New Fault Discrimination under the Influence of Rayleigh Noise

Yagang ZHANG, Zengping WANG
State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Baoding, 071003, China
yagangzhang@ncepu.edu.cn

***Abstract*—The researches in this paper mainly provide service for wide area adaptive backup protection. A new fault discriminant technology based on the criterion for fault category and non-fault category will be explored. In the researches, for the common fault types in power system, fully considering the influence of wind power, we have discussed the new fault discriminant technology under Rayleigh noise. Simulation results have shown that even there are random disturbances from Rayleigh noise, the criterion for fault category and non-fault category can still accurately identify system faults.**

***Index Terms*—fault discrimination, wide area measurement system, wide area backup protection, Rayleigh distribution, wind power.**

I. INTRODUCTION

Wide area measurement system and wide area backup protection are hot issues in current power system research field [1-5]. Figure 1 presents a fundamental structural composition of wide area measurement system. But the existing wide area backup protection is still in the early stage of theoretical research and exploration. There is still a long way to go to realize engineering application. There are many areas that still need to be researched more profoundly, such as further exploration about wide area relay protection and how to use the information resources and communication conditions that provided by the rapid development of the current intelligent power grid [6-8]. The main future research directions about wide area backup protection include [9-12]:

- Rapid analytical algorithm for fault recognition and isolation;
- Constitution mechanism and system frame of the wide area backup protection;
- Organization, selection and fusion mechanism;
- The constitution and simulation of the wide area backup protection communication network;
- The reliability evaluation about the wide area backup protection system.

The new type of backup protection can utilize electric information in a much wider extent within the system.

The wide area backup protection that discriminates fault on basis of synchronized multi-point measurement information is the starting point of fault discrimination algorithm research in this paper. In paper [13], utilizing real-time measurements of phasor measurement unit, we are using mainly Breadth-first search, Depth-first search and cluster analysis, and seeking after for the uniform laws of electrical quantities' marked changes. According to line fault and bus-bar fault(single-phase fault, phase-to-phase fault and three-phase fault) in complex electric power systems, we have carried out a great deal of simulation experiments and obtained ideal results. In paper [14], massive simulation experiments have fully proven that the fault identification can be performed successfully by principal component analysis and calculation. In paper [15], based on different kinds of faults in electric power system, the pattern classification technology and linear discrimination principle are able to quickly and accurately identify the fault components and fault sections, and eventually accomplish fault isolation.

The paper is organized as follows. In Section 2, the criterion for fault category and non-fault category is introduced. In Section 3, considering the influence of wind power, the fault discrimination under the influence of Rayleigh noise based on fault and non-fault category criterion is clarified in detail. Finally, the paper is concluded in Section 4.

II. THE CRITERION FOR FAULT CATEGORY AND NON-FAULT CATEGORY

Suppose there is a sample $X=(x_1,\cdots,x_p)$ which comes from one of the $A_1,\cdots,A_G$ populations. It is known that the probability density function of population A_g is $f_g(x)$ and corresponding prior probability is $q_g(g=1,\cdots,G)$.

For the sample $X=(x_1,\cdots,x_p)$, a certain category rule can divide R into subspaces $R_1,\cdots,R_G$ ($R_i\bigcap R_j=\phi,$ $i,j=1,\cdots,G$). If X falls into R_g , then one can determine that X came from the population A_g . Of course, the misjudgement cannot be completely avoided, and our focus is how to minimize the average loss of misjudgement [16-18].

Let $L(h\,|\,g)$ be the misjudgement loss that X belongs to A_g is divided into A_h ,

