The Novel Fault Analysis Method of the Power Grid with Inverter Interfaced Distribution Generators

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ABSTRACT

The special fault current characteristics of inverter interfaced distribution generator (IIDG) make the conventional fault analysis method based on synchronous generator not applicable to a power grid with such IIDGs. In order to address this issue, according to the special fault current characteristics of IIDG, the problems of conventional fault analysis method when it is applied for the power grid with IIDGs are pointed out firstly. Based on it, a novel fault analysis method of the power grid with IIDGs is proposed. Lots of simulation cases show that the proposed fault analysis method has high calculation accuracy, which can meet the requirements of short-circuit calculation of the power grid and setting calculation of relay protection.

Keyword: inverter-interfaced distribution generator (IIDG), fault current characteristics, fault analysis method, relay protection calculation

INTRODUCTION

Nowadays, more and more distributed generators (DGs) have been integrated into the power grid, since DGs have the following three advantages. Firstly, DGs can provide effective technological means for the utilization of environmental friendly energy sources, which can address the concerns on environment protection. Secondly, DGs can be located dispersedly and flexibly to satisfy the increasing power demand, which can reduce the investment caused by the expansion of transmission and distribution system. Thirdly, DGs can be reserve of the main power supply and improve the power supply reliability.

It is known that most types of DG (like photovoltaic generation system, fuel cell, full-converter wind turbine and so on) should interface to the power grid with inverters, which can be defined as inverter-interfaced distributed generators (IIDGs) [1-3]. Due to the increasing integrated capacity of IIDGs, the fault characteristics of the power grid have been changed greatly, and the performance of conventional relaying protection has faced severe challenges [4-6]. In order to ensure the safety of the power grid and IIDGs, the study and improvement of the relaying protection are of great significance. As we all know, the relaying protection identifies the fault element according to the change characteristics of electrical quantities (or nonelectrical quantities) when the grid fault occurs. Hence, the fault analysis method and subsequent fault characteristics study of the power grid is the basis of the study of the relaying protection.

For the conventional fault analysis method, the power supply is the conventional synchronous generator. However, the fault current characteristics (including the transient characteristics and steady-state characteristics) of IIDG are much different from those of conventional synchronous generator [7], which make the conventional fault analysis method no longer applicable for the power grid with IIDGs.

In order to address the issues of conventional relay protection brought by the penetration of IIDGs, it is necessary to propose a novel fault analysis method for the power grid with IIDGs, according to fault current characteristics of IIDG. Aimed at it, scholars have carried out many research works. By representing IIDG equivalently with its steady-state model applied 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 inverter during grid fault, the normal operating mode of IIDG cannot be reserved [10]. Hence, IIDG cannot be equivalently replaced by its steady-state model applied for load flow calculation. In [10], the fault characteristics of IIDG with P-Q control or V-f control are studied with simulation, and then the conventional fault analysis method is extended to take IIDG contribution into consideration. In [11], according to the dynamic characteristics of IIDG, the equivalent model of IIDG during 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 behavior of IIDG cannot meet the requirements of grid code. Hence, the short-circuit calculation results of the proposed fault analysis methods are not in accordance with realistic situation. In [13], the fault current characteristics of IIDG are studied theoretically according to the LVRT requirements, and then a fault analysis method for the distribution network with single IIDG is proposed. However, the proposed fault analysis method is not applicable for the power grid with multi IIDGs.

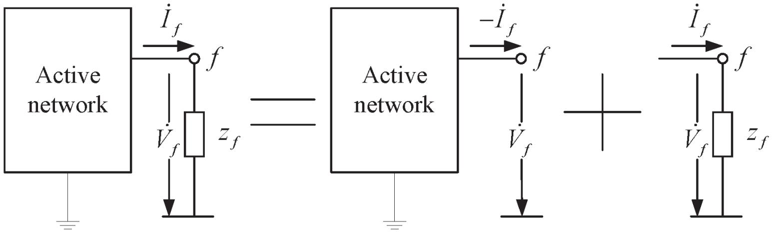
In order to fill this gap, the conventional fault analysis method is studied firstly. Then the issues of the conventional fault analysis method when it is applied for the power grid with IIDGs are pointed out. Based on it, a novel fault analysis method which can be applicable for the power grid with IIDGs is proposed. Finally, simulation cases are studied with PSCAD/EMTDC to validate the effectiveness of the novel fault analysis method.

