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Power supply risk assessment method for relay protection system faults

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Abstract: The influence and the potential risk due to hidden faults of a relay protection system on power supply in distribution systems are paid more and more attention to. A probability analysis method is used to analyse fault characteristics and action mechanism of dominant faults, hidden misoperation and non-operation of the relay protection systems, and failure probability model of relay protection system is constructed and simplified. The effects of dominant faults, hidden misoperation and non-operation of the relay protection systems on the reduced power supply load power are analysed, and a probabilistic model for reduced power supply load power is constructed by three parts corresponding to dominant faults, hidden misoperation and non-operation. A probability calculation method of power supply risk occurrence due to hidden faults of relay protecttion system is proposed considering the fault probability of the relay protection systems, the frequency of the hidden faults occurring in operation period, the reduced power supply load power or load power outage, and the connection mode of the in-lines, out-lines and transformers in a substation. The feasibility and applicability of the proposed method for estimation of risk value probability of the relay protection systems is verified by two studied examples.

Key words: reduced power supply load power, relay protection systems, risk value, power supply risk assessment

1. Introduction

In power systems, not only the faults occurred in primary systems affect system operation, but also the faults occurred in secondary systems affect system operation. A hidden failure of a protection system may cause an incorrect and inappropriate removed circuit action [1-20]. With the large-scale access of new energy sources to the power grid, the influence of hidden faults of the relay protection systems is more serious and complicated, making reliability and risk assessment of the relay protection systems a hot research topic [21-22], for example, least square estimation, fault tree analysis, the Markov state space method [23-26], parameter estimation method and Bayesian network method [27-29]. The structure characteristics, sampling method and the trip mode of relay protection devices have great influence on the reliability of the relay protection system [30-31]. The least square estimation method [32], least squares method and the mean rank method [33], least square method [34], improved small sample parameter estimation method [35]-[36] and so on are used to carry out parameter estimation of the relay protection systems, and to evaluate the reliability of the relay protection systems, allowing to obtain good results. The reliability research work of relay protection system is mainly focused on the reliability model [37]-[39] and the reliability analysis [40]-[45], for example, the reliability model of relay protection system is constructed by reliability block diagram method and matrix analysis method [38]; according to the structure characteristics of different process of the relay protection systems, the reliability model for different lines is constructed [40]. The reliability of the relay protection system is analyzed qualitatively according to different action modes [41].

Like fault impact of primary systems, the impact of faults, misoperation and refusal operation of the relay protection systems on power systems is very serious, and the potential risk is extremely huge. The principle mistakes in relay protection setting calculation can result in the failure of the protection systems and the potential risk [46-47], hardware and software invalidation or failure can also cause the failure of protection system, and result in serious risk [3]. There are many hidden and explicit events with uncertainties in the relay protection system, and these events may bring power system a great of risk [48-52]. The risk value of dominant event and hidden event caused by the uncertainty of the relay protection systems can be derived from the product of the probability of these uncertain events and loss value [53-58].

In this paper, the calculation model for power supply risk value due to hidden faults of the relay protection systems in power networks with simple structure or electromagnetic loops is established by using the method of probability analysis, and two power grids are taken as examples to illustrate the proposed calculation method.

2. Probability analysis of reduced power supply load power due to hidden faults of relay protection system

Figure 1 shows a power supply system interconnected by two substations with electromagnetic loops in high and low voltage side. In the power supply system, two substations are interconnected by some tie-lines in high and low voltage side.