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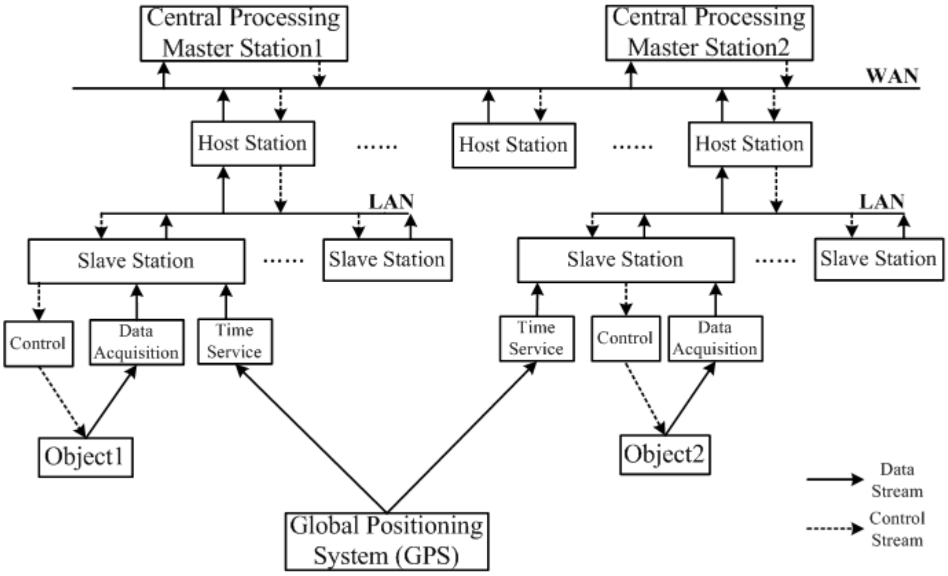

Figure 1. The structural composition of wide area measurement system

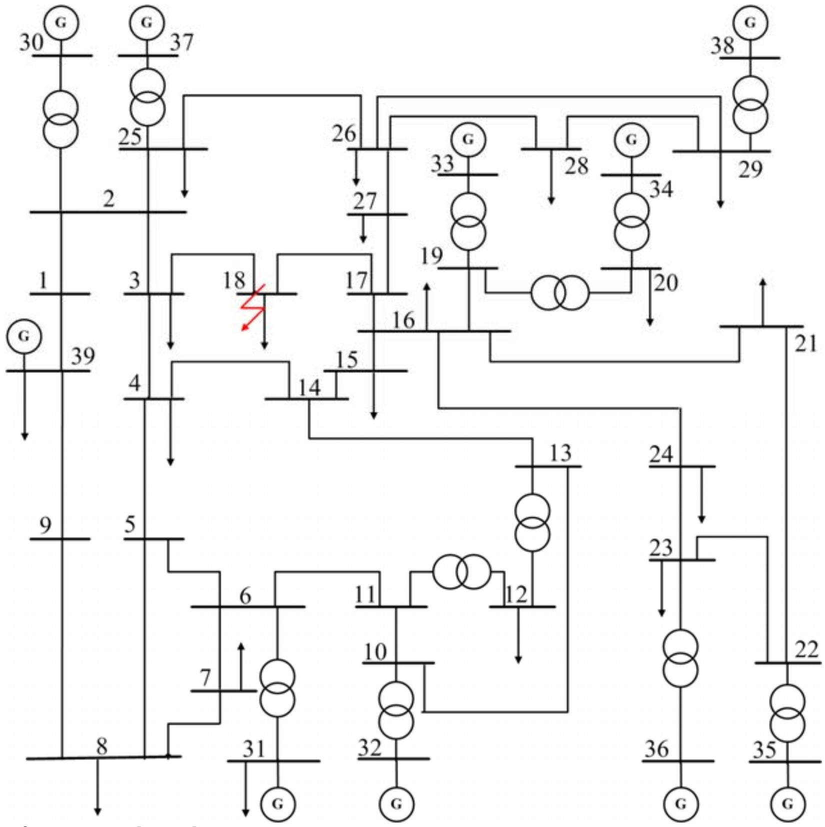

Figure 2. The electric diagram of IEEE 39 nodes with 10 generators

$$L(h|g)\begin{cases} =0, & \text{If } h=g \\ >0, & \text{If } h\neq g \end{cases} \quad (1)$$

The corresponding misjudgement probability is,

$$P(h|g)=\int_{R_h} f_g(X)dX \quad (2)$$

And the average probability of misjudgement is,

$$\sum_{g=1}^{G} q_g \left(\sum_{\substack{h=1 \\ h\neq g}}^{G} P(h|g) \right) \quad (3)$$

