\,((E_i \cap T) \cap (S0 \cup S1 \cup \cdots \cup Sn)) \\ =& \sum_{j=0}^{n} Pr\,(E_i \cap T \cap Sj) \\ =& \sum_{j=0}^{n} Pr\left(\frac{T}{E_i \cap Sj}\right) Pr\,(E_i \cap Sj)\,. \end{aligned}$$

Since event E_i is independent of Sj, that is, the occurrence of a fault is independent of the state of the GRS, then

$$Pr\,(E_i \cap Sj) = Pr\,(E_i)\,Pr(Sj). \tag{6}$$

Hence,

$$Pr\,(E_i \cap T) = \sum_{j=0}^{n} Pr\left(\frac{T}{E_i \cap Sj}\right) Pr\,(E_i)\,Pr(Sj) \tag{7}$$

and

$$Pr\left(E_i \cap \bar{T}\right) = \sum_{j=0}^{n} Pr\left(\frac{\bar{T}}{E_i \cap Sj}\right) Pr\,(E_i)\,Pr(Sj). \tag{8}$$

Since $F_1, F_2, \ldots, F_{N_c}$ are independent of each other, by assuming that fault process on a circuit is a homogeneous Poisson process and the failure rate of circuit i is λ_i, the probability $Pr(E_i)$ is given as follows:

$$\begin{aligned} Pr\,(E_i) =& Pr\,(F_i) \prod_{j \neq i} Pr\left(\bar{F}_j\right) \\ =& \left(1 - e^{-\lambda_i t}\right) e^{-\sum_{j \neq i} \lambda_j t}. \end{aligned} \tag{9}$$

These four classes comprise another state space of the GRS where the original states $Sj (j = 0, 1, \ldots, n)$ have been condensed to $C_j (j = 1, 2, 3, 4)$. Based on this state space, we have

$$Pr\,(E_i \cap T) = \sum_{j=1}^{4} Pr\left(\frac{T}{E_i \cap C_j}\right) Pr\,(E_i)\,Pr\,(C_j) \tag{10}$$

and

$$Pr\left(E_i \cap \bar{T}\right) = \sum_{j=1}^{4} Pr\left(\frac{\bar{T}}{E_i \cap C_j}\right) Pr\,(E_i)\,Pr\,(C_j)\,. \tag{11}$$

Each basic input event E_i belongs to a group either active (denoted as AC) or inactive (denoted as $\overline{AC}$). The active input is the input that triggers GRS to trip and the inactive input is the input that does not activate tripping. Given basic input event E_i and C_j, the system output event is completely determined.

TABLE III
IMPACT EVALUATION FOR TRANSIENT INSTABILITY

Cost Component	Unit	Expected Value	Stand. Dev.	95% C.I.
Generator startup	\$/case	5,000	500	4,000-6,000
Redispatch	\$/MWhr	50	5	40-60

Therefore, the conditional probability term in (10) and (11) is 0 or 1 as

$$E_i \subset AC \Rightarrow \begin{cases} Pr\left(\frac{T}{E_i \cap C_j}\right) = \begin{cases} 1 & \text{j=1,2} \\ 0 & \text{j=3,4} \end{cases} \\ Pr\left(\frac{\bar{T}}{E_i \cap C_j}\right) = \begin{cases} 1 & \text{j=3,4} \\ 0 & \text{j=1,2} \end{cases} \end{cases}$$

$$E_i \subset AC \Rightarrow \begin{cases} Pr\left(\frac{T}{E_i \cap C_j}\right) = \begin{cases} 1 & \text{j=1,3} \\ 0 & \text{j=2,4} \end{cases} \\ Pr\left(\frac{\bar{T}}{E_i \cap C_j}\right) = \begin{cases} 1 & \text{j=2,4} \\ 0 & \text{j=1,3.} \end{cases} \end{cases}$$

Assume failure rates on both lines are $\lambda = 4.58e - 5 outage/h$[4], so we have

$$\begin{aligned} Pr(F_i) =& 1 - e^{-\lambda} \\ =& 1 - e^{-4.58\times10^{-5}} \approx 4.5799 \times 10^{-05} \quad i = 1,2 \\ Pr(E_1) =& Pr(E_2) = Pr(F_1)\, Pr(\bar{F}_2) \\ =& \left(1 - e^{-4.58\times10^{-5}}\right) e^{-4.58\times10^{-5}} \approx 4.5797 \times 10^{-05} \\ Pr(E_3) =& Pr(\bar{F}_1)\, Pr(\bar{F}_2) = e^{2(-4.58\times10^{-5})} \\ \approx& 9.9991e - 01 \\ Pr(E_4) =& P(F_1)\, P(F_2) = \left(1 - e^{-4.58\times10^{-5}}\right)^2 \\ \approx& 2.098e - 09. \end{aligned}$$

Thus, the probabilities $Pr(T \cap E_i)$ and $Pr(\bar{T} \cap E_i)$, required in (1) and (2), are shown in Table IV.

