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Fault Factor Analysis in Complicated Electrical Engineering

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Abstract—**Wide area adaptive backup protection is one of the research hotspots in complicated electric power system field. The researches in this paper are mainly serving wide area protection system. We will study a novel fault factor analysis in complicated electric power system, and this scheme can reduce the influence of relay protection's wrong action device on fault detection. It has been proved by a large number of simulation experiments, even if there is the influence of random disturbance, the system failure in electric power system can be rapidly and effectively analysed by utilizing a fault factor analysis scheme.**

Index Terms—**Fault factor analysis, backup protection, random disturbance, PMU.**

I. INTRODUCTION

Wide area adaptive backup protection is one of the research hotspots in the complicated electrical engineering field. The fixed value setting of traditional remote backup protection is acquired by off-line setting calculation. Due to the complicatedness of the system structure and the variety of the operation mode that can be considered, it is difficult to dedicate enough attention to both sensitivity and selectivity, which makes it hard to ensure the fixed value can effectively adapt to the running condition of current power grid to reach the best performance [1], [2]. Because it cannot distinguish whether the malfunction is caused by internal fault or the power flow transfer, the remote backup protection makes wrong operation quite often and causes cascading trip that leads to larger range of accident. The available approach to solve those problems is using online adaptive setting algorithm to actively modify fixed value or using power flow transfer recognition algorithm to effectively lock the related protection [3]–[5]. Online adaptive setting uses event trigger mode, chases the operation mode change of the power grid in real-time, and online adjusts the related fixed value of backup protection on the premise of identifying fault point to avoid mismatch protection and to improve sensitivity [6], [7]. However, online adaptive setting scheme produces big error toward disturbance area (influence domain). Thus it cannot correctly reflect the actual running condition and cannot guarantee the reliability. Also, after online setting, it still needs time coordination of protection and fixed value coordination to guarantee the selectivity. Power flow transfer recognition algorithm correlates with emergence control and uses superposition principle and the grid structure before event to form power flow transfer factor and to estimate branch current [8], [9]. It also compares with measured currents to determine whether the line produces power flow transfer. In practice, after removing the branch, the current of generator and load branch will change rapidly under the regulation of automatic regulating device. Together with the wide usage of the nonlinear element in the power grid, the calculation accuracy of power flow transfer factor needs to be further improved.

According to complicated electrical engineering, we have carried out a large number of basic researches. In [10], based on real-time measurement of phasor measurement units, we used mainly pattern classification technology and linear discrimination principle of pattern recognition theory to search for laws of electrical quantity marked changes. The simulation results indicate that respectively study on the phase voltage, positive sequence voltage, negative sequence voltage, phase current, positive sequence current, negative sequence current of single-phase grounding faults and the positive sequence voltage, positive sequence current of three-phase short circuit faults, the pattern classification technology and linear discrimination principle are able to quickly and accurately identify the fault components and fault sections. In [11], based on the classification criteria of multiple populations, according to different kinds of failures, we have provided an effective fault identification technique for electrical engineering.

The researches in this paper are mainly serving wide area protection system. We will study a novel fault factor analysis in complicated electrical engineering. This paper is organized as follows. In Section II, the theoretical foundation for factor analysis is introduced. In Section III, for general fault modes, the fault factor analysis in complicated electrical engineering is discussed carefully. Particularly, fully considering the influence of random disturbance, the fault factor analysis scheme is clarified in detail. Finally, the paper is concluded in

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Section IV.

II. THE THEORETICAL FOUNDATION FOR FACTOR ANALYSIS

Factor analysis is a kind of technology for dimension reduction and for data simplification. It can explore the fundamental structure of data by investigating the internal dependency relationship among multi-variable, and adopt a few abstract variables to represent their essential data structure. The common factors in factor analysis are common influencing factors that cannot be directly observed, but they are objective existing [12], [13]. Each variable can be expressed as the sum of the linear function of common factors and special factor [14], [15], namely

$$X_i = a_{i1}F_1 + a_{i2}F_2 + \cdots + a_{im}F_m + \varepsilon_i, \tag{1}$$

where $i = 1, 2, \cdots, p$, $F_1, F_2, \cdots, F_m$ are common factors, ε_i is special factor of X_i. This model can also be expressed in matrix form

$$X = AF + \varepsilon, \tag{2}$$

where $A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ a_{p1} & a_{p2} & \cdots & a_{pm} \end{pmatrix} = (A_1, A_2, \cdots, A_m),$

$X = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_p \end{pmatrix}$, $F = \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_p \end{pmatrix}$, $\varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_p \end{pmatrix}$, and satisfies:

- $m \le p$,
- $\operatorname{cov}(F, \varepsilon) = 0$, that is, the common factors and special factors are uncorrelated,
- $D_F = D(F) = \begin{pmatrix} 1 & & 0 \\ & 1 & \\ & & \ddots & \\ 0 & & & 1 \end{pmatrix} = I_m$, that is, the common factors are uncorrelated and their variance is 1,
- $D_\varepsilon = D(\varepsilon) = \begin{pmatrix} \sigma_1^2 & & 0 \\ & \sigma_2^2 & \\ & & \ddots & \\ 0 & & & \sigma_p^2 \end{pmatrix} = I_m$, that is, the special factors are uncorrelated, but their variances are not always equal.