CONVENTIONAL FAULT ANALYSIS METHOD

The conventional fault analysis method based on the node voltage equation is studied, which can provide guidance for proposing the fault analysis method which can be applicable for the power grid with IIDGs.

Symmetrical Fault Analysis

As shown in Figure 1(a), the node f of the active network is faulted through a 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.



(a) fault model of active network (b) the original network (c) fault branch

Figure 1. Symmetrical fault analysis

According to the superposition principle, the fault mode of active network shown in Figure 1(a) can be divided into two parts: the original network as shown in Figure 1(b) and the fault branch as shown in Figure 1(c). It can be found from Figure 1(b) that 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 voltage of node *i* 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 the set of active nodes in the network, Z_{ij} is the mutual impedance between node *i* and node *j*.

It can be found from (1) that the node voltage consists of two items. The first item $\sum_{j \in G} Z_{ij} \dot{I}_j$ represents the node voltage before the fault occurs which is caused by all the current sources in the network. The first item is so-called normal component of the node voltage, which can be denoted by $\dot{V}_i^{(0)}$. The second item $- Z_{if} \dot{I}_f$ is the fault component of the node voltage, which is caused by the short circuit current $\dot{I}_f$ when all the current sources in the network are disconnected. The superposition of the two voltage components is equal to the realistic node voltage after the fault occurs, i.e.

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

For the 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 occurs, Z_{ff} is the self-impedance of the faulted node *f*.

Meanwhile, according to the fault branch shown in Figure 1(c), the following equation can be obtained.

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

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

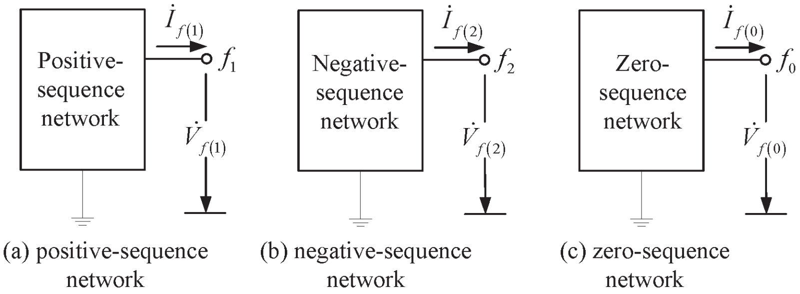
$$\dot{I}_f = \frac{\dot{V}_f^{(0)}}{Z_{ff} + z_f} \tag{5}$$

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

Unsymmetrical Fault Analysis

No matter what kind of unsymmetrical fault takes place, the sequence networks can be equivalently represented by two-port networks from the fault port, as shown in Figure 2.

For the conventional fault analysis method, the negative-sequence current is supposed to flow through the same elements with 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.



(a) positive-sequence network (b) negative-sequence network (c) zero-sequence network

Figure 2. Unsymmetrical fault analysis

Similar with the symmetrical fault analysis, the sequence voltages of node *i* when an unsymmetrical fault occurs 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.

THE ISSUES OF CONVENTIONAL FAULT ANALYSIS METHOD

According to the fault current characteristics study of IIDG [7], it can be found only the positive-sequence current is provided by IIDG, no matter under conditions of symmetrical voltage dips or asymmetrical voltage dips. Moreover, on condition that the generator voltage drops suddenly, the transient component in the fault current provided by IIDG is so small and damped so quickly that can be neglected. If a fault occurs in the realistic power grid, the generator voltage cannot drop suddenly, which will bring a relatively long transient period to the fault current of IIDG. However, it has no influence on the steady state component of the fault current which means that there is only positive-sequence component in the steady state fault current provided by IIDG under conditions of grid faults. Hence, IIDG can be replaced by a constant positive-sequence current source equivalently under grid fault conditions, as shown in Figure 3.

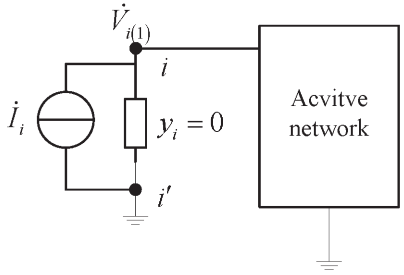


Figure 3. The equivalent positive-sequence current source model of IIDG

In Figure 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 terminal voltage. The equivalent mathematic model of IIDG 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 $2(1-\alpha_i) \le \sqrt{1.2^2 - \left(i^*_{d0i}\right)^2}$, then $I_i = \sqrt{\left(i^*_{d0i}\right)^2 + 4(1-\alpha_i)^2}$, and $\varphi_{cvi} = \arctan\left[2(1-\alpha_i)/i^*_{d0i}\right]$.