It is assumed that the number of in-lines in substation I and substation II is respectively N_{LI} and N_{LII}, the load power in substation I submits to normal distribution with an expected value of $\mu_{\mathrm{D}}^{\mathrm{I}}$ and a variance of $\delta_{\mathrm{DI}}: S_{\mathrm{D}}^{\mathrm{I}} \sim N(\mu_{\mathrm{D}}^{\mathrm{I}}, \delta_{\mathrm{DI}}^{2})$, the load power in substation II submits to normal distribution with an expected value of $\mu_{\mathrm{D}}^{\mathrm{II}}$ and a variance of $\delta_{\mathrm{DII}}: S_{\mathrm{D}}^{\mathrm{II}} \sim N(\mu_{\mathrm{D}}^{\mathrm{II}}, \delta_{\mathrm{DII}}^{2})$, the load rate $k_{\mathrm{IL}i}$ of line $i(i=1, 2, \cdots, N_{\mathrm{LI}})$ in substation I submits to normal distribution with an expected value of $\mu_{\mathrm{Ik}i}$ and a variance of $\delta_{\mathrm{Ik}i}$: $k_{\mathrm{IL}i} \sim N(\mu_{\mathrm{Ik}i}, \delta_{\mathrm{Ik}i}^{2})$, the load rate $k_{\mathrm{IIL}i}$ of line $i(i = 1, 2, \cdots, N_{\mathrm{LII}})$ in substation I submits to normal distribution with an expected value of $\mu_{\mathrm{IIk}i}$ and a variance of $\delta_{\mathrm{IIk}i}$: $k_{\mathrm{IIL}i} \sim N(\mu_{\mathrm{IIk}i}, \delta^2_{\mathrm{IIk}i})$.

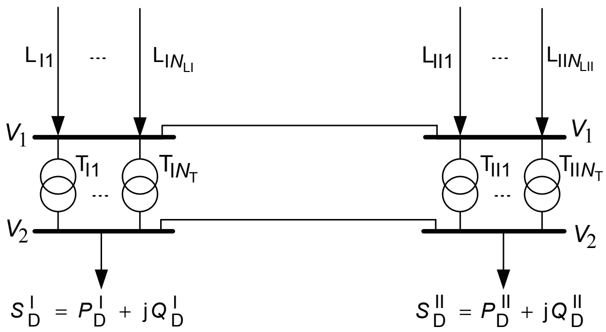

Fig. 1. A power supply system interconnected by two substations with electromagnetic loops in high and low voltage side

When two substations are interconnected by tie-lines in high and low voltage side, an electromagnetic loop network is formed and power flows through tie-lines between two substations. The fault of relay protection devices will result in the disconnection or overload of the circuit.

Due to the fault of the relay protection systems, the fault probability occurring in line i of substation I is:

$$P_{\mathrm{Ik}i} = \mathrm{Pr}_{\mathrm{IF}i} + \mathrm{Pr}_{\mathrm{IWD\text{-}B}i} + \mathrm{Pr}_{\mathrm{IJD\text{-}B}i} \tag{1}$$

where: $\mathrm{Pr}_{\mathrm{IJD\text{-}B}i}$ may be approximated as:

$$\begin{aligned}\mathrm{Pr}_{\mathrm{IJD\text{-}Bi}} &= P(k_{\mathrm{IL}i} \le 1)P_{\mathrm{H}} + [P(1 \le k_{\mathrm{IL}i} \le 1.1)][0.05\frac{(P-P_{\mathrm{H}})}{0.4}] \\ &+ [P(1.1 \le k_{\mathrm{IL}i} \le 1.2)][0.15\frac{(P-P_{\mathrm{H}})}{0.4}] + [P(1.2 \le k_{\mathrm{IL}i} \le 1.3)][0.25\frac{(P-P_{\mathrm{H}})}{0.4}] \\ &+ [P(1.3 \le k_{\mathrm{IL}i} \le 1.4)][0.35\frac{(P-P_{\mathrm{H}})}{0.4}] + [1 - P(k_{\mathrm{IL}i} \le 1.4)]P.\end{aligned} \tag{2}$$

