Study on Current Protection in Distribution Network with Distributed Generation

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ABSTRACT: *Running with distributed generation, configuration of distribution network will be changed, that influences strength, flowing direction and duration of fault current. It analysed influence on current protection in main feeder, recloser and conventional branch line protection through the calculation formula of fault current before and after distributed generation synchronization development. In Matlab/Simulink, it constructed distribution network model with distributed generation, used simulation examples to prove influence on current protection and put forward improvement measures which can meet requirements of relay protection in distribution network.*

Categories and Subject Descriptors: J.2 [Physical Sciences and Engineering]; Electronics : **C.2.2 [Network Protocols]**

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1. Introduction

With the high quality requirements of power consumers, especially after several power outages around the world in recent years, centralized power grid presents its shortcomings in the guarantee of reliability and power quality. What's more, energy resources and environmental protection are the prerequisites of sustainable development, with the circumstance of energy shortage nowadays, distributed generation has been well developed because of its apparent advantages, for example, cleanliness, low cost on resources of power transmission and distribution as well as the operation expense, high power reliability [1]. However, running with distributed generation, the configuration of distribution network will be changed and then influences the allocation of relay protection and the settings of operation value [2-5]. The main cause is the severely changed fault current.

2. Distributed Generation

Distributed generation (DG) is a kind of micro type generation system whose capacity range from several kilowatts to 50 megawatts, it is built for customers' special requirements, it can sustain the current distribution network, it is always installed just around the users and compatible with surroundings. DG contains photovoltaic power generation, wind power generation, fuel cell power generation, micro turbine power generation, biomass energy power generation and so on [6].

2.1 Photovoltaic power generation [7-10]

The energy conversion device of photovoltaic power generation is solar cell, it is also known as photovoltaic cell. The principle of solar cell power generation is the photovoltaic effect. When sunlight shines on the solar cell, battery absorbs the light to produce photoelectron-hole pairs. In the cell under the action of electric field, electrons and holes are separated, opposite charges accumulate at both ends of the battery, which produce the photovoltage. Extract electrodes on both sides of the built-in electric field and connect to the load, the optical current is generated, and thus the power can be outputted. In this way, the light energy becomes electricity which is put into practice directly.

2.2 Wind power generation [11-13]

As viewed from energy transformation, the wind generating set is divided into two parts: the wind turbine and generator. Wind speed acts on wind turbine blades to produce torque, the torque drives hub to rotate, it is connected to the asynchronous generator rotor by high speed shaft of the gearbox, brake and coupling, which generate electricity to run. The most promising application prospect of wind power generation is to be used in off-grid areas. It provides electricity to the remote rural and pastoral areas and island residents.

2.3 Fuel cell power generation [14]
The working principle of fuel cell is that: when hydrogen combines with oxygen to produce water, hydrogen emits a electron and becomes the positive charge at first; at the same time, oxygen gets the electron from hydrogen and becomes the negative charge, combined with the opposite charges, then the neutral water is produced. In the chemical reaction between hydrogen and oxygen, electron transfer occurs, take out the electrons and add them to the load connected externally, the load power supply realizes. Typically, the fuel cell power plant is mainly consist of three parts: fuel processing part, battery reactor part, power electronics converter controlling part.

2.4 Micro turbine power generation [15]
Micro turbine is a mini steam turbine based on natural gas, methane, gasoline and diesel oil. Its power efficiency may reach 30%, when realizing the combination of heat and power, the efficiency can be increased to 75%. The characteristics of micro turbine are small volume, light weight, high efficiency and easy operation and maintenance. It is the most mature distributed power with the strongest commercial competitiveness.

Different type, capacity and synchronization place lead to different fault current. Table 1 provides the fault current injectability of various types of DG. It can be found from Table 1 that the injectability of fault current of DG like converter, synchronous machine and induction machine range form 100% to 1000% and the maximum injectability of fault current can reach 1000%. This value can be used for short-circuit calculation to analyse the most severe fault condition [16].