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 $\varphi_{cvi} = \arctan\left[2(1-\alpha_i) \Big/ \sqrt{1.2^2 - 4(1-\alpha_i)^2}\right]$.

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

It is noted that i^*_{d0i} is the active current reference value of IIDG before the fault occurs.

From the equivalent mathematic model of IIDG, it can be found that the conventional fault analysis method is no more applicable 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 with the positive-sequence network. However, it is untenable for IIDG. The branch of IIDG should only exist in the positive-sequence network, but not exist in the negative-sequence network, since there is only positive-sequence component in the fault current of IIDG.

2) As (2) shows, for the conventional fault analysis method, the fault component of the node voltage is $-Z_{if}\dot{I}_f$, which is caused by short circuit current $\dot{I}_f$ when all the current sources in the network are disconnected. The hypothesis that the above calculation method of the node voltage fault component can be effective is the subtransient reactance and subtransient potential of the synchronous generator keep constant before and after the fault occurrence. However, the hypothesis is not untenable for IIDG. According to the equivalent mathematic model of IIDG, it can be found that the magnitude of the equivalent positive-sequence current source of IIDG changes before and after the fault occurrence. Hence, in order to calculate the fault components of node voltages in the power grid with IIDGs, the current sources in the network cannot be disconnected. Likewise, the calculation method of branch current fault component in the conventional fault analysis method is either no more applicable for the power grid with IIDGs.

3) It can be found from (2), (5) and (6) that 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 whose column number is equal to the number of the faulted node are needed for short circuit calculation. The reason is that there is only the fault current $\dot{I}_f$ injecting into the superimposed network. However, as stated above, the magnitude of the equivalent positive-sequence current source of IIDG changes before and after the fault occurrence, hence, the current sources in the network cannot be disconnected in the superimposed network. It means that not only the elements whose column number is equal to the number of the faulted node, but only the elements whose column numbers are equal to the numbers of IIDGs interfaced nodes are needed for the short circuit calculation of the power grid with IIDGs. Besides, according to the equivalent mathematic model of IIDG, the magnitude of the equivalent positive-sequence current source of IIDG is related to the positive-sequence component of the generator terminal voltage. Hence, both the bus impedance matrices and equivalent mathematic model of IIDG are needed to implement the fault analysis, which makes the fault analysis much more complicated and the conventional fault analysis method no more applicable.

Generally speaking, the penetration of IIDGs impacts the conventional fault analysis method greatly. In order to satisfy the fault analysis requirements of the power grid with IIDGs and establish a solid basis for the study of relaying protection, it is necessary to propose a novel fault analysis method which can be applicable for the power grid with IIDGs.

THE NOVEL FAULT ANALYSIS METHOD

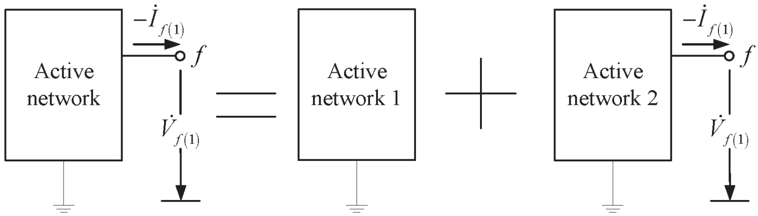
According to the above issues of the conventional fault analysis method, a novel fault analysis method which can be applicable for the power grid with IIDGs is proposed.

Firstly, according to the fault current characteristics of IIDG that only the positive-sequence current 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 with 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, decompose the original network shown in Figure 1(b) into two parts: the normal network before the fault occurrence and the superimposed network, as shown in Figure 4.



(a) original network (b) normal network (c) superimposed network

Figure 4. Decomposition of positive-sequence network

For the normal network shown in Figure 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 the set of active nodes (including all the conventional synchronous generators and IIDGs interfaced nodes) in the network,

For the superimposed network shown in Figure 4(c), all the current sources representing conventional synchronous generators should be disconnected, but the controlled positive-sequence current sources representing IIDGs cannot be disconnected. Denote the controlled positive-sequence current sources representing IIDGs in the superimposed network by $\Delta\dot{I}_{DG,k}$. $\Delta\dot{I}_{DG,k}$ is the fault components 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, $\dot{I}_{DG0,k}$ is the output current of IIDG interfaced with node *k* before the fault occurrence.