Adopting a similar analysis approach, total reduced load power $S_{\mathrm{D-JG}}$ due to hidden faults of the relay protection systems is formulated as:

$$S_{\mathrm{D-JG}} = S_{\mathrm{D-F}} + S_{\mathrm{D-BJD}} + S_{\mathrm{D-BWD}}, \tag{3}$$

$$S_{\mathrm{D-F}} = [C^1_{N_{\mathrm{LI}}} \mathrm{Pr}_{\mathrm{IF}i}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{LI}-1}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}} + C^1_{N_{\mathrm{LII}}} \mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}-1}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}}] \cdot$$

$$\frac{1}{N_{\mathrm{LI}} + N_{\mathrm{LII}}}(S^{\mathrm{I}}_{\mathrm{D}} + S^{\mathrm{II}}_{\mathrm{D}}) + [C^2_{N_{LI}} \mathrm{Pr}_{\mathrm{IF}i}{}^2(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{LI}-2}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}}$$

$$+C^2_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}{}^2(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_L-2}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}}+C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{LI}-1}\cdot$$

$$(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}-1}]\frac{2}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}(S^{\mathrm{I}}_{\mathrm{D}}+S^{\mathrm{II}}_{\mathrm{D}})+\dots+\mathrm{Pr}_{\mathrm{IIF}}{}^{N_{LI}}\mathrm{Pr}_{\mathrm{IIIF}}{}^{N_{\mathrm{LII}}}(S^{\mathrm{I}}_{\mathrm{D}}+S^{\mathrm{II}}_{\mathrm{D}}), \tag{4}$$

$$S_{\mathrm{D-BJD}}=[\sum_{i=1}^{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{ID-BJD}i}+\sum_{i=1}^{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IID-BJD}i}-C^2_{N_{LI}}\mathrm{Pr}_{\mathrm{ID-BJD}i}{}^2-C^2_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IID-BJD}i}{}^2$$

$$-C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{ID-BJD}i}C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IID-BJD}i}]\cdot[(\sum_{i=1}^{N_{\mathrm{LI}}}k_{\mathrm{IL}i}S_{\mathrm{ILN}_i}+\sum_{i=1}^{N_{\mathrm{LII}}}k_{\mathrm{IIL}i}S_{\mathrm{IILN}_i})-(S^{\mathrm{I}}_{\mathrm{D}}+S^{\mathrm{II}}_{\mathrm{D}})], \tag{5}$$

$$S_{\mathrm{D-BWD}}=[C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}})^{N_{LI}-1}\cdot(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}})^{N_{\mathrm{LII}}}+C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIFi}}(1-$$

$$\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}})^{N_{\mathrm{LII}}-1}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}})^{N_{\mathrm{LI}}}]\cdot\frac{1}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}(S^{\mathrm{I}}_{\mathrm{D}}+S^{\mathrm{II}}_{\mathrm{D}})+[C^2_{N_{LI}}\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}}{}^2\cdot$$

$$(1-\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}})^{N_{LI}-2}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}})^{N_{\mathrm{LII}}}+C^2_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}}{}^2(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}})^{N_{\mathrm{LII}}-2}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}})^{N_{\mathrm{LI}}}$$

$$+C^2_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}}{}^2(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}})^{N_{\mathrm{LII}}-2}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}})^{N_{\mathrm{LI}}}+C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}}C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}}$$

$$(1-\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}})^{N_{LI}-1}\cdot(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}})^{N_{\mathrm{LII}}-1}]\frac{2}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}(S^{\mathrm{I}}_{\mathrm{D}}+S^{\mathrm{II}}_{\mathrm{D}})$$

$$+\dots+\mathrm{Pr}_{\mathrm{IWD\text{-}Bi}}{}^{N_{LI}}\mathrm{Pr}_{\mathrm{IIWD\text{-}Bi}}{}^{N_{\mathrm{LII}}}(S^{\mathrm{I}}_{\mathrm{D}}+S^{\mathrm{II}}_{\mathrm{D}}). \tag{6}$$

Because $S^{\mathrm{I}}_{\mathrm{D}}\sim N(\mu^{\mathrm{I}}_{\mathrm{D}},\delta^2_{\mathrm{DI}})$ and $S^{\mathrm{II}}_{\mathrm{D}}\sim N(\mu^{\mathrm{II}}_{\mathrm{D}},\delta^2_{\mathrm{DII}})$, so:

$$S_{\mathrm{D-JG}}\sim N(\mu_{\mathrm{D-JG}},\sigma^2_{\mathrm{D-JG}}), \tag{7}$$

