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Research on Fault Location in Distributed Network with DG Based on Complex Correlation Thevenin Equivalent and Strong Tracking Filter

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Abstract: With the introduction of distributed generators (DG), the traditional distribution system characterized by radical network becomes a multi-source one. Therefore the accuracy of the equivalent model of distributed generators directly affects the precision of fault location. To solve this problem, this paper proposed a fault location method based on complex correlation Thevenin equivalent and strong tracking filter (STF) in distribution network with DG. Strong tracking filter (STF) can be used for real-time extraction of fundamental wave phase and amplitude of single phase voltage and current, and fast track the power parameters mutation. The method of complex correlation Thevenin equivalent takes into account the randomness of measurement data, DG impedance and load to overcome measurement error caused by the uncertainty of the data, so that the construction of the DG impedance model is more accurate. Simulation results show that the method of fault location proposed in this paper has advantages of high accuracy and strong robustness.

Keywords: Distributed generator (DG), Complex correlation Thevenin equivalent, Strong tracking filter (STF), Fault location, Impedance model.

1. Introduction

Research on fault location has always been an important issue for the power system [1]. Due to the complexity of power distribution network topology structure, prone to failure, the distribution network fault diagnosis and repair at home and abroad has been a focus in the study of electrical workers [2-4]. With the introduction of the distributed generators (DG), the traditional radial distribution network evolved into a multi-source one, which made the feeder protection and fault location analysis based on the feeder terminal unit (FTU) of the distribution automation become more complex [5-8]. Fault section location is the basis of precise fault location.

As a result of the DG access, fundamental changes have taken place in the structure of the traditional distribution network, fault location methods must adapt to the change. In distributed network with DG, multi-layer perception (MLP) neural network is used to determine the exact fault type and location first, with the normalization of main power source fault currents, then input to the trained neural network to get the exact fault location, which is proposed in literature [9]. The article [10] mainly studies the effects of DG on automatic

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reclosing switch and fuse coordinated ability in the distribution system. It uses the classification techniques to classify them under the condition of fault, and according to the current direction and the amplitude value that FTU monitored at the point DG access to distribution network to determine fault section. The article [11] proposed a new automatic fault localization method based on radial basis function neural network (RBFNN) in distribution network with DG, this method using RBF neural network can accurately determine the fault type and fault location. Literature [12] proposed a multi-agent based fault diagnosis method in distribution network with DG, distribution network is divided into several parts by using the relay agent, and measure bus current, the fault type is detected and fault location is determined. The monotonicity and continuity of the short-circuit current produced by each power source has nothing to do with other DGs, on the basis of this feature, a new fault line locating method is proposed, which includes the formation of the fault matching table by pre-fault off-line calculation and matching process. This is studied in the article [13]. However, the above method requires a specific topology of the distribution network with DG, and in some operation mode, considerable pre-accident simulation needs to be done. When distribution structure or operation mode changes, it will not apply, the versatility and practicality of this method needs to be improved.

Above methods all have certain disadvantages, this paper puts forward a fault locating method based on the complex correlation Thevenin equivalent and strong tracking filter (STF) in distribution network with DG. This method put forward the definition of fault characteristic value, built the three phase impedance model of distribution network with DG ,analyze fault characteristic value of each node, and search for the node whose fault characteristic value is smallest, so as to decide the fault section, and tested by simulations.

2. Real-time Extraction of Single-phase Voltage Fundamental Phase Based on STF

2.1. Complex State Space Description of Voltage Signal

Discrete form of single phase voltage signal can be expressed as

$$y_k = \sum_{n=1}^{N} A_n \sin\left(k\omega_n T_s + \varphi_n\right) + v_k, N = 1, 2\cdots, \quad (1)$$

where A_n and φ_n is the n-th sinusoidal component amplitude and initial phase angle in single-phase voltage signal respectively; ω_n is the frequency of the n-th sinusoidal component; T_s is the sampling time interval, v_k is the white Gaussian noise added to the single phase voltage.

Assumes that the single phase voltage signal contains only fundamental component, Equation (1) can be simplified as follows:

$$\begin{aligned} y_k &= A_1 \sin(k\omega_1 T_s + \varphi_1) \\ &= (-0.5j)(A_1 e^{j(k\omega_1 T_s + \varphi_1)}) + (0.5j)(A_1 e^{-j(k\omega_1 T_s + \varphi_1)}) \end{aligned} \quad (2)$$

where ω_1 is the fundamental frequency, A_1 is the fundamental amplitude, φ_1 is the fundamental initial phase.