Hence, the fault component of 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 the set of IIDGs interfaced nodes in the network.

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

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

With combination of (7) and (11), the sequence voltages of node *i* are

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

The fault components of the output currents of IIDGs $\Delta\dot{I}_{DG,k}$ is unknown and related to the positive-sequence voltages of generator terminals. Hence, (12) cannot be solved only with fault boundary conditions. In order to implement 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 faulted node can be expressed in (13) and (14) respectively.

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

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

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

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

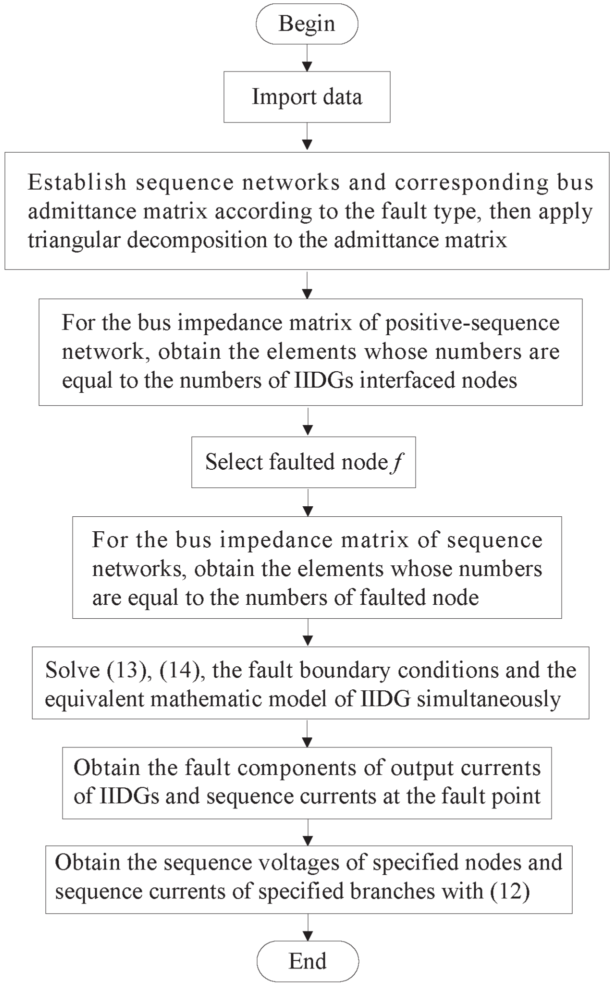
It can be found from (12), only the elements whose column numbers are equal to the numbers of faulted node and IIDGs interfaced nodes are needed for the fault analysis of the power grid with IIDGs.

Figure 5 depicts the schematic diagram of the novel fault analysis method.

CASE STUDY

To validate the novel fault analysis method, simulation model of the power grid with IIDGs is built with PSCAD/EMTDC, as shown in Figure 6.

In Figure 6, the types of all transmission lines are the same, and the line parameters are: $r_{(1)}=r_{(2)}=0.17\Omega/\text{km}$, $x_{(1)}=x_{2)}=0.394\Omega/\text{km}$. The whole lengths of L1, L2, L3, L4, L5 and L6 are respectively 5 km, 6 km, 10 km, 2 km, 0.5 km and 0.5 km. The capacities of the two grid-connected IIDGs are both 1 MW. 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, the leakage reactance is 0.065 pu. The equivalent impedances of LD1 and LD2 are both 120+*j*39.11 Ω, and the equivalent impedance of LD3 is 80+*j*26.08 Ω.



