ELEKTROTEHNIŠKI VESTNIK 81(5): 256-262, 2014
ORIGINAL SCIENTIFIC PAPER

A Novel Fault-Analysis Method for the Power Grid with Inverter-Interfaced Distribution Generators

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Abstract. Because of the special fault-current characteristics of the inverter-interfaced distribution generator (IIDG) , the conventional fault-analysis method based on the synchronous generator cannot be used for the power grid with IIDGs. The paper points out the problems of using the conventional fault-analysis method for the power grid with IIDGs and proposes a novel fault-analysis method for the power grid with IIDGs. Numerous simulation cases show that the proposed fault-analysis method is accuracte to meet the requirements of short-circuit calculation of the power grid and relay protection.

Keywords: inverter-interfaced distribution generator (IIDG), fault-current characteristics, fault-analysis method

Nova metoda za analizo kratkostičnih tokov v omrežju z invertersko priključenimi razpršenimi viri

V prispevku je prikazana problematika konvencionalne analize kratkostičnih tokov v elektroenergetskem omrežju z invertersko priključenimi razpršenimi viri. Na osnovi analize delovanja elektroenergetskega omrežja z invertersko priključenimi razpršenimi viri, v prispevku predlagamo novo metodo za analizo kratkostičnih tokov. Eksperimentalni rezultati potrjujejo pravilnost metode in njeno uporabnost pri zaščiti omrežja.

1 INTRODUCTION

Nowadays, more and more distributed generators (DGs) are being integrated into the power grid for following three reasons. Firstly, DGs provide on effective technological means for utilization of environmentally friendly energy sources, thus good for the environmental protection. Secondly, DGs can be located dispersedly and flexibly to meet the increasing power demand, and can reduce in this way the investment into expanding the transmission and distribution system. Thirdly, DGs can be reserve of the main power supply to improve the power supply-reliability.

It is known that most DG types (like photovoltaic generation system, fuel cell, wind turbine, etc) are interface with the power grid with interfaced inverters. The are the so-called inverter-interfaced DGs [1-3]. Due to the increasing integrated capacity of IIDGs, the fault characteristics of the power grid have changed greatly and the performance of the conventional relay protection has faced severe challenges [4-6]. In order to assure safety of the power grid and IIDGs, the study and improvement of the relay protection are of great significance. As we know, the relay protection identifies the fault element according to the changed characteristics of the electrical magnitude (or nonelectrical magnitude) of the grid fault occurance. Hence, the fault-analysis method and the subsequent fault-characteristics study of the power grid are the basis for setting the relay protection system.

For the conventional fault-analysis method, the power is supplied by the conventional synchronous generator. However, the fault-current characteristics (including the transient and steady-state characteristics) of IIDG are much different from those of the conventional synchronous generator [7], which means that the conventional fault-analysis method is of the use for the power grid with IIDGs.

To solve the issues of conventional relay protection using IIDGs. Searching for an efficient fault-analysis method for the power grid with IIDGs scholars have carried out many research works. By equivalently representing IIDG with its steady-state model for load-flow calculation, the fault-analysis methods for the distribution network with IIDGs and other DGs are proposed in [8, 9]. However, due to the dynamic response of the inverter during a grid fault, the normal

Received 1 September 2014
Accepted 20 October 2014

IIDG operating mode cannot be provided [10]. Hence, IIDG cannot be replaced by its steady-state model for load-flow calculation. In [10], the fault characteristics of IIDG with the P-Q or V-f control are studied with simulation and the conventional fault-analysis method is extended to take the IIDG contribution into consideration. In [11], a model of IIDG during a grid fault and an improved fault-analysis method are proposed. However, the low-voltage ride-through (LVRT) [12] is not considered in [10, 11] and the IIDG behavior cannot meet the requirements of the grid code. Hence, the short-circuit calculation results of the proposed fault-analysis methods are not in accordance with the realistic situation. In [13], the IIDG fault-current characteristics are studied theoretically to meet the LVRT requirements and a fault-analysis method for the distribution network with a single IIDG is proposed. However, the proposed fault-analysis method is not applicable for a multi IIDGs.