The state variable of voltage signal is defined as

$$\begin{bmatrix} x_{1k} \\ x_{2k} \\ x_{3k} \end{bmatrix} = \begin{bmatrix} e^{j\omega_1 T_s} \\ A_1 e^{j(k\omega_1 T_s + \varphi_1)} \\ A_1 e^{-j(k\omega_1 T_s + \varphi_1)} \end{bmatrix}, \quad (3)$$

Therefore, the nonlinear state space description of voltage signal is given by equation (4).

$$\begin{aligned} x_{k+1} &= f(x_k) + w_k \\ y_k &= Hx_k + v_k \end{aligned}, \quad (4)$$

where $x = \left[x_1 \quad x_2 \quad x_3\right]^T$; $f(x_k) = \left[x_{1k} \quad x_{1k}x_{2k} \quad x_{3k}/x_{1k}\right]^T$; $H = \left[0 \quad -0.5j \quad 0.5j\right]$. Excitation process noise w_k and measurement noise v_k is not related and zero-mean Gaussian white noise, and they satisfies the condition as follows.

$$\begin{aligned} E\left(w_k w_j^T\right) &= Q_k \delta(k, j) \\ E\left(v_k v_j^T\right) &= R_k \delta(k, j) \end{aligned}, \forall k, j \geq 0, \quad (5)$$

where $E(\bullet)$ is the mathematical expectation; Q_k is the covariance matrix of process noise w_k ; R_k is the covariance matrix of measurement noise v_k . $\delta(k, j)$ is the Kronnecker delta function, its definition is given as follows.

$$\delta(k, j) = \begin{cases} 0, k \neq j \\ 1, k = j \end{cases}, \quad (6)$$

When voltage signal contains harmonic components, state variables can be expanded. For example, if voltage signal contains the fifth harmonic, formula (7) can be added to the state variables defined in formula (3).

$$\begin{bmatrix} x_{4k} \\ x_{5k} \end{bmatrix} = \begin{bmatrix} A_5 e^{j(k\omega_5 T_s + \varphi_5)} \\ A_5 e^{-j(k\omega_5 T_s + \varphi_5)} \end{bmatrix}, \quad (7)$$

2.2. State Variables Estimation with STF

STF can recursively estimate the state variables defined in formula (4), the process is shown below.

1) Prediction stage. This step is to calculate the value of the state prediction and covariance matrix of the prediction error.

The value of the state prediction is

$$\hat{x}_{k+1|k} = f(\hat{x}_k), \quad (8)$$

The covariance matrix of the prediction error is

$$P_{k+1|k} = \lambda_{k+1} F_{k+1|k} P_k F_{k+1|k}^T + Q_k, \quad (9)$$

where $F_{k+1|k} = \left.\frac{\partial f(x_k)}{\partial x_k}\right|_{x_k=\hat{x}_k} = \begin{bmatrix} 1 & 0 & 0 \\ x_{2k} & x_{1k} & 0 \\ -x_{3k}/x_{1k}^2 & 0 & 1/x_{1k} \end{bmatrix}$

$\lambda_{k+1} \geq 1$ is the suboptimal fading factor. It is calculated as follows:

$$\lambda_{k+1} = \begin{cases} \lambda_0, \lambda_0 \geq 1 \\ 1, \lambda_0 < 1 \end{cases}, \lambda_0 = \frac{tr[N_{k+1}]}{tr[M_{k+1}]}, \quad (10)$$

$$\begin{aligned} N_{k+1} &= V_{k+1} - HQ_k H^T - \beta R_{k+1} \\ M_{k+1} &= HF_{k+1|k} P_k F_{k+1|k}^T H \end{aligned}, \quad (11)$$

where $tr[\bullet]$ is the matrix trace operator, $\beta \geq 1$ is the selected weakening factor, V_{k+1} is the covariance matrix of the actual output residuals, it is unknown in practice, and can be estimated by equation (12).

$$V_{k+1} = \begin{cases} \varepsilon_1 \varepsilon_1^T, & k = 1 \\ \dfrac{\rho V_k + \varepsilon_{k+1}\varepsilon_{k+1}^T}{1+\rho}, & k \geq 1 \end{cases}, \quad (12)$$

where $0 \leq \rho \leq 1$ is the forgetting factor, and generally $\rho = 0.95$.