$$\mu_{\mathrm{D-JG}}=(\mu^{\mathrm{I}}_{\mathrm{D}}+\mu^{\mathrm{II}}_{\mathrm{D}})[[C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}-1}\cdot(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}}+C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}-1}$$

$$(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}}]\cdot\frac{1}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}+[C^2_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}{}^2(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}-2}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}}+C^2_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}{}^2$$

$$1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_L-2}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}}+\frac{2C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}-1}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}-1}]$$

$$+\dots+\mathrm{Pr}_{\mathrm{IIF}}{}^{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IIIF}}{}^{N_{\mathrm{LII}}}+[C^1_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{LI}-1}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}}$$

$$+C^1_{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}-1}\cdot(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{\mathrm{LI}}}]\frac{1}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}+[C^2_{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}{}^2$$

$$(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{LI}-2}\cdot(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}}+C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i}{}^{2}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}-2}$$

$$(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{\mathrm{LI}}}+C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}\,C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{LI}-1}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}-1}]$$

$$\frac{2}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}+\cdots+\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}{}^{N_{LI}}\,\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i}{}^{N_{\mathrm{LII}}}-(\sum_{i=1}^{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}+\sum_{i=1}^{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}-C_{N_{LI}}^{2}\,\mathrm{Pr}_{\mathrm{IF}i}{}^{2}$$

$$-C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIF}i}{}^{2}-C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IF}i}\,C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i})]+[\sum_{i=1}^{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}+\sum_{i=1}^{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}-C_{N_{LI}}^{2}\,\mathrm{Pr}_{\mathrm{IF}i}{}^{2}$$

$$-C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIF}i}{}^{2}-C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IF}i}\,C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i}]\cdot(\sum_{i=1}^{N_{\mathrm{LI}}}\mu_{\mathrm{Ik}i}S_{\mathrm{ILN_i}}+\sum_{i=1}^{N_{\mathrm{LII}}}\mu_{\mathrm{IIk}i}S_{\mathrm{IILN_i}}). \tag{8}$$

$$\sigma_{\mathrm{D-JG}}=(\sigma_{\mathrm{D}}^{\mathrm{I}}+\sigma_{\mathrm{D}}^{\mathrm{II}})[[C_{N_{\mathrm{LI}}}^{1}\cdot\,\mathrm{Pr}_{\mathrm{IF}i}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{LI}-1}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}}+C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i}$$

$$(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}-1}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}}]\frac{1}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}+[C_{N_{\mathrm{LI}}}^{2}\,\mathrm{Pr}_{\mathrm{IF}i}{}^{2}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}-2}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}}$$

$$+C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIF}i}{}^{2}(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{L}-2}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{\mathrm{LI}}}+C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IF}i}\,C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IF}i})^{N_{LI}-1}\cdot$$

$$(1-\mathrm{Pr}_{\mathrm{IIF}i})^{N_{\mathrm{LII}}-1}]\frac{2}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}+\cdots+\mathrm{Pr}_{\mathrm{IIF}}{}^{N_{LI}}\,\mathrm{Pr}_{\mathrm{IIIF}}{}^{N_{\mathrm{LII}}}+[C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{I\mathrm{WD\text{-}B}i}$$

$$(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{LI}-1}\cdot\,(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}}+C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}-1}\cdot$$

$$(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{\mathrm{LI}}}]\frac{1}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}+[C_{N_{\mathrm{LI}}}^{2}\,\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}{}^{2}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{LI}-2}\cdot$$

$$(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}}+C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i}{}^{2}(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}-2}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{\mathrm{LI}}}$$

$$+C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}\,C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i}(1-\mathrm{Pr}_{\mathrm{IWD\text{-}B}i})^{N_{LI}-1}\cdot\,(1-\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i})^{N_{\mathrm{LII}}-1}]\frac{2}{N_{\mathrm{LI}}+N_{\mathrm{LII}}}$$