Now the risk of transient instability with GRS can be computed. Let $Pg1$, $Pg2$ and $Pg3$ represent the generation of unit 1, unit 2 and unit 3 respectively and assuming all three units are generating 60% capacity (210 MW each), we have

1) $E_1 \cap T$: fault, clear line 1, trip 1 unit for 3 h

$$Im(E_1 \cap T) = 150Pg1 + 5{,}000 = \$36{,}500.$$

2) $E_1 \cap \bar{T}$: fault, clear line 1, fail to trip, lose plant for 10 h

$$\begin{aligned} Im\left(E_1 \cap \bar{T} \cap K\right) =& 500(Pg1 + Pg2 + Pg3) + 15{,}000 \\ =& \$330{,}000 \\ Im\left(E_1 \cap \bar{T} \cap \bar{K}\right) =& \$0. \end{aligned}$$

3) $E_2 \cap T$: fault, clear line 2, trip 1 unit for 3 h (same as 1)

$$Im(E_2 \cap T) = 150Pg1 + 5{,}000 = \$36{,}500.$$

4) $E_1 \cap \bar{T}$: fault, clear line 2, fail to trip, loss plant for 10 h (same as 2)

$$\begin{aligned} Im\left(E_2 \cap \bar{T} \cap K\right) =& 500(Pg1 + Pg2 + Pg3) + 15{,}000 \\ =& \$330{,}000 \\ Im\left(E_2 \cap \bar{T} \cap \bar{K}\right) =& \$0. \end{aligned}$$

[4]We use 1 h as the time unit for the risk calculation since at operation level; 1 h is a reasonable time frame for decision making.

TABLE IV
PROBABILITY REQUIRED IN (1) AND (2)

$Pr(E_1 \cap T)$	=	$Pr(E_1)[Pr(C_1) + Pr(C_2)] = 4.4838e - 05$
$Pr(E_1 \cap \bar{T})$	=	$Pr(E_1)[Pr(C_3) + Pr(C_4)] = 9.5869e - 07$
$Pr(E_2 \cap T)$	=	$Pr(E_2)[Pr(C_1) + Pr(C_2)] = 4.4838e - 05$
$Pr(E_2 \cap \bar{T})$	=	$Pr(E_2)[Pr(C_3) + Pr(C_4)] = 9.5869e - 07$
$Pr(E_3 \cap T)$	=	$Pr(E_3)[Pr(C_1) + Pr(C_3)] = 2.9688e - 04$
$Pr(E_3 \cap \bar{T})$	=	$Pr(E_3)[Pr(C_2) + Pr(C_4)] = 9.9961e - 01$
$Pr(E_4 \cap T)$	=	$Pr(E_4)[Pr(C_1) + Pr(C_2)] = 2.0536e - 09$
$Pr(E_4 \cap \bar{T})$	=	$Pr(E_4)[Pr(C_3) + Pr(C_4)] = 4.3909e - 11$

5) $E_3 \cap T$: no fault, no line clear, trip 1 unit for 3 h due to GRS nuisance trip (same as 1 and 3, if line re-energization cost is negligible)

$$Im(E_3 \cap T) = 150Pg1 + 5{,}000 = \$36{,}500.$$

6) $E_3 \cap \bar{T}$: no fault, no line clear, no trip

$$Im\left(E_3 \cap \bar{T}\right) = \$0.$$

7) E_4: fault, clear line 1 and 2, loss plant for 10 h

$$Im(E_4) = 500(Pg1 + Pg2 + Pg3) + 15{,}000 = \$330{,}000.$$

From (2), we have

$$\begin{aligned} Pr\left(K \cap \bar{T} \cap E_1\right) =& \sum_{n=1}^{4} Pr\left(\bar{T} \cap E_1\right) \times Pr\left(\frac{A = n}{\bar{T} \cap E_1}\right) \\ & \times Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A = n)}\right) \\ =& 9.5869e - 07 \\ & \times \left(0.8 \times Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A = 1)}\right)\right. \\ & + 0.15 \times Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A = 2)}\right) \\ & + 0.05 \times Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A = 3)}\right) \\ & \left. + 0 \times Pr\left(\frac{K}{\bar{T} \cap E_i \cap (A = 4)}\right)\right). \end{aligned}$$