In order to fill the gap, the first to study the conventional fault-analysis method to define the problem of using it for the power grid with IIDGs, and to proposed a novel fault-analysis method. Finally, the simulation cases are studied with PSCAD/EMTDC to validate the effectiveness of the novel fault-analysis method.

2 CONVENTIONAL FAULT-ANALYSIS METHOD

The conventional fault-analysis method based on the node-voltage equation is studied to provide guidance for proposing a novel the fault-analysis method to be used for the power grid with IIDGs.

2.1 Symmetrical-fault analysis

As shown in Fig.1, node f of the active network is faulted through fault impedance z_f . It is noted that fault impedance z_f is not taken into consideration when the bus impedance or admittance matrix is built for fault-analysis.

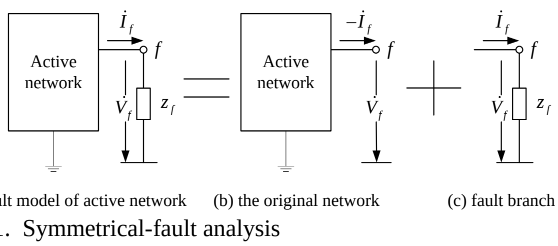

Fig.1. Symmetrical-fault analysis

According to the superposition principle, the fault mode of the active network shown in Fig.1(a) is divided into two parts: the original network as shown in Fig.1(b) and the fault branch shown in Fig.1(c). As seen from Fig.1(b), the short circuit of the original network can be regarded as an additional injection current $-\dot{I}_f$ flow into the network through node f . Hence, the node i voltage can be expressed as

$$\dot{V}_i = \sum_{j\in G} Z_{ij}\dot{I}_j - Z_{if}\dot{I}_f \tag{1}$$

where G is a set of the network active nodes, Z_{ij} is the mutual impedance between node i and node j .

As shown in (1), the node voltage consists of two items. The first item is $\sum_{j\in G} Z_{ij}\dot{I}_j$. It represents the node voltage before the fault occurance is caused by all the network current sources. This is the so-called normal component of the node voltage denoted by $\dot{V}_i^{(0)}$. The second item is $-Z_{if}\dot{I}_f$. It is the fault component of the node voltage caused by short circuit current $\dot{I}_f$ when all the network current sources are disconnected. The superposition of the two voltage components equals the real node voltage after the fault occurance, i.e.

$$\dot{V}_i = \dot{V}_i^{(0)} - Z_{if}\dot{I}_f \tag{2}$$

For faulted node f ,

$$\dot{V}_f = \dot{V}_f^{(0)} - Z_{ff}\dot{I}_f \tag{3}$$

Where $\dot{V}_f^{(0)} = \sum_{j\in G} Z_{fj}\dot{I}_j$ is the normal voltage of node f before the fault occurance and Z_{ff} is the self-impedance of faulted node f .

According to the fault branch shown in Fig.1(c), the following equation is obtained.

$$V_f - z_f\dot{I}_f = 0 \tag{4}$$

Hence, fault current $\dot{I}_f$ is

$$\dot{I}_f = \frac{\dot{V}_f^{(0)}}{Z_{ff} + z_f} \tag{5}$$

With fault current $\dot{I}_f$ and (3), the voltage of any network node can be calculated and the current of any branch then obtained.

2.2 Asymmetrical-fault analysis

When the symmetrical fault takes place, the sequence networks can be equivalently represented by two-port networks from the fault port, as shown in Fig. 2.

For the conventional fault-analysis method, the negative-sequence current is supposed to flow through the same elements as the positive-sequence current. Hence, the negative-sequence network has the same structure with the positive-sequence network, but the difference is that the negative-sequence potentials of all the power sources are zero.