So, the average misjudgement loss of a certain category rule is,

$$\sum_{g=1}^{G} q_g \left(\sum_{\substack{h=1 \\ h\neq g}}^{G} P(h|g)L(h|g) \right) \quad (4)$$

And the average loss that a sample X belongs to A_g is divided into A_h is,

$$E_h(X)=\sum_{\substack{g=1 \\ g\neq h}}^{G} \frac{q_g f_g(X)}{\sum_{i=1}^{G} q_i f_i(X)} L(h|g) = \sum_{\substack{g=1 \\ g\neq h}}^{G} q_g f_g(X) L(h|g) \quad (5)$$

If

$$E_h(X) = \min_{1 \le i \le G}\{E_i(X)\} \tag{6}$$

then X will be divided into the population A_h .

In conclusion, the criterion for fault category and non-fault category can be summarized as follows:

Suppose it is known that the probability density function $f_g(X)$ and prior probability q_g of the population $A_g(g=1,\cdots,G)$, the misjudgement loss is $L(h\,|\,g)$ ($h=1,\cdots,G$). So, the category functions can be expressed as,

$$q_g f_g(X) \quad (g=1,\cdots,G) \tag{7}$$

If

$$q_h f_h(X) = \max_{1 \le g \le G}\{q_g f_g(X)\} \tag{8}$$

then X will be divided into the h^{th} population.

In practice, the normal probability density function is widespread, we only need to estimate the parameters of $f_g(X)$,

$$f_g(X) = \frac{\left|S^{-1}\right|^{\frac{1}{2}}}{(2\pi)^{\frac{p}{2}}} e^{[-\frac{1}{2}(X-\bar{X}_g)' S^{-1} (X-\bar{X}_g)]} \tag{9}$$

TABLE I. THE RAYLEIGH RANDOM DISTURBANCE IN SYMMETRICAL SHORT CIRCUIT FAULT

No.	1	2	3
Bus1	1.3204	0.6926	0.1766
Bus2	0.3616	0.5091	1.3024
Bus3	0.5594	0.6193	0.8631
Bus4	0.6095	0.9947	0.9781
Bus5	0.0347	0.2309	0.9214
Bus6	0.6703	0.3536	0.3428
Bus7	0.2468	0.3236	0.6791
Bus8	1.0044	0.7310	0.7410
Bus9	0.5593	0.1538	0.4188
Bus10	0.8050	0.9238	1.0025
Bus11	0.9933	0.0361	0.7040
Bus12	0.7189	0.1441	0.4040
Bus13	0.4576	0.7046	0.3838
Bus14	0.4535	0.2656	0.1494
Bus15	0.4240	0.6941	0.7202
Bus16	1.4331	0.8618	0.5735
Bus17	0.4967	0.4327	1.4769
Bus18	0.5515	0.1156	0.5452
Bus19	0.5773	0.4438	0.4257
Bus20	1.0589	1.0979	0.3312
Bus21	0.9784	0.4471	0.6604
Bus22	0.8202	0.7174	0.1737
Bus23	0.8932	0.9386	0.3469
Bus24	0.8386	0.5484	0.2615
Bus25	0.3656	0.9501	1.2742
Bus26	0.2082	0.3787	0.3472
Bus27	0.3938	1.1498	0.2184
Bus28	0.8268	0.5059	0.3170
Bus29	0.5810	0.6408	0.5808
Bus30	0.6477	0.3268	0.5452
Bus31	1.1863	0.9028	0.3730
Bus32	0.1146	0.8865	0.4840
Bus33	0.1826	0.4548	0.1792
Bus34	0.4030	1.1836	0.2764
Bus35	0.2772	0.9634	0.0418
Bus36	1.2488	0.3816	0.1994
Bus37	0.7556	0.1575	1.1438
Bus38	0.6257	0.2099	0.6502
Bus39	0.7120	1.2012	0.7307