The a_{ij} in this model is factor loading, it is the load of the i-th variable on the j-th factor. If the variable X_i is considered as a point in m-dimensional space, then a_{ij} is just its projection on the coordinate axis F_j. In fact, A is the factor loading matrix.

Assume that the original vector $X = (X_1, X_2, \cdots, X_p)'$ has been standardized transformation, if random vector X satisfies the factor model $X = AF + \varepsilon$, the correlation matrix of X is R, so

$$R = AA' + D_\varepsilon. \tag{3}$$

Let

$$R^* = R - D_\varepsilon = AA'. \tag{4}$$

Then R^* is the approximate correlation matrix of X, and the main diagonal element of R^* is h_i^2. In fact, R^* is a nonnegative definite matrix. Let $R^* = (r_{ij}^*)_{p\times p}$, so

$$r_{ij}^* = \sum_{k=1}^{m} a_{ik}a_{jk} = \begin{cases} r_{ij}, & i \ne j, \\ r_{ii} - \sigma_i^2, & i = j, \end{cases} \quad i, j = 1, 2, \cdots, p. \tag{5}$$

In order to obtain $A_1 = (a_{11}, a_{21}, \cdots, a_{p1})'$, under the condition of $r_{ij}^* = \sum_{k=1}^{m} a_{ik}a_{jk}$, $(i, j = 1, 2, \cdots, p)$, one makes $g_1^2 = \sum_{i=1}^{p} a_{i1}^2$ reach maximum, which is a conditional extremum problem. Now let's construct objective function

$$\varphi(a_{11}, a_{21}, \cdots, a_{p1}) = \frac{1}{2}g_1^2 - \frac{1}{2}\sum_{i=1}^{p}\sum_{j}^{p}\lambda_{ij}\Big[\sum_{k=1}^{m} a_{ik}a_{jk} - r_{ij}^*\Big], \tag{6}$$

where λ_{ij} is a Laplace coefficient. For R^* is a symmetric matrix, then $\lambda_{ij} = \lambda_{ji}$. So:

$$\begin{cases} \dfrac{\partial\varphi}{\partial a_{i1}} = a_{i1} - \sum\limits_{j=1}^{p} \lambda_{ij}a_{j1} = 0, & i = 1, 2, \cdots, p, \\ \dfrac{\partial\varphi}{\partial a_{it}} = -\sum\limits_{j=1}^{p} \lambda_{ij}a_{jt} = 0, & t \ne 1. \end{cases} \tag{7}$$

If the largest eigenvalve of R^* is λ_1^*, its corresponding unit eigenvector is t_1^*. Considering the constraint condition $g_1^2 = \sum_{i=1}^{p} a_{i1}^2 = A_1'A_1 = \lambda_1^*$, and $t_1^{*\prime}t_1^* = 1$, A_1 should be

$$A_1 = \sqrt{\lambda_1^*}\,t_1^*. \tag{8}$$

Obviously, A_1 is still a eigenvector corresponding to λ_1^*, and satisfies $A_1'A_1 = \lambda_1^* t_1^{*\prime} t_1^* = \lambda_1^* = g_1^2$, then one can get the first column A_1 in matrix A. So we obtain the factor loading matrix

$$A = (\sqrt{\lambda_1^*}t_1^*, \sqrt{\lambda_2^*}t_2^*, \cdots, \sqrt{\lambda_m^*}t_m^*) = (t_1^*, t_2^*, \cdots, t_m^*)\begin{pmatrix} \sqrt{\lambda_1^*} & & 0 \\ & \ddots & \\ 0 & & \sqrt{\lambda_m^*} \end{pmatrix}. \tag{9}$$

III. FAULT FACTOR ANALYSIS IN COMPLICATED ELECTRICAL ENGINEERING

According to different kinds of short circuit faults, we have carried through large numbers of simulation experiments, and the results have demonstrated that the fault factor analysis scheme proposed in this paper is successful.

Let's take an unsymmetrical short circuit fault in IEEE 39-bus system as an example. Figure 1 presents the electric diagram of IEEE 39-bus system. In the system structure, Bus18 is the actual fault position. By BPA simulation and program calculation with MATLAB, the node negative sequence voltages have been obtained. Particularly, we have considered the influence of random disturbance.

Let's provide the critical calculated results. The component matrix is listed in Table I.

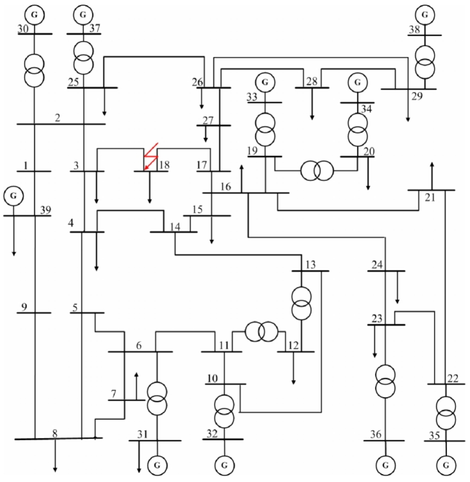

Fig. 1. IEEE 39-BUS new England power system.