2) Updating stage. This step is to calculate the constructed gain matrix, and update the state estimation value and the covariance matrix of estimation error.

The gain matrix is

$$K_{k+1} = P_{k+1|k} H^T \left(HP_{k+1|k} H^T + R_{k+1} \right)^{-1}, \quad (13)$$

The state estimation value is

$$\hat{x}_{k+1} = \hat{x}_{k+1|k} + K_{k+1}\varepsilon_{k+1}, \quad (14)$$

where actual output residuals is $\varepsilon_{k+1} = (y_{k+1} - \hat{y}_{k+1|k})$, $\hat{y}_{k+1|k} = H\hat{x}_{k+1|k} + R_{k+1}$.

The covariance matrix of estimation error is

$$P_{k+1} = (I - K_{k+1}H)P_{k+1|k}, \quad (15)$$

The state variable is recursively estimated with STF, by formula (16) – formula (18) the fundamental frequency, amplitude and phase at $(k+1)T_s$ can be obtained [14]. Fig. 1 is the flowchart of the STF-based fundamental phase real-time extracting method for single-phase grid voltage.

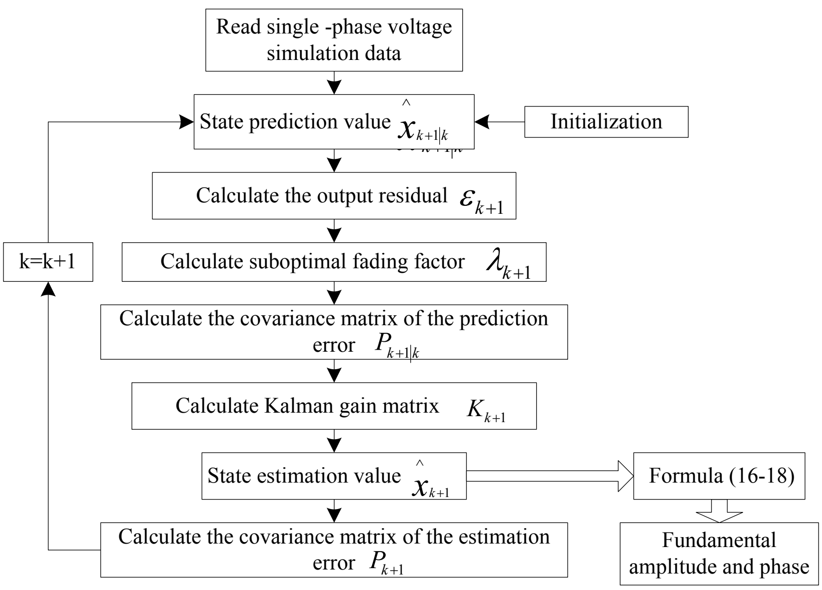

Fig. 1. The flowchart of the STF-based fundamental phase real-time extracting method for single-phase grid voltage.

$$\hat{f}_{k+1} = \frac{1}{2\pi T_s}\left[\operatorname{Im}(\ln(\hat{x}_{1_{k+1}}))\right], \quad (16)$$

$$\hat{A}_{1_{k+1}} = \left|\hat{x}_{2_{k+1}}\right|, \quad (17)$$

$$\hat{\varphi}_{1_{k+1}} = \operatorname{Im}\left[\ln(\frac{\hat{x}_{2_{k+1}}}{\left|\hat{x}_{2_{k+1}}\right| \times (\hat{x}_{1_{k+1}})^{k+1}})\right], \quad (18)$$

3. Complex Correlation Thevenin Equivalent Model of Main Source and DG

By the Thevenin's theorem, the impedance model of main feeder source and DG can respectively be equivalent to an ideal voltage source with an internal resistance. Assuming that each phase current and voltage of the main feeder source and DG can be measured simultaneously (this is feasible under the condition of existing technology), then the positive sequence, negative sequence and zero sequence of them can be measured before fault and during fault. The modeling process of main feeder source and DG impedance model is the same, take some DG as an example to describe its modeling process in detail:

According to the asymmetry theory of electrical network, DG can be equivalent to positive sequence, negative sequence and zero sequence networks shown in Fig. 2

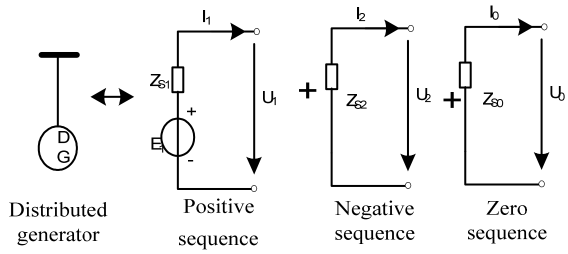

Fig. 2. DG equivalent sequence network diagram.