$$+\cdots+\mathrm{Pr}_{\mathrm{IWD\text{-}B}i}{}^{N_{LI}}\,\mathrm{Pr}_{\mathrm{IIWD\text{-}B}i}{}^{N_{\mathrm{LII}}}-(\sum_{i=1}^{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}+\sum_{i=1}^{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}-C_{N_{\mathrm{LI}}}^{2}\,\mathrm{Pr}_{\mathrm{IF}i}{}^{2}-C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIF}i}{}^{2}$$

$$-C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IF}i}\,C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i})]+(\sum_{i=1}^{N_{\mathrm{LI}}}\mathrm{Pr}_{\mathrm{IF}i}+\sum_{i=1}^{N_{\mathrm{LII}}}\mathrm{Pr}_{\mathrm{IIF}i}-C_{N_{\mathrm{LI}}}^{2}\,\mathrm{Pr}_{\mathrm{IF}i}{}^{2}-C_{N_{\mathrm{LII}}}^{2}\,\mathrm{Pr}_{\mathrm{IIF}i}{}^{2}-C_{N_{\mathrm{LI}}}^{1}\,\mathrm{Pr}_{\mathrm{IF}i}$$

$$C_{N_{\mathrm{LII}}}^{1}\,\mathrm{Pr}_{\mathrm{IIF}i})(\sum_{i=1}^{N_{\mathrm{LI}}}\sigma_{\mathrm{Ik}i}S_{\mathrm{ILN}_i}+\sum_{i=1}^{N_{\mathrm{LII}}}\sigma_{\mathrm{IIk}i}S_{\mathrm{IILN}_i}). \tag{9}$$

3. Power supply risk value calculation due to hidden faults of the relay protection systems

In large substation, the load is generally supplied by two or more set of main transformers in parallel operation. Hidden faults of the relay protection systems may cause misoperation or refusal operation of the transformer or in-lines, out-lines, and lead to over-load events on other transformers or lines, and also result in power supply load reduction events and outage events in the substation.

The risk value of the relay protection systems due to hidden events with uncertainties is determined by the following factors, such as occurrence probability of hidden events, occurrence frequency λ in operation period, reduced power supply load power or losing load power due to outage events [59]. In a substation, the risk value R_S due to over-load, reduced power supply load or outage events caused by the hidden faults of the relay protection systems is formulated as:

$$R_S = p_L S_{LOSS} \sqrt{\lambda (1 + \frac{\sigma^2}{S_{LOSS}^2})^2}\ , \tag{10}$$

where: p_L is fault probability of the relay protection systems in in-lines, σ is variance of reduced power supply load power or losing load power due to hidden faults of the relay protection systems and is determined using historical statistics.

When there are N_{LI} bar of in-lines, the failure probability of the relay protection systems in each in-line is completely different. Assume that the fault probability of the relay protection systems in each in-line is p_{Li} ($i = 1, 2, \ldots, N_{LI}$), the probability of simultaneous fault of the relay protection systems is the product of failure probability of each in-line:

$$p_L = \prod_{i=1}^{N_{LI}} p_{Li}\ .$$

For a transformer in separate operation, the risk value R_S due to over-load, reduced power supply load or outage events caused by the hidden faults is:

$$R_S = p_T S_{LOSS} \sqrt{\lambda (1 + \frac{\sigma^2}{S_{LOSS}^2})^2}\ , \tag{11}$$

where: p_T is fault probability of the relay protection systems in a transformer.

For N_S set of different transformers in parallel operation, the risk value R_S due to over-load, reduced power supply load or outage events caused by the hidden faults of the relay protection systems is:

$$R_S = p_{T1} p_{T2} \cdots p_{TN_S} S_{LOSS} \sqrt{\lambda (1 + \frac{\sigma^2}{S_{LOSS}^2})^2}\ , \tag{12}$$

where: $p_{\mathrm{T}\,j}\,(j=1,2,\ldots,N_{\mathrm{S}})$ is fault probability of the relay protection systems in transformer j.