When the generation level is 210 MW, the following probabilities are obtained by performing time domain simulations of the specified fault type at various location along the circuit [14], [15]

$$\begin{aligned} Pr\left(\frac{K}{\bar{T} \cap E_1 \cap (A = 1)}\right) =& 0 \\ Pr\left(\frac{K}{\bar{T} \cap E_1 \cap (A = 2)}\right) =& 2.3256e - 01 \\ Pr\left(\frac{K}{\bar{T} \cap E_1 \cap (A = 3)}\right) =& 8.1395e - 01 \\ Pr\left(\frac{K}{\bar{T} \cap E_1 \cap (A = 4)}\right) =& 0. \end{aligned}$$

Thus,

$$Pr\left(K \cap \bar{T} \cap E_i\right) = 7.2459e - 08.$$

From (1), we have

$$\begin{aligned} Risk\,(E_1) =& Risk\,(T \cap E_1) + Risk\left(K \cap \bar{T} \cap E_1\right) \\ =& Pr\left(K \cap \bar{T} \cap E_1\right) Im\left(K \cap \bar{T} \cap E_1\right) \\ &+ Pr\,(T \cap E_1)\,Im\,(T \cap E_1) \\ =& 330\,000 \times 7.2459e - 08 + 4.4838e - 05 \times 36\,500 \\ =& \$1.6605 \end{aligned}$$

Similarly, we can get $Risk(E_2) = \$1.6605$, $Risk(E_3) = \$10.8361$ and $Risk(E_4) = \$6.9218e{-}04$. Thus, the total risk at generation level 210 MW is

$$Risk = \sum_{i=1}^{4} Risk\,(E_i) = \$14.1578.$$

G. Make Decision

Here, an example about how to determine the GRS optimal arming point is presented.

- *Make Decision Only Based on Risk*

  In present industry practice, the GRS arming point is obtained deterministically based on worst-case scenario regardless of arming time. The three phase fault is the most severe fault, but due to the rarity of its occurrence, its influence on risk may be less than the influence of other fault types. Therefore the deterministic arming point which is obtained only considering the three phase fault is not always equal to the probabilistic arming point which accounts for the influence from all four types of faults. The RBSA criteria for identifying the optimal arming point is: "arm to minimize risk." Therefore, if we plot risk versus generation level for GRS unarmed and GRS armed, the optimal arming point is when the two curves cross. In other words, for generation levels operating below the arming point, risk with armed GRS is larger than risk with GRS not armed and for generation levels above the arming point, risk with armed GRS is smaller than risk with GRS not armed. In our example, the total risk expression for the system with GRS is

$$\begin{aligned} Risk(K \cup T) =& \sum_{i=1}^{4} Risk\,(E_i) \\ =& \sum_{i=1}^{2} Pr\left(K \cap \bar{T} \cap E_i\right) Im\left(K \cap \bar{T} \cap E_i\right) \\ &+ \sum_{i=1}^{3} Pr\,(T \cap E_i)\,Im\,(T \cap E_i) \\ &+ Pr\,(E_4)\,Im\,(E_4)\,. \end{aligned} \quad (12)$$

  Assuming that the probability of GRS tripping event is zero, according to (12), we can obtain the expression for the system without GRS as follows:

$$\begin{aligned} Risk(K) =& \sum_{i=1}^{4} Risk\,(E_i) \\ =& \sum_{i=1}^{2} Pr\,(K \cap E_i)\,Im\,(K \cap E_i) \\ &+ Pr\,(E_4)\,Im\,(E_4)\,. \end{aligned} \quad (13)$$

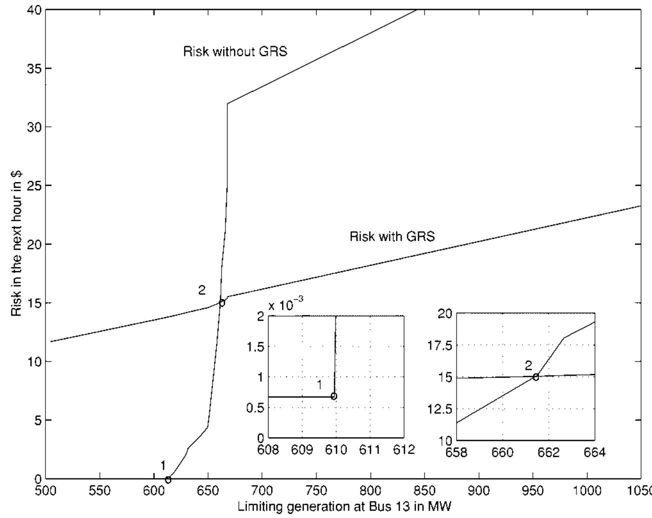

Fig. 5. Risk with and without GRS.