In Fig. 2, the positive sequence impedance Z_L of the load impedance is constant, then the positive sequence voltage equations of the Thevenin equivalent circuit can be rewritten as follows:

$$V = E - IZ_S, \quad V = IZ_L \quad (19)$$

where V is the positive sequence voltage of access point; I represents sequence current to the positive sequence load; Z_S is the equivalent positive sequence impedance of DG; E is the equivalent positive sequence voltage of DG; Z_S represents the positive sequence impedance of the load.

Adding a small signal variation δ to voltage equation (19), it can be expressed as follows:

$$V + \delta V = (E + \delta E) - (I + \delta I)(Z_S + \delta Z_S)$$
$$V + \delta V = (I + \delta I)(Z_L + \delta Z_L)$$

or

$$\delta Z_L = \frac{\delta V}{I} - \frac{V}{I^2}\delta I, \quad (20)$$

$$\frac{\delta E}{I} - \delta Z_S + \frac{(E - V)}{I^2}\delta I = \frac{\delta V}{I}, \quad (21)$$

Multiply (21) by (20) and take the average over a large number of measured voltages and currents, equation (20) can be expressed as:

$$E - V = \frac{I^* R_{VV} - V^* R_{VI}}{V^* \frac{R_{II}}{I} - I^* \frac{R_{VI}^*}{I}}, \quad (22)$$

where R_{xy} is the covariance of variables *x* and *y*. The covariance of two variables, *x* and *y*, provides a statistical measure of how strongly correlated these variables are. The definition of the covariance of complex variables *x* and *y*, R_{xy} is given as follows:

$$R_{xy} = \langle (x - u_x)(y - u_y) \rangle = \langle x_i y_i \rangle - u_x u_y,$$

where $u_x = \langle x_i \rangle$ and $u_y = \langle y_i \rangle$ is the mean value of x_i and y_i. Note that the impedance of the load side, Z_L, has no statistical correlation with the impedance of source side, Z_S. In other words, the impedance of the load size is statistically independent from the impedance of the source side .Hence, the covariance of variables Z_L and Z_S is zero ($R_{Z_L Z_S} = 0$). Same reason can be applied to source voltage, *E*, and load impedance, Z_L.The covariance of variable *E* and Z_L is zero($R_{EZ_L} = 0$).

From (19) and (22), the equivalent positive sequence impedance of the system, Z_S is

$$Z_S = \frac{I^* R_{VV} - V^* R_{VI}}{V^* R_{II} - I^* R_{VI}^*}, \quad (23)$$

where I^* represents the complex conjugate of I. Since each parameter type is complex, so the result

Z_S is a complex number. The positive sequence current and voltage data in Formula (23) is short circuit data.

Complex correlation Thevenin equivalent method can be applied to calculate for the positive, negative and zero sequence impedance of DG, then impedance model of DG can be obtained.

Similarly, complex correlation Thevenin equivalent method can be used to obtain the impedance model of the main source. The specific flowchart is shown in Fig. 3.

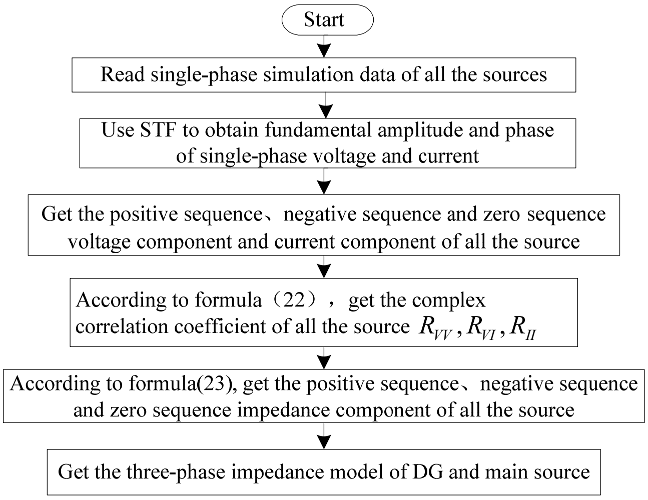

Fig. 3. The flowchart of building DG impedance model based on complex correlation Thevenin equivalent and STF.