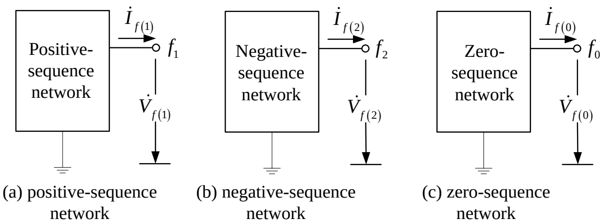

Fig.2 Asymmetrical fault-analysis

Similarly as the symmetrical-fault analysis, the sequence voltages of node *i* of the occurance of a asymmetrical fault can be expressed as

$$\begin{cases}\dot{V}_{i(1)} = \dot{V}_{i(1)}^{(0)} - Z_{if(1)}\dot{I}_{f(1)} \\ \dot{V}_{i(2)} = -Z_{if(2)}\dot{I}_{f(2)} \\ \dot{V}_{i(0)} = -Z_{if(0)}\dot{I}_{f(0)}\end{cases} \quad (6)$$

The sequence voltages of any node and the sequence currents of any branch in the network can be obtained by solving (6) and the fault boundary conditions.

3 CONVENTIONAL FAULT-ANALYSIS METHOD

According to the IIDG fault-current characteristics study [7], only the positive-sequence current is provided by IIDG when the symmetrical or asymmetrical voltage dips. Moreover, of the sudden occur of the generator voltage, the transient component in the fault current provided by IIDG is so that small and damped so quickly that it can be neglected. When a fault occurs in a real power grid, the generator voltage don't drop suddenly with transient period to the IIDG fault current relatively long. However, it don't affect the steady-state component of the fault current which means that there is only the positive-sequence component in the steady state fault current provided by IIDG of the grid-fault occurance. Hence, IIDG can be equivalently replaced by a constant positive-sequence current source of the grid-fault occurance as shown in Fig. 3.

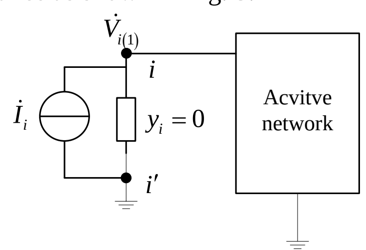

Fig. 3. Equivalent IIDG positive-sequence current-source model

In Fig. 3, $\dot{I}_i = I_i \angle \varphi_{ci}$ represents the equivalent positive -sequence current source, and $\dot{V}_{i(1)} = \alpha_i \angle \varphi_{vi}$ is the positive-sequence component of the generator voltage. The equivalent IIDG mathematical model can be expressed as:

1) If $\alpha_i > 0.9$, then $I_i = i_{d0}^*$, and $\varphi_{cvi} = \varphi_{ci} - \varphi_{vi} = 0$.

2) If $0.4 \le \alpha_i \le 0.9$, and $2(1-\alpha_i) \le \sqrt{1.2^2 - (i_{d0i}^*)^2}$, then $I_i = \sqrt{(i_{d0i}^*)^2 + 4(1-\alpha_i)^2}$,and $\varphi_{cvi} = \arctan\frac{2(1-\alpha_i)}{i_{d0i}^*}$.

3) If $0.4 \le \alpha_i \le 0.9$, and $2(1-\alpha_i) > \sqrt{1.2^2 - (i_{d0i}^*)^2}$, then $I_i = 1.2$,and $\varphi_{cvi} = \arctan\frac{2(1-\alpha_i)}{\sqrt{1.2^2 - 4(1-\alpha_i)^2}}$.

4) If $\alpha_i < 0.4$, then $I_i = 1.2$, and $\varphi_{cvi} = 90^\circ$.

As noted, i_{d0i}^* is the IIDG active-current reference value before the fault occurance.

As seen from the equivalent IIDG mathematical model, the conventional fault-analysis method cannot be used for the power grid with IIDGs for the following three reasons.