Begin

Import data

Establish sequence networks and corresponding bus admittance matrix according to the fault type, then apply triangular decomposition to the admittance matrix

For the bus impedance matrix of positive-sequence network, obtain the elements whose numbers are equal to the numbers of IIDGs interfaced nodes

Select faulted node *f*

For the bus impedance matrix of sequence networks, obtain the elements whose numbers are equal to the numbers of faulted node

Solve (13), (14), the fault boundary conditions and the equivalent mathematic model of IIDG simultaneously

Obtain the fault components of output currents of IIDGs and sequence currents at the fault point

Obtain the sequence voltages of specified nodes and sequence currents of specified branches with (12)

End

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

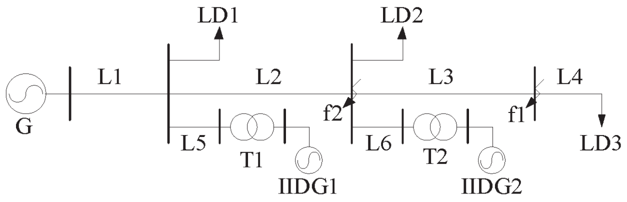


Figure 6. Diagram of simplified power grid with IIDGs

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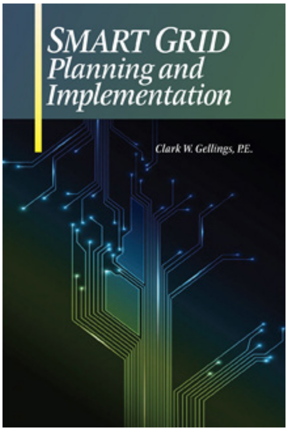

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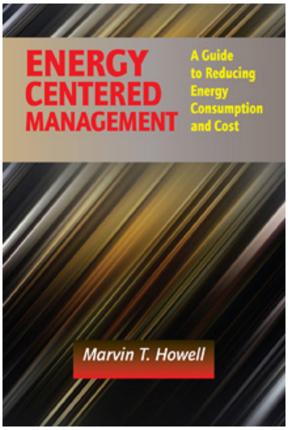

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Table 1 and Table 2 respectively give the comparisons of theoretical values and measured values of fault currents when three-phase fault occurs at f1 and f2. Table 3 and Table 4 respectively give the comparisons of theoretical values and measured values of fault currents when Phase-B-to-Phase-C fault occurs at f1 and f2. It is noted that the unit of magnitude is ampere (A), and the unit of angel is degree (°).

From Tables 1, 2, 3 and 4, it can be concluded 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 relaying protection study of the power grid with IIDGs.

SIMULATION MODEL VERIFICATION AND VALIDATION

The simulation model is built according to Figure 6, and the IIDG model is built according to Ref. [7] which has been verified and validated. In this context, the mathematic equations and logic of the simulation model are verified. Moreover, in the simulation model, the grid is represented by an ideal voltage source, and the load LD1, LD2 and LD3 are respectively represented by a branch which consists of a resistor and an inductor. Generally speaking, the simulation model consists of basic modules (such as transmission line, transformer and so on) which are provided by PSCAD/EMTDC and have been validated by lots of users all over the world for many years. It means that the simulation model is technically correct.

Furthermore, according to Tables 1 through 4, the simulation results agree with the theoretical analysis results quite well, since the largest absolute error of magnitude between the simulation results and the theoretical analysis results is only 0.63% and the largest absolute error of 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.

CONCLUSION

The fault current characteristics of IIDG are much different from those of conventional synchronous generator, which make the conventional fault analysis method no more applicable for the power grid with

Table 1. Branch currents on condition that three-phase fault occurs at f1

	Output current of IIDG1		Output current of IIDG2		Current at the fault point	
	Mag.	**Ang.**	**Mag.**	**Ang.**	**Mag.**	**Ang.**
theoretical 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 occurs at f2

	Output current of IIDG1		Output current of IIDG2		Current at the fault point	
	Mag.	**Ang.**	**Mag.**	**Ang.**	**Mag.**	**Ang.**
theoretical 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 on condition that Phase-B-to-Phase-C fault occurs at f1

	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.
theoretical 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 on condition that Phase-B-to-Phase-C fault occurs at f2

	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.
theoretical 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

IIDGs. According to the fault current characteristics of IIDG, a novel fault analysis method is proposed in this article.

For the novel fault analysis method, IIDG is equivalently represented by a positive-sequence current source whose magnitude is related to the positive-sequence component of generator terminal voltage. Then the fault analysis is implemented by solving the node voltage equations of sequence networks, fault boundary conditions and the equivalent mathematic model of IIDG simultaneously. Besides, only the elements whose column numbers are equal to the numbers of 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 novel fault analysis method has high calculation accuracy, which can well satisfy the requirements of fault analysis and relaying protection study of the power grid with IIDGs.

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