  Based on (12) and (13), we obtain Fig. 5. Without GRS, when the generation level is below the deterministic limit of 610 MW, the system risk results only from $Risk(E_4)$, which indicates simultaneous loss of line 12–13 and 23–13. Thus the risk value is very small. As the generation level increases beyond 610 MW, the system begins to incur risk from three phase fault, two phase faults, line to line faults and one phase faults, successively. For example, the steep portion of the curve corresponds to the generation level for which one phase faults are stable or not depending on where on the line they occur. The high slope is due to the fact that one phase faults are most likely. The gradual increase in the without-GRS curve for generation levels above 668 MW and in the with-GRS curve for all generation levels is caused by the increased economic impact associated with losing an increasingly larger amount of generation. Finally, when the generation level is above 668 MW, any type of fault located anywhere on either line will cause instability and contribute risk.

  Fig. 5 shows that the generation level 661.5 MW ($Pg1 = Pg2 = Pg3 = 220.5$ MW, point 2) is the optimal arming point based on the expect value of risk, while using the worst-case scenario (three phase fault at Bus 13) gives us the arming point 610 MW ($Pg1 = Pg2 = Pg3 = 203$ MW, point 1). By arming the GRS at the generation level 610 MW, the system risk is actually increased by \$13.72/h. Hence the traditional worst-case scenario method to determine the arming point can unnecessarily increase risk. On the other hand, when the GRS is armed at the generation level 800 MW ($Pg1 = Pg2 = Pg3 = 267$ MW), the system risk is decreased by \$19.82/h, which could be subsequently used as an indication of worth to the system of operating a GRS.

- *Make Decision Based on Both Risk and its Variance*

  This decision is only based on the expected value of risk. Fig. 6 gives the standard deviation (S.D.) of system risk with GRS and without GRS. The method for computing the variance is described in [16]. It shows before generation level 627 MW ($Pg1 = Pg2 = Pg3 = 209$ MW, point 3), both the expected value and the variance of risk without

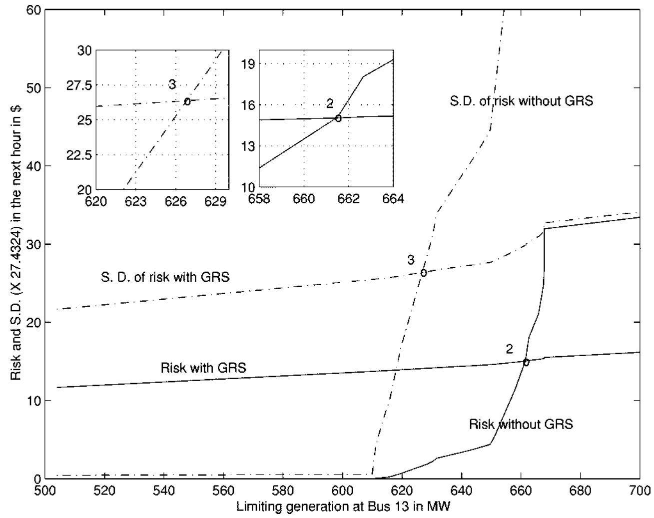

Fig. 6. Variance of risk with and without GRS.

GRS are smaller than those with GRS, while between generation level 627 MW (point 3) and generation level 661.5 MW point 2, expected value of risk without GRS is smaller than that of with GRS, but the variance of risk without GRS is larger than that with GRS; finally, after generation level 661.5 MW (point 2), both the expected value and the variance of risk without GRS are larger than those with GRS. Thus, the points between generation level 627 MW (point 3) and generation level 661.5 MW (point 2) are all Pareto efficient points, which means one cannot find a point that, when with GRS, has both smaller expected value of risk and variance than those without GRS, or vice versa. The system operator's subjective preference to the risk and variance will determine the generation level to arm the GRS among these points.

V. Conclusions

In this paper, the issue of risk brought by using special protection systems (SPS) is raised. A generic procedure is developed for risk based assessment of SPS. To illustrate the proposed approach, an example, using a portion of the IEEE reliability test system together with an illustration of the GRS logic, is provided to show how to calculate GRS reliability and how to integrate the influence of GRS reliability into the risk-based security assessment. Risk based assessment of SPS is useful for various decision making problems. Our illustration of GRS arming level identification shows one of these problems. Others include monitoring of total, composite system risk and providing a price signal for operational decisions affecting security. As SPS continue to proliferate, it seems that their reliability will become more difficult to ensure. The generic procedure proposed in this paper offers a step toward addressing this problem.

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