4. Fault Location Method Based on Complex Correlation Thevenin Equivalent and STF

4.1. Fault Feature Extraction

Assuming that the DGs are located in nodes *Bus (1), Bus (2) ... Bus (m)* , the falut occurred in noad j and the voltage and the injection current of each power supply can be synchronously measured. The measured voltage and current signals before the fault are $\dot{V}_{BUS}(1),\dot{V}_{BUS}(2)\ldots\dot{V}_{BUS}(m)$ and $\dot{I}_{BUS}(1),\dot{I}_{BUS}(2)\ldots\dot{I}_{BUS}(m)$; The measured voltage and current signals when the fault occurred are $\dot{V}_{BUS}'(1),\dot{V}_{BUS}'(2)\ldots\dot{V}_{BUS}'(m)$ and $\dot{I}_{BUS}'(1),\dot{I}_{BUS}'(2)\ldots\dot{I}_{BUS}'(m)$. The voltage of the fault point before fault, noted as $\dot{V}_j^{oc}$, can be calculated by the system node fault equation. When the fault occurred in node j , The fault current can be calculated as equation (24) by the fault voltage component in source measurement point.

$$\dot{I}_{fj}(i)=Y(i,j)(\dot{V}_{BUS}(i)-\dot{V}_{BUS}(i)),(i=1,2,\ldots,m), \quad (24)$$

The fault current generated by all power supplies is

$$I_{fj0}=(Z(j,j)+R_g)^{-1}\cdot V_j^{oc}, \quad (25)$$

Here, R_g is the fault grounding resistance, $\dot{V}_j^{oc}=\sum_{k=1}^{m}Z(j,k)\dot{I}_{BUS}(k)$.

The error between the fault current of the fault phase calculated by each power supply and the fault current of the fault phase calculated by all power supplies is defined as fault characteristic value. Its mathematical expression is as following.

$$E(j)=\sum_{i=1}^{m}|I_{fj}(i)-I_{fj0}|, \quad (26)$$

4.2. Fault Location Method Based on STF and Complex Correlation Thevenin Equivalent

According to the electrical network theory, the fault current at fault point generated by the common interaction of power sources is equal to that calculated by fault voltage component at measurement points. According to the theory, the fault eigenvalue at fault point in distribution network with DG is 0. So a node with smallest eigenvalue is the associated node of fault branch.

Differential evolution algorithm is used to obtain precise fault distance after the fault section is identified. The specific flowchart of fault location method based on STF and complex correlation Thevenin equivalent is shown in Fig.4.