TABLE I. THE COMPONENT MATRIX BASED ON FAULT FACTOR ANALYSIS IN IEEE 39-BUS SYSTEM.

BUS	Fault Factor			
	1	2	3	4
BUS1	0.87	0.097	-0.331	0.352
BUS2	0.542	0.839	0.044	0.011
BUS3	0.868	-0.116	0.197	0.442
BUS4	0.868	-0.214	0.448	-0.017
BUS5	0.724	0.429	0.502	0.202
BUS6	0.022	-0.753	-0.657	-0.027
BUS7	0.951	-0.272	0.144	0
BUS8	0.725	0.321	-0.09	-0.602
BUS9	0.307	-0.085	0.943	0.093
BUS10	0.836	-0.537	0.013	-0.107
BUS11	0.828	0.209	-0.351	-0.384
BUS12	0.588	-0.069	0.092	-0.801
BUS13	0.753	0.366	0.439	0.327
BUS14	0.949	0.105	0.297	-0.006
BUS15	0.866	0.368	-0.303	-0.154
BUS16	0.901	0.004	-0.337	0.274
BUS17	0.983	-0.186	-0.004	-0.005
BUS18	0.99	-0.082	-0.087	0.074
BUS19	0.169	-0.535	-0.408	0.721
BUS20	0.632	-0.74	0.229	-0.022
BUS21	0.46	-0.582	0.644	-0.188
BUS22	0.648	-0.756	-0.073	-0.055
BUS23	0.034	0.75	-0.565	0.343
BUS24	0.863	-0.181	-0.334	-0.332
BUS25	0.34	0.443	0.674	0.483
BUS26	0.978	-0.076	0.046	-0.189
BUS27	0.866	0.188	0.095	0.454
BUS28	0.868	0.142	0.101	-0.466
BUS29	0.872	-0.369	0.28	-0.159
BUS30	0.844	-0.535	0.039	0.007
BUS31	0.74	0.018	-0.457	0.494
BUS32	-0.184	0.879	0.36	-0.253
BUS33	0.814	0.511	-0.248	0.122
BUS34	-0.652	-0.572	0.308	0.39
BUS35	0.438	0.836	-0.243	0.222
BUS36	0.385	0.864	0.191	0.261
BUS37	0.618	0.317	-0.687	-0.211
BUS38	0.363	-0.768	-0.219	0.479
BUS39	-0.131	0.067	0.988	0.048

In the component matrix, the expression of each factor can be obtained by this coefficient matrix with the original variables. And the first fault factor is expressed as

$$\begin{aligned}\text{Fault Factor } 1 = {} & 0.870B1 + 0.542B2 + 0.868B3 + \\ & +0.868B4 + 0.724B5 + 0.022B6 + 0.951B7 + \\ & +0.725B8 + 0.307B9 + 0.836B10 + 0.828B11 + \\ & +0.588B12 + 0.753B13 + 0.949B14 + 0.866B15 + \\ & +0.901B16 + 0.983B17 + 0.990B18 + 0.169B19 + \\ & +0.632B20 + 0.460B21 + 0.648B22 + 0.034B23 + \\ & +0.863B24 + 0.340B25 + 0.978B26 + 0.866B27 + \\ & +0.868B28 + 0.872B29 + 0.844B30 + 0.740B31 - \\ & -0.184B32 + 0.814B33 - 0.652B34 + 0.438B35 + \\ & +0.385B36 + 0.618B37 + 0.363B38 - 0.131B39. \qquad (10)\end{aligned}$$

It must be pointed out that the fault factor expressions are corresponding to the nodes in the power grid. In a super large scale grid, the expressions are no doubt more complicated. The core of fault factor analysis lies in the detection process does not depend on any fault factor expression, but the coefficient features of each node.

In the first fault factor, we can draw this conclusion: the factor loading coefficient of BUS18 is 0.990, which is the biggest one in all the factor loading coefficients. So, one can determine that BUS18 is the actual fault position. This conclusion is completely consistent with the practical situation. In summary, the system failure in complicated electrical engineering can be rapidly and effectively analysed by utilizing fault factor analysis scheme.

The total time consumption of location process by fault factor analysis is 0.1020 s, which is also in the range of the delayed time of backup protection. Therefore, the fault factor analysis scheme provided in this paper is successful.

IV. CONCLUSIONS

In this paper, we utilize real time dynamic information of complicated electrical engineering provided by PMU to analyse the system failure. Under traditional monitoring condition, the online rapid diagnosis of power grid fault is mainly based on relay protection and circuit breaker action provided by SCADA system [16], [17], and this greatly depends on the correct action of relay protection and circuit breaker. The fault factor analysis that we are providing is mainly based on factor analysis theory, and this scheme can reduce the influence of relay protection's wrong action device on fault detection. As it has been proved by a large number of simulation experiments, the system failure in complicated electrical engineering can be rapidly and effectively analysed by utilizing fault factor analysis scheme.

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