1) For the conventional fault-analysis method, the negative-sequence network has the same structure as the positive-sequence network. However, it is unenable for IIDG. The IIDG branch should exist in the positive-sequence network and not in the negative-sequence network, since there is only the positive-sequence component in the IIDG fault current.

2) As show in (2), for the conventional fault-analysis method, the fault component of the node voltage is $-Z_{if}\dot{I}_f$. It is caused by short circuit current $\dot{I}_f$ when all the network current sources are disconnected. For the above calculation method of the node voltage fault component to be effective, the subtransient reactance and subtransient potential of the synchronous generator shuold be kept constant before and after the fault occurrence. However, the condition is not unenable for IIDG. According to the equivalent IIDG mathematic model, the magnitude of the equivalent IIDG positive-sequence current source changes before and after the fault occurrence. Hence, in order to calculate the fault components of the node voltages in the power grid with IIDGs, the network current sources cannot be disconnected. Likewise, the calculation method of the branch-current fault component in the conventional fault-analysis method cannot be used for the power grid with IIDGs.

3) As seen from (2), (5) and (6), all the used elements in the conventional fault-analysis method are those of the *f*-th column in the impedance matrices. Hence, for the conventional fault-analysis method, only the elements with the column number equal to the number of the faulted node are needed for the short-circuit calculation. The reason is fault current $\dot{I}_f$ that is the only one injected into the superimposed network. However, as stated above, the magnitude of the equivalent IIDG positive-sequence current source changes be fore and after the fault occurrence, hence, the network current sources cannot be disconnected in the superimposed network. It means that not only the elements with the

column number is equal to the number of the faulted node, but also the elements with the column numbers are equal to the numbers of the IIDGs-interfaced nodes are needed for the short-circuit calculation of the power grid with IIDGs. Besides, according to the equivalent IIDG mathematical model, the magnitude of the equivalent IIDG positive-sequence current source is related to the positive-sequence component of the generator voltage. Hence, both the bus impedance matrices and equivalent IIDG mathematic model are needed to implement the fault-analysis, which makes the fault-analysis much more complicated and the conventional fault-analysis method inapplicable.

Generally speaking, the IIDG penetration impacts the conventional fault-analysis method greatly. In order to meet the fault-analysis requirements of the power grid with IIDGs and establish a solid basis for the relay protection study, it is necessary to propose a novel fault-analysis method to be used for the power grid with IIDGs.

4 NOVEL FAULT-ANALYSIS METHOD

In this chapter, a novel fault-analysis method to be used for the power grid with IIDGs is proposed.

Firstly, as ti is only the positive-sequence current that is provided by IIDG whatever the fault type is, replace IIDG with a positive-sequence current source equivalently, and then establish sequence networks.

Secondly, for the negative-sequence and zero-sequence networks, the fault-analysis method is the same as the conventional analysis method. The negative-sequence and zero-sequence voltages of node i are

$$\begin{cases} \dot{V}_{i(2)} = -Z_{if(2)}\dot{I}_{f(2)} \\ \dot{V}_{i(0)} = -Z_{if(0)}\dot{I}_{f(0)} \end{cases} \tag{7}$$

Finally, for the positive-sequence network, the original network shown in Fig.1(b) is decomposed into two parts: the normal network before the fault occurrence and superimposed network, as shown in Fig.4.

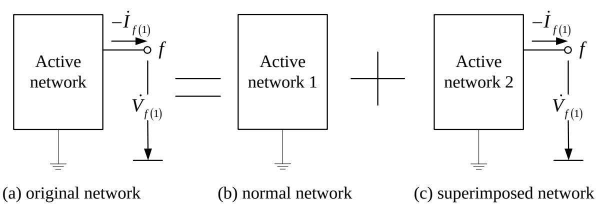

Fig. 4. Decomposition of the positive-sequence network

For the normal network shown in Fig. 4(b), the normal component of the positive-sequence voltage of node i is

$$\dot{V}_{i(1)}^{(0)} = \sum_{j\in G_1} Z_{ij}\dot{I}_j \tag{8}$$

where G_1 is a set of network active nodes (including all the conventional synchronous generators and IIDGs-interfaced nodes).