For N_{S} set of the same transformers in parallel operation, the risk value R_{S} due to over-load, reduced power supply load or outage events caused by the hidden faults of the relay protection systems is:

$$R_{\mathrm{S}} = p_{\mathrm{T}}^{N_{\mathrm{S}}} S_{\mathrm{LOSS}} \sqrt{\lambda\left(1+\frac{\sigma^2}{S_{\mathrm{LOSS}}^2}\right)^2}\,. \tag{13}$$

Assume that the fault probability of each line of the relay protection systems is the same, the load is supplied by N_{S} set of the same transformers and N_{LI} bar of the same lines in parallel operation, the risk value R_{S} due to over-load, reduced power supply load or outage events caused by the hidden faults in lines and transformers is:

$$R_{\mathrm{S}} = p_{\mathrm{L}}^{N_{\mathrm{LI}}} p_{\mathrm{T}}^{N_{\mathrm{S}}} S_{\mathrm{LOSS}} \sqrt{\lambda\left(1+\frac{\sigma^2}{S_{\mathrm{LOSS}}^2}\right)^2}\,. \tag{14}$$

4. Studied example analysis

The supply system with electromagnetic loops between 220 kV BQ substation and 220 kV HX substation is taken as a study example, as shown in Fig. 2. It is found from Fig. 2 that there is some tie-lines in high and low voltage side between 220 kV BQ substation and 220 kV HX substation, and some electromagnetic loops are generated. There are three 220 kV in-lines in 220 kV BQ substation, which is respectively SBA line, SBB line, XB line. The permitted transfer power of SBA line and SBB line is 380 MVA, the permitted transfer power of XB line is 360 MVA.

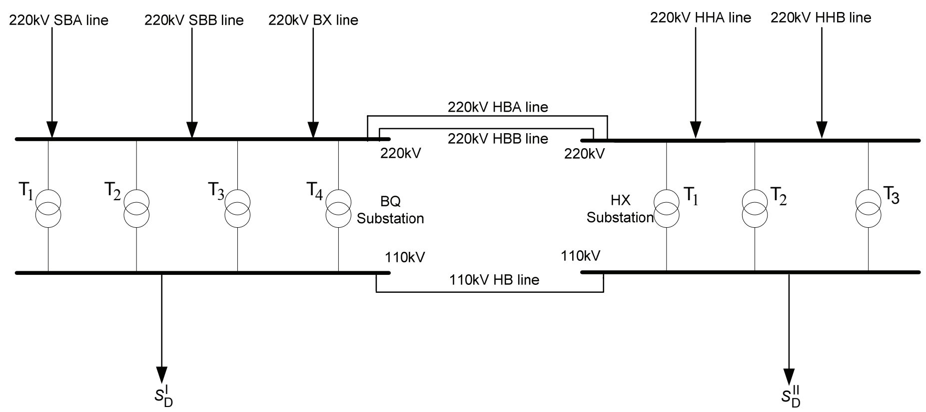

Fig. 2. The supply system with electromagnetic loops between 220 kV BQ substation and 220 kV HX substation

There are two 220 kV in-lines in 220 kV HX substation, which is respectively HHA line, HHB line. The permitted transfer power of HHA line and HHB line is 375 MVA.

Table 1. Reduced power supply load, its corresponding probability distribution and risk value due to hidden faults of relay protection system in the supply system with electromagnetic loops between 220 kV BQ substation and 220 kV HX substation

Reduced power supply load power interval	Probability/%	Risk value/MVA
$S_{\mathrm{LOSS}} \leq 150$ MVA	0.56	0.9391
150 MVA $\leq S_{\mathrm{LOSS}} \leq$ 200 MVA	8.17	14.870
200 MVA $\leq S_{\mathrm{LOSS}} \leq$ 250 MVA	34.16	78.735
250 MVA $\leq S_{\mathrm{LOSS}} \leq$ 300 MVA	41.23	115.24
300 MVA $\leq S_{\mathrm{LOSS}} \leq$ 350 MVA	14.42	47.416
350 MVA $\leq S_{\mathrm{LOSS}} \leq$ 400 MVA	1.43	5.4100
400 MVA $\leq S_{\mathrm{LOSS}}$	0.04	0.1600