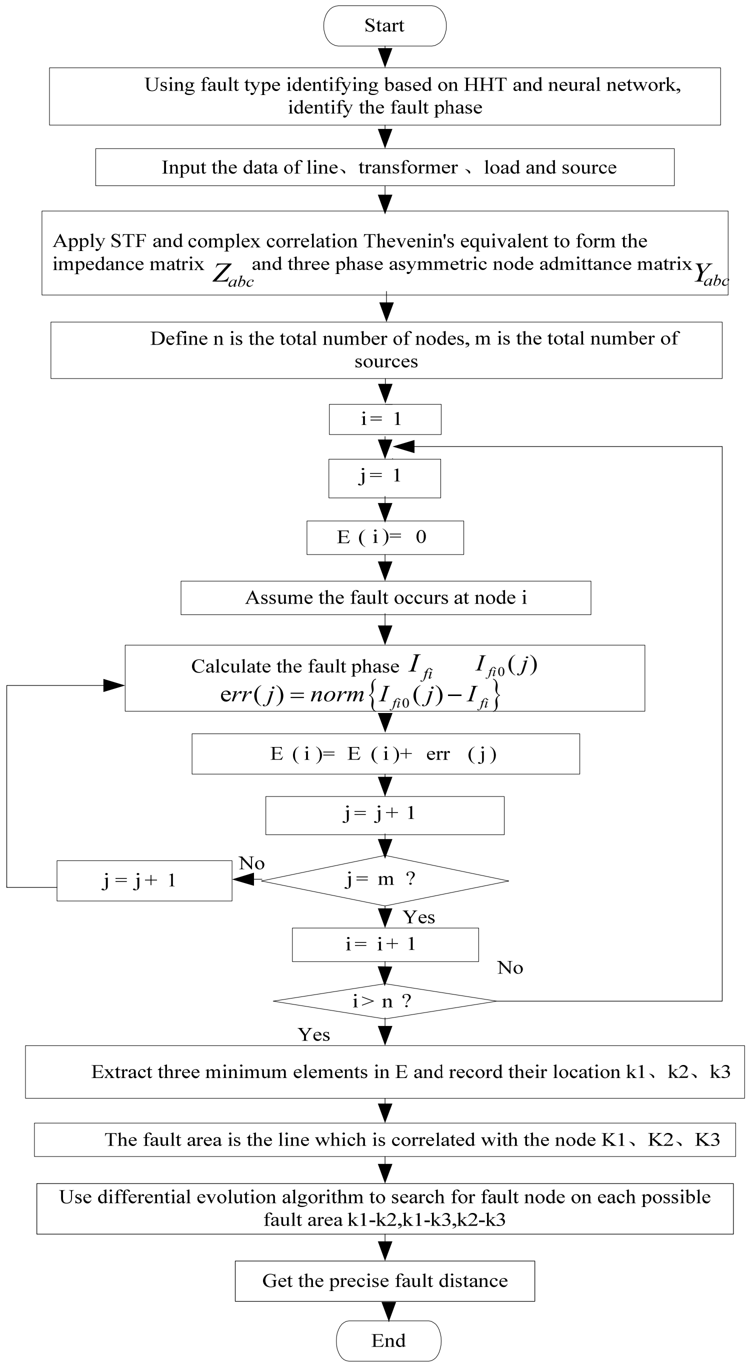

Fig. 4. The flowchart of fault location method based on STF and complex correlation Thevenin equivalent.

5. Simulations in Different Fault Conditions

5.1. The Simulation Model

The method proposed in this paper is tested in an actual 6 KV substation AiDing in XinJiang. The distribution network simulation system model is built in Matlab/Simulink, which is shown as Fig. 5. The total load is 3.6 MVA, the line number is shown in Table 1, the DG unit capacity and access point is shown in Table 2, all the DG units account for 47 % of the total load.

5.2. Simulation Results

The precision of the DG impedance model built by the method proposed in this paper is evaluated by the ranging results based on three-phase impedance model and differential evolution algorithm, and compared with that built by traditional Thevenin equivalent, while the model of other components (transformer, feeder, load and so on) in distribution network with DG is the same.

Table 1. Line number.

Line	Start point	End point	Line	Start point	End point	Line	Start point	End point
1	1	2	21	27	29	41	17	42
2	2	19	22	26	31	42	42	43
3	2	3	23	31	32	43	42	44
4	3	4	24	31	33	44	44	45
5	4	5	25	10	11	45	45	46
6	5	6	26	11	34	46	45	47
7	6	20	27	11	12	47	47	49
8	6	7	28	12	35	48	49	50
9	9	7	29	12	13	49	49	51
10	10	7	30	13	36	50	47	48
11	11	8	31	13	14	51	44	52
12	22	23	32	14	37	52	52	53
13	22	24	33	37	38	53	53	55
14	8	9	34	37	39	54	53	54
15	9	25	35	14	15	55	54	56
16	9	10	36	15	40	56	56	58
17	10	26	37	15	16	57	56	57
18	26	30	38	16	41	58	52	59
19	26	27	39	16	17	59	59	60
20	27	28	40	17	18	60	60	61
61	61	63	62	61	62	63	59	64

Table 2. The capacity and access point of DG unit.

Name	Access point	Capacity /MVA	Name	Access point	Capacity /MVA
DG1	50	0.5	DG4	64	0.3
DG2	41	0.2	DG5	34	0.2
DG3	24	0.4			

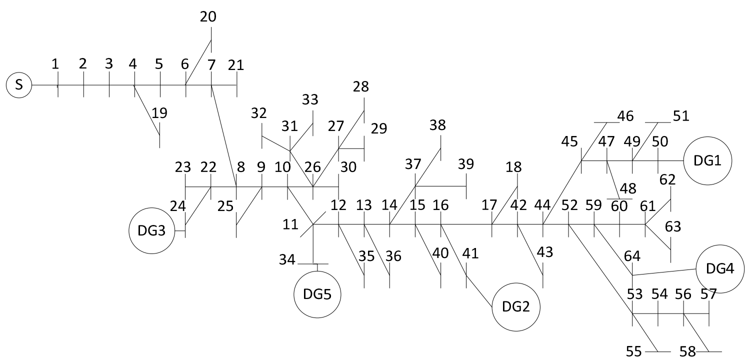

Fig. 5. The topology of simulation model.