For the superimposed network shown in Fig. 4(c), all the current sources representing the conventional synchronous generators are disconnected, but the controlled current sources representing IIDGs remain connected. The controlled current sources representing IIDGs in the superimposed network by $\Delta\dot{I}_{DG,k}$. $\Delta\dot{I}_{DG,k}$ is the fault component of the output currents of IIDGs which can be expressed as

$$\Delta\dot{I}_{DG,k} = \dot{I}_{DGf,k} - \dot{I}_{DG0,k} \tag{9}$$

Where $\dot{I}_{DGf,k}$ is the output current of IIDG interfaced with node k after the fault occurrence and $\dot{I}_{DG0,k}$ is the output current of IIDG interfaced with node k before the fault occurrence.

Hence, the fault component of the positive-sequence voltage of node i is

$$\Delta\dot{V}_{i(1)} = \sum_{k\in G_2} Z_{ik}\Delta\dot{I}_{DG,k} - Z_{if}\dot{I}_{f(1)} \tag{10}$$

Where G_2 is a set of the IIDGs-interfaced nodes in the network.

The real positive-sequence voltage of node i after the fault occurrence is

$$\dot{V}_{i(1)} = \dot{V}_{i(1)}^{(0)} + \Delta\dot{V}_{i(1)} = \dot{V}_{i(1)}^{(0)} + \sum_{k\in G_2} Z_{ik}\Delta\dot{I}_{DG,k} - Z_{if}\dot{I}_{f(1)} \tag{11}$$

Combining (7) and (11), the sequence voltages of node i are

$$\begin{cases} \dot{V}_{i(1)} = \dot{V}_{i(1)}^{(0)} + \sum_{k\in G_2} Z_{ik}\Delta\dot{I}_{DG,k} - Z_{if}\dot{I}_{f(1)} \\ \dot{V}_{i(2)} = -Z_{if(2)}\dot{I}_{f(2)} \\ \dot{V}_{i(0)} = -Z_{if(0)}\dot{I}_{f(0)} \end{cases} \tag{12}$$

The fault components of the IIDG output currents $\Delta\dot{I}_{DG,k}$ are unknown and are related to the positive-sequence voltages of the generator terminals. Hence, (12) cannot be solved only with the fault boundary conditions. In order to implement the fault-analysis for the power grid with IIDGs, the following approaches should be adopted.

Firstly, according to (11) and (12), the positive-sequence voltages of the IIDGs interfaced nodes and sequence voltages of the faulted node are expressed in (13) and (14), respectively.

$$\dot{V}_{m(1)} = \dot{V}_{m(1)}^{(0)} + \sum_{k\in G_2} Z_{mk}\Delta\dot{I}_{DG,k} - Z_{mf}\dot{I}_{f(1)},\ m\in G_2 \tag{13}$$

$$\begin{cases} \dot{V}_{f(1)} = \dot{V}_{f(1)}^{(0)} + \sum_{k\in G_2} Z_{fk}\Delta\dot{I}_{DG,k} - Z_{ff}\dot{I}_{f(1)} \\ \dot{V}_{f(2)} = -Z_{ff(2)}\dot{I}_{f(2)} \\ \dot{V}_{f(0)} = -Z_{ff(0)}\dot{I}_{f(0)} \end{cases} \tag{14}$$

Then, if the IIDG output currents are available before the fault occurrence, $\Delta\dot{I}_{DG,k}$ and sequence currents at the fault point can be obtained by solving (13), (14), the fault boundary conditions and the equivalent IIDG mathematical model.