It is assumed that the load power in 220 kV BQ substation submits to normal distribution, and the load rate in SBA and SBB line, XB line, HHA and HHB line submits to normal distribution respectively with an expected value of 0.6, 0.65, 0.7 and a variance of 0.15, 0.07, 0.10. It is also assumed that the fault rate of the relay protection device of the two substations is the same, and the rate of dominant faults and non-operation is assumed respectively 0.000008981 and 0.000000930. If the probability P_{H} of hidden faults of relay protection systems in normal states is a lower value, such as 0.000000077, and the correct operation probability P of the relay protection systems is a higher value, such as 0.999999, the following values related to the hidden faults are obtained: $\mathrm{Pr}_{\mathrm{WD\text{-}B}i} = 0.000059$, $\mu_{\mathrm{D-JG}} = 0.000837$, $\sigma_{\mathrm{D-JG}} = 0.000184054$. $S_{\mathrm{D-JG}}$ submits to normal distribution with an expected value of 0.0002285 and a variance of 0.000039367: $N(0.00083, 0.000184^2)$; and the probability for 220 kV SBA line and 220 kV SBB line is $\mathrm{Pr}_{\mathrm{WD\text{-}B}i}$ = 0.000059, 220 kV XB line: $\mathrm{Pr}_{\mathrm{WD\text{-}B}i}$ = 0.000000113, 220 kV HHA line and 220 kV HHB line: $\mathrm{Pr}_{\mathrm{WD\text{-}B}i}$ = 0.00001768.

The interval of reduced power supply load power due to hidden faults of the relay protection systems in the supply system with electromagnetic loops between 220 kV BQ substation and 220 kV HX substation submits to normal distribution with an expected value of 417 MVA. The reduced power supply load and its probability is shown in Table. 1.

The upper and lower boundary values of reduced power supply load power is respectively $\overline{S}_{\mathrm{LOSS}}$, $\underline{S}_{\mathrm{LOSS}}$, then the average value and variation value of reduced power supply load power is respectively determined by:

$$S_{\mathrm{La}} = \frac{\overline{S}_{\mathrm{LOSS}} + \underline{S}_{\mathrm{LOSS}}}{2}, \tag{15}$$

$$\Delta S_{\mathrm{LOSS}} = \overline{S}_{\mathrm{LOSS}} - \underline{S}_{\mathrm{LOSS}}. \tag{16}$$

Considering probability p_S of reduced power supply load power in a certain interval, the risk value of reduced power supply load power due to hidden faults of the relay protection systems is formulated by:

$$R_S = p_S S_{La}\sqrt{\lambda(1+\frac{\Delta S_{LOSS}^2}{S_{La}^2})^2}\,. \tag{17}$$

The risk value of reduced power supply load power due to hidden faults of the relay protection systems in the supply system with electromagnetic loops between 220 kV BQ substation and 220 kV HX substation is shown in Table. 1. It is seen from the Table. 1 that if the probability of reduced power supply load power in a certain interval is large, then the risk value of reduced power supply load power due to hidden faults of the relay protection systems is also large; if the probability of reduced power supply load power in a certain interval is small, then the risk value of reduced power supply load power due to hidden faults of the relay protection systems is also small.

5. Conclusions

In this paper, the calculation model for power supply risk value due to hidden faults of the relay protection systems in power networks with simple structure or electromagnetic loops is established by using the method of probability analysis, and two power grids are taken as examples to illustrate the proposed calculation method. The following conclusions are obtained:

1) The events of over-load, reduced power supply load or outage are caused by hidden faults of the relay protection systems with uncertainties, and the estimation of the risk value of theses events are determined by such factors as occurring probability of hidden events, occurring frequency in operation period, the reduced power supply load power or the losing load power due to outage events and so on.
2) The reduced power supply load power due to hidden faults of the relay protection systems in a supply system with simple structure or electromagnetic loops submit to normal distribution, and correspond to a certain probability value in a certain interval. When the probability of reduced power supply load power in a certain interval is large, the risk value of reduced power supply load power due to hidden faults of the relay protection systems is also large; when the probability of reduced power supply load power in a certain interval is small, the risk value of reduced power supply load power due to hidden faults of the relay protection systems is also small.

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