TABLE II. THE RAYLEIGH RANDOM DISTURBANCE IN UNSYMMETRICAL SHORT CIRCUIT FAULT

No.	1	2	3
Bus1	0.0322	0.0163	0.0252
Bus2	0.0104	0.0129	0.0331
Bus3	0.0388	0.0114	0.0321
Bus4	0.0328	0.0283	0.0112
Bus5	0.0418	0.0355	0.0234
Bus6	0.0592	0.0340	0.0517
Bus7	0.0338	0.0158	0.0278
Bus8	0.0249	0.0209	0.0527
Bus9	0.0190	0.0459	0.0344
Bus10	0.0243	0.0464	0.0136
Bus11	0.0315	0.0157	0.0229
Bus12	0.0259	0.0262	0.0112
Bus13	0.0355	0.0268	0.0205
Bus14	0.0241	0.0319	0.0249
Bus15	0.0389	0.0076	0.0094
Bus16	0.0313	0.0373	0.0322
Bus17	0.0117	0.0137	0.0294
Bus18	0.0452	0.0515	0.0135
Bus19	0.0256	0.0219	0.0129
Bus20	0.0226	0.0649	0.0531
Bus21	0.0551	0.0200	0.0531
Bus22	0.0115	0.0291	0.0085
Bus23	0.0161	0.0186	0.0535
Bus24	0.0355	0.0160	0.0080
Bus25	0.0067	0.0382	0.0166
Bus26	0.0119	0.0136	0.0113
Bus27	0.0107	0.0276	0.0019
Bus28	0.0178	0.0204	0.0456
Bus29	0.0046	0.0076	0.0133
Bus30	0.0353	0.0275	0.0362
Bus31	0.0284	0.0450	0.0606
Bus32	0.0151	0.0261	0.0193
Bus33	0.0426	0.0077	0.0211
Bus34	0.0089	0.0140	0.0278
Bus35	0.0158	0.0238	0.0459
Bus36	0.0323	0.0198	0.0293
Bus37	0.0277	0.0323	0.0205
Bus38	0.0572	0.0334	0.0098
Bus39	0.0476	0.0319	0.0219

During the course of judgement, the g which maximizes the category function $q_g f_g(X)$ is what we need. In order to get the simplest form of category function, let's take logarithm and get,

$$\ln(q_g f_g(X)) = \ln q_g + \ln \frac{\left|S^{-1}\right|^{\frac{1}{2}}}{(2\pi)^{\frac{p}{2}}} - \frac{1}{2} X' S^{-1} X + X' S^{-1} \bar{X}_g - \frac{1}{2} \bar{X}_g' S^{-1} \bar{X}_g \tag{10}$$

Let

$$\begin{cases} \ln(q_g f_g(X)) = y_g(X), \\ C_g = S^{-1}\bar{X}_g = (C_{1g}, \cdots, C_{pg})', \\ C_{0g} = -\dfrac{1}{2} \bar{X}_g' S^{-1} \bar{X}_g \end{cases} \tag{11}$$

So the ultimate category function can be expressed as,

$$y_g(X) = \ln q_g + C_{0g} + C_{1g} x_1 + \cdots + C_{pg} x_p, \quad (g=1,\cdots,G) \tag{12}$$

For observed values of sample $X = (x_1, \cdots, x_p)$, we can get $y_1(X), y_2(X), \cdots, y_G(X)$. If

$$y_h(X) = \max_{1 \le g \le G}\{y_g(X)\} \quad (13)$$

then the sample X will be divided into the h^{th} population.

III. Fault Discrimination under the Influence of Rayleigh Noise Based on Fault and Non-fault Category Criterion

A. The suitable fields of Rayleigh distribution

Rayleigh distribution is the most common distribution type that used to describe the time-varying manner on received envelope of smooth fading signal or independent multi-path components [19-22]. In stationary narrow band Gaussian process, the one dimensional distribution of its envelope is just Rayleigh distribution. If two components of a stochastic two dimensional vector obey independent normal distribution, their variances are equal, the modulus of this vector will also render as Rayleigh distribution [23-25].

In the researches of electrical engineering, especially in wind power fields, generally speaking, wind speed and wind direction can produce wind velocity. The absolute values of real component and imaginary component are usually obeying Rayleigh distribution.