Finally, the sequence voltages of any node and sequence currents of any branch in the network can be obtained with (12).

As seen from (12), only the elements with the column numbers are equal to the numbers of the faulted node and IIDGs-interfaced nodes are needed for the fault-analysis of the power grid with IIDGs.

Fig. 5 shows a schematic diagram of the novel fault-analysis method.

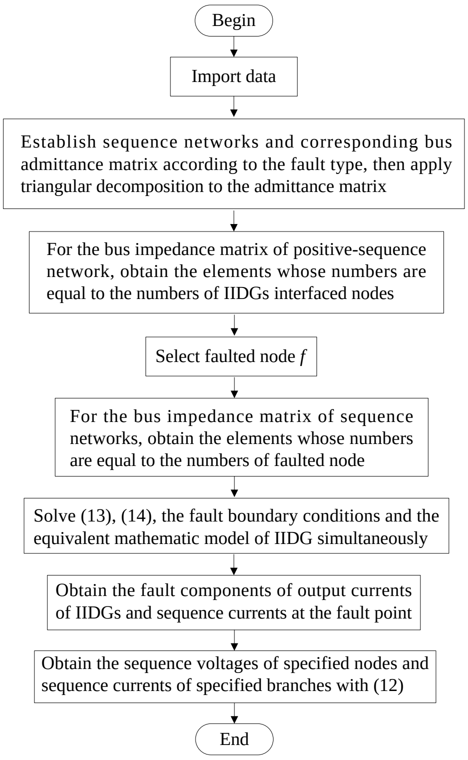

Fig. 5. Diagram of the fault-analysis method of the power grid with IIDGs

5 CASE STUDY

In order to validate the novel fault-analysis method, a simulation model of the power grid with IIDGs was built with PSCAD/EMTDC, as shown in Fig. 6.

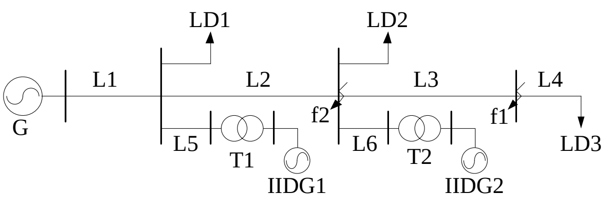

Fig. 6 Diagram of the simplified power grid with IIDGs

In Fig. 6, the transmission lines are of the same type and the line parameters are $r_{(1)}=r_{(2)}=0.17\Omega/\text{km}$ and $x_{(1)}=x_{(2)}=0.394\Omega/\text{km}$. The total lengths of *L*1, *L*2, *L*3, *L*4, *L*5 and *L*6 are 5 km, 6 km, 10 km, 2 km, 0.5 km and 0.5 km respectively. The capacity of the two grid-connected IIDGs is 1 MW each. The parameters of T1 and T2 are the same. The rated capacity is 1.25/1.25MVA, the turn ratio is 0.38 kV/10.5 kV, the winding type is *Y/D* and the leakage reactance is 0.065 pu. The equivalent impedances of *L*D1 and *L*D2 are $120+j39.11\ \Omega$, and the equivalent impedance of *L*D3 is $80+j26.08\ \Omega$.

Table 1 and Table 2 compare the calculated and measured values of the fault currents of the three-phase fault occurance at *f*1 and *f*2 respectively. Table 3 and Table 4 compare the calculated and measured values of fault currents of the Phase-B-to-Phase-C fault occurance at *f*1 and *f*2 respectively. It is noted that the unit of the magnitude is the ampere (A), and the unit of the angel is the degree (°).

From Table 1, Table 2, Table 3 and Table 4, it can be found the theoretical values agree with measured values very well, which validates the effectiveness of the novel fault-analysis method. Hence, the novel fault-analysis method can satisfy the requirements of fault-analysis and relay protection study of the power grid with IIDGs.