Under different operation modes, set different fault types, and fault location is carried out on the basis of the method shown in Fig. 3, the results are shown in Table 3 (length is limited, only part of the fault location results is listed). Note that, in Table 3, 'Ranging Result A' means that the result is obtained by the method proposed in this paper, 'Ranging Result B' means that the result is obtained by traditional Thevenin equivalent.

From the ranging results A shown in Table 3, it is more accurate than that by traditional Thevenin equivalent.

In other words, the precision of DG impedance model based on STF and complex correlation Thevenin equivalent is better than traditional methods. Simulation results show that the method proposed in this paper is effective.

Table 3. The contrast of the fault location result.

Operation Mode	Fault Type	Fault Line	Fault Distance	Ranging Result A	Ranging Result B
Direct Grounding	Single phase	1	1.5	1.4944	1.4927
Direct Grounding	Single phase	8	1.6	1.4197	1.3785
Direct Grounding	Single phase	6	2.0	1.9878	1.9676
Direct Grounding	Single phase	7	1.7	1.5067	1.4993
Direct Grounding	Single phase	2	2.5	2.4228	2.364
Direct Grounding	Two phase	11	1.1	0.8979	0.7512
Direct Grounding	Two phase	26	2.0	2.2564	2.2795
Direct Grounding	Two phase	33	1.9	1.5707	1.3964
Direct Grounding	Two phase	2	1.6	1.5341	1.478
Direct Grounding	Two phase	57	1.4	1.3032	1.2313
Direct Grounding	Three phase	3	1.4	1.2474	1.2119
Direct Grounding	Three phase	23	2.5	2.7956	2.8973
Direct Grounding	Three phase	9	1.1	0.9861	0.8925
Direct Grounding	Three phase	47	1.6	1.2093	1.1295
Direct Grounding	Three phase	59	2.4	2.7783	2.8933
Non-grounding	Two phase	6	1.7	1.5777	1.5694
Non-grounding	Two phase	10	1.9	1.8141	1.6801
Non-grounding	Two phase	25	1.9	1.9963	2.1016
Non-grounding	Two phase	17	2.5	2.3562	2.3111
Non-grounding	Two phase	18	1.0	1.1848	1.2033
Non-grounding	Three phase	2	1.5	1.6244	1.6548
Non-grounding	Three phase	23	2	2.0003	1.9991
Non-grounding	Three phase	26	1.9	2.0676	2.1235
Non-grounding	Three phase	11	0.9	0.7988	0.7890
Non-grounding	Three phase	18	1.3	1.0823	1.0576
By arc-suppressing coil	Two phase	1	1.2	1.2001	1.2016
By arc-suppressing coil	Two phase	27	1.3	1.3642	1.3904
By arc-suppressing coil	Two phase	24	2.3	2.1809	2.1298
By arc-suppressing coil	Two phase	15	1.8	1.6177	1.5702
By arc-suppressing coil	Two phase	29	1.6	1.6305	1.6598
By arc-suppressing coil	Three phase	13	2.5	2.4941	2.4917
By arc-suppressing coil	Three phase	28	2.6	2.4195	2.3761
By arc-suppressing coil	Three phase	36	2.0	1.9978	1.9956
By arc-suppressing coil	Three phase	50	1.7	1.5067	1.4993
By arc-suppressing coil	Three phase	42	2.5	2.4224	2.3621

6. Conclusions

The fault occurring in distribution network with DG can affect the system greatly. This paper proposed a fault location method based on complex correlation Thevenin equivalent and STF in distribution network with DG. STF is used to extract the fundamental amplitude and phase of single-voltage real-time. On this basis, complex correlation Thevenin equivalent is applied to the establishment of DG impedance model. The simulation results show that this method using the correlation between multiple measurement information can overcome the error from the randomness of measurement information. Compared with the traditional Thevenin equivalent, it has a higher accuracy and wider application prospect.

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