The cumulative distribution function (CDF) of Rayleigh distribution can be expressed as:

$$F(x) = P(X \le x) = \begin{cases} 1 - e^{-\frac{x^2}{2\sigma^2}}, & x > 0 \\ 0, & x \le 0 \end{cases} \quad (14)$$

And the corresponding probability density function (PDF) is:

$$f(x) = \begin{cases} \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}, & x > 0 \\ 0, & x \le 0 \end{cases} \quad (15)$$

So, let's consider the stochastic Rayleigh disturbances caused by wind power and explore a new fault discriminant technology.

B. Fault discrimination under the influence of Rayleigh noise in symmetrical short circuit fault

Let us illustrate the new fault discriminant technology with IEEE 39-bus system, which are also internationally accepted as the standard power system test case. Figure 2 is the electric diagram of IEEE 39 nodes with 10 generators. In order to simulate the obtained synchro-phasor data from

TABLE III. THE POSTERIOR PROBABILITY AND DISCRIMINANT CLASSIFICATION RESULTS IN SYMMETRICAL SHORT CIRCUIT FAULT (N-NORMAL NODE; F-FAULT NODE)

Node	**Classification**	**Posterior probability (Fault category)**	**Posterior probability (Normal category)**	**Discriminant classification**
Bus1	N	0.00015	0.99985	N
Bus2	N	0.00002	0.99998	N
Bus3	N	0.01029	0.98971	N
Bus4	N	0.00001	0.99999	N
Bus5	N	0.00260	0.99740	N
Bus6	N	0.02655	0.97345	N
Bus7	N	0.00474	0.99526	N
Bus8	N	0.00006	0.99994	N
Bus9	N	0.00447	0.99553	N
Bus10	N	0.00000	1.00000	N
Bus11	N	0.03148	0.96852	N
Bus12	N	0.12854	0.87146	N
Bus13	N	0.00114	0.99886	N
Bus14	N	0.46364	0.53636	N
Bus15	N	0.00115	0.99885	N
Bus16	N	0.00065	0.99935	N
Bus17	N	0.00281	0.99719	N
Bus18	F	0.99955	0.00045	F
Bus19	N	0.00345	0.99655	N
Bus20	N	0.00002	0.99998	N
Bus21	N	0.00351	0.99649	N
Bus22	N	0.00114	0.99886	N
Bus23	N	0.00005	0.99995	N
Bus24	N	0.05942	0.94058	N
Bus25	N	0.00000	1.00000	N
Bus26	N	0.09819	0.90181	N
Bus27	N	0.00203	0.99797	N
Bus28	N	0.00420	0.99580	N
Bus29	N	0.00011	0.99989	N
Bus30	N	0.00074	0.99926	N
Bus31	N	0.00001	0.99999	N
Bus32	N	0.00001	0.99999	N
Bus33	N	0.00407	0.99593	N
Bus34	N	0.00000	1.00000	N
Bus35	N	0.00006	0.99994	N
Bus36	N	0.00121	0.99879	N
Bus37	N	0.00009	0.99991	N
Bus38	N	0.00105	0.99895	N
Bus39	N	0.00000	1.00000	N

the PMUs in practice, the software named BPA has been adopted in this paper.

In the structure of electricity grid, Bus18 appears three-phase to ground fault. By simulation trials, using the actual measurement data of corresponding variables, and considering the influence of wind power, we further introduce Rayleigh random disturbance $\xi \sim R(\sigma)$, see Table I, the discrimination of fault component and non-fault component will be completed successfully.

Based on the criterion for fault category and non-fault category, the linear discriminant model can be calculated,

$$\begin{aligned} F_1(x) &= -12.246 + 13.262x_1 \\ &\quad - 0.927x_2 + 6.354x_3 \\ F_2(x) &= -25.163 + 13.567x_1 \\ &\quad + 8.116x_2 + 13.172x_3 \end{aligned} \tag{16}$$

And the posterior probabilities and discriminant classification results based on symmetrical short circuit fault have been listed in Table III.