Table 1. Branch currents on condition that three-phase fault occurance at *f*1

	Output current of IIDG1		**Output current of IIDG2**		**Current at the fault point**	
	Mag.	**Ang.**	**Mag.**	**Ang.**	**Mag.**	**Ang.**
Calculated values	63.01	34.96	65.68	91.59	621.37	114.81
Measured values	63.51	35.29	65.93	91.84	624.92	114.40

Table 2. Branch currents on condition that three-phase fault occurance at *f*2

	Output current of IIDG1		**Output current of IIDG2**		**Current at the fault point**	
	Mag.	**Ang.**	**Mag.**	**Ang.**	**Mag.**	**Ang.**
Calculated values	65.63	64.35	0.00	/	1249.56	112.56
Measured values	65.91	64.78	0.04	-68.06	1256.78	113.88

Table 3. Branch currents of the Phase-B-to-Phase-C fault occurance at *f*1

	Output current of IIDG1				Output current of IIDG2				Current at the fault point			
	Pos.-Seq. comp.		Neg.-Seq. comp.		Pos.-Seq. comp.		Neg.-Seq. comp.		Pos.-Seq. comp.		Neg.-Seq. comp.	
	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
Calculated values	57.9	22.6	0.00	/	66.0	40.9	0.00	/	325.2	116.1	325.2	-63.9
Measured values	57.7	22.2	2.2	171.8	65.9	40.7	2.4	161.4	326.5	116.2	326.5	-63.8

Table 4. Branch currents of the Phase-B-to-Phase-C fault occurance at *f*2

	Output current of IIDG1				Output current of IIDG2				Current at the fault point			
	Pos.-Seq. comp.		Neg.-Seq. comp.		Pos.-Seq. comp.		Neg.-Seq. comp.		Pos.-Seq. comp.		Neg.-Seq. comp.	
	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
Calculated values	635.5	34.8	0.00	/	659.4	88.3	0.00	/	609.5	115.8	609.5	-64.2
Measured values	635.2	34.6	4.8	167.9	659.3	86.7	7.8	163.5	610.0	115.9	610.0	-64.1

6 VERIFICATION AND VALIDATION OF THE SIMULATION MODEL

The simulation model was built according to Fig. 6, and the IIDG model according to Ref. [7] was verified and validated. In this context, the mathematical equations and logic of the simulation model were verified. Moreover, in the simulation model, the grid is represented by an ideal voltage source, and the loads LD1, LD2 and LD3 are represented by a branch consisting of a resistor and inductor. The simulation model is composed of the basic modules (such as transmission line, transformer, etc) provided by PSCAD/EMTDC were validated by numerous users all over the world over many years. This means that the simulation model is correct.

Furthermore, according to Tables 1, 2, 3 and 4, the simulation results agree with the theoretical-analysis results quite well, since the largest absolute error of the magnitude between the simulation results and the theoretical-analysis results is only 0.63% and the largest absolute error of the angle between the simulation results and the theoretical-analysis results is only 1.77%. Hence, the simulation results and the theoretical-analysis results verify each other.

6 CONCLUSIONS

As there is a great difference between the fault-current characteristics of IIDG and of conventional synchronous generator, the conventional fault-analysis method cannot be used for the power grid with IIDGs. A novel fault-analysis method is therefor proposed in this paper.

For the novel fault-analysis method, IIDG is represented by a positive-sequence current source of the magnitude corresponding to the positive-sequence generator-terminal voltage. Then the fault-analysis is implemented by solving the node-voltage equations of the sequence networks and the fault boundary conditions and setting up an equivalent IIDG mathematical model. Besides, only the elements with the column numbers equal to the numbers of the faulted node and IIDGs-interfaced nodes in the bus impedance matrices are needed for the fault-analysis of the power grid with IIDGs. The simulation results show that the calculation accuracy of the novel fault-analysis method well meet the requirements of fault-analysis and relay protection study of the power grid with IIDGs.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 51177058).

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