In Table III, the discriminant classification results have clearly shown that the accuracy of classification has reached 100%. The results from discriminant classification are fully consistent with the actual real situation.

TABLE IV. THE POSTERIOR PROBABILITY AND DISCRIMINANT CLASSIFICATION RESULTS IN UNSYMMETRICAL SHORT CIRCUIT FAULT
(N-NORMAL NODE; F-FAULT NODE)

Node	Classification	Posterior probability (Fault category)	Posterior probability (Normal category)	Discriminant classification
Bus1	N	0.00000	1.00000	N
Bus2	N	0.00000	1.00000	N
Bus3	N	0.00000	1.00000	N
Bus4	N	0.00000	1.00000	N
Bus5	N	0.00000	1.00000	N
Bus6	N	0.00000	1.00000	N
Bus7	N	0.00000	1.00000	N
Bus8	N	0.00000	1.00000	N
Bus9	N	0.00000	1.00000	N
Bus10	N	0.00000	1.00000	N
Bus11	N	0.00000	1.00000	N
Bus12	N	0.00000	1.00000	N
Bus13	N	0.00000	1.00000	N
Bus14	N	0.00000	1.00000	N
Bus15	N	0.00000	1.00000	N
Bus16	N	0.00000	1.00000	N
Bus17	N	0.00001	0.99999	N
Bus18	F	1.00000	0.00000	F
Bus19	N	0.00000	1.00000	N
Bus20	N	0.00000	1.00000	N
Bus21	N	0.00000	1.00000	N
Bus22	N	0.00000	1.00000	N
Bus23	N	0.00000	1.00000	N
Bus24	N	0.00000	1.00000	N
Bus25	N	0.00000	1.00000	N
Bus26	N	0.00000	1.00000	N
Bus27	N	0.00000	1.00000	N
Bus28	N	0.00000	1.00000	N
Bus29	N	0.00000	1.00000	N
Bus30	N	0.00000	1.00000	N
Bus31	N	0.00000	1.00000	N
Bus32	N	0.00000	1.00000	N
Bus33	N	0.00000	1.00000	N
Bus34	N	0.00000	1.00000	N
Bus35	N	0.00000	1.00000	N
Bus36	N	0.00000	1.00000	N
Bus37	N	0.00000	1.00000	N
Bus38	N	0.00000	1.00000	N
Bus39	N	0.00000	1.00000	N

C. Fault discrimination under the influence of Rayleigh noise in unsymmetrical short circuit fault

Now let us discuss a more generalized unsymmetrical short circuit fault, in the structure of electricity grid, Bus18 appears single-phase to ground fault. Considering the influence of wind power, another Rayleigh random disturbance $\eta \sim R(\sigma)$ is introduced, see Table II. Based on the criterion for fault category and non-fault category, the linear discriminant model is calculated and can be expressed as,

$$\begin{aligned} F_1(x) &= -65.410 + 365.063x_1 \\ &\quad + 539.925x_2 + 39.486x_3 \\ F_2(x) &= -8.930 + 180.923x_1 \\ &\quad + 137.505x_2 + 55.996x_3 \end{aligned} \tag{17}$$

The posterior probabilities and discriminant classification results based on unsymmetrical short circuit fault are listed in Table IV. It can be seen from the discriminant classification results, the misjudgment ratio is zero. Even there are random disturbances from Rayleigh noise, the criterion for fault category and non-fault category can still accurately identify system faults.

IV. Conclusion

Wide area measurement system and wide area backup protection are hot issues in current power system research field. The new type of backup protection can utilize electric information in a much wider extent within the system. The wide area backup protection that discriminates fault on basis of synchronized multi-point measurement information is the starting point of fault discrimination algorithm research in this paper. In the researches of wind power fields, generally speaking, the absolute values of real component and imaginary component are usually obeying Rayleigh distribution. For the usual fault types in power system, fully considering the influence of wind power, we have explored a new fault discriminant technology under Rayleigh noise. The simulation results show that even there are random disturbances from Rayleigh noise, the criterion for fault category and non-fault category can still accurately identify system faults.

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