DG type	Injectability of fault current
Converter	100% ~ 400%
Synchronous machine	500% ~ 1000%
Induction machine	500% ~ 1000%

Table 1. Fault Current Injectability of Various Types of DG

3. Distribution network and configuration of relay protection

Compared with the relay protection of high voltage power grid, the configuration of relay protection in distribution network is easier. It contains over current protection, over voltage protection, distance protection and so on. For the traditional low voltage distribution network and medium voltage distribution network are always single power radial network, main feeder usually uses three section current protection that is current instantaneous trip protection (protection section I), time delay current instantaneous trip protection(protection section II) and definite time over current protection(protection section III). Current instantaneous trip protection sets action value in accordance with the method of escaping the maximum three-phase short-circuit current when the end of line faults, it can not protect the whole line. Time delay current instantaneous trip protection sets action value according to having sensitivity when the end of line faults and coordinates with the current instantaneous trip protection of adjacent line, it can protect the whole line. Definite time over current protection sets action value in the light of the method to hide from the maximum load current and coordinates with the definite time over current protection of adjacent line, it can protect the full-length of adjacent line. The settings of action time of these current protections are different but compatible [17]. In addition, for these not all cable line, the use of three phase one shot reclosure can guarantee faster power restoration after transient faults [18]. At the same time, the reclosureÿsectionalizer and fuse on the branch line coordinate, this kind of protection has no directivity [19, 20].

4. The influence of DG on relay protection in distribution network

Running with DG, the configuration of distribution network changes from a single power radial network to a more complicated one which has two or more power supply. In the distribution network, the power flow, direction, duration and strength of fault current all will change [21, 22].

4.1 The influence of DG on current protection in main feeder
Figure 1 is the structure chart of distribution network with DG. Microgrid is consist of DG, energy storage units and loads [23, 24]. The voltage class inserted in distribution network is usually $10kV$. Figure 2 is the equivalent circuit diagram when K_1 is short dot. Figure 3 is the equivalent circuit diagram when K_2 is short dot.

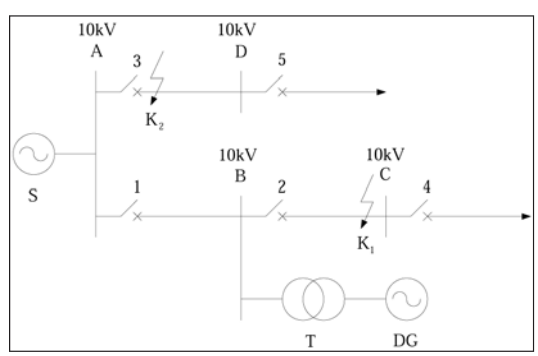

Figure 1. Structure chart of distribution network with DG

In Figure 2 and Figure 3, E_s is the electric potential of system power, X_s is the reactance of system power. E_{DG}

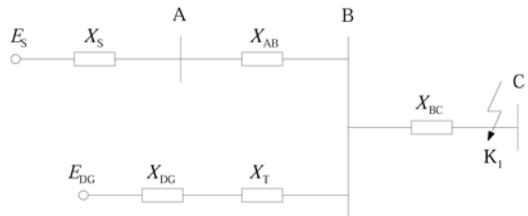

Figure 2. Equivalent circuit diagram when K_1 is short dot

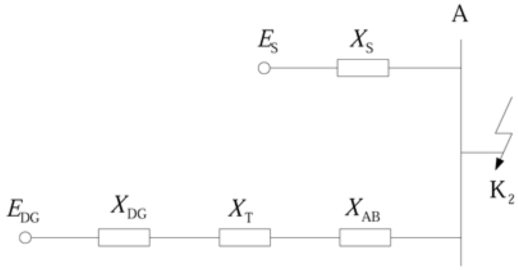

Figure 3. Equivalent circuit diagram when K_2 is short dot

is the electric potential of DG, X_{DG} is the reactance of DG, X_T is the reactance of transformer, X_{AB} is the reactance of line AB, X_{BC} is the reactance of line BC. Parameters above are all per-unit values.

4.1.1 Enlargement of protective range of line

In Figure 1, K_1 is short dot, I_{K2} is the fault current flowing through protection 2 before DG synchronization.

$$E_{eq} = E_S \tag{1}$$

$$X_{eq} = X_S + X_{AB} + X_{BC} \tag{2}$$

$$I_{K2} = \frac{E_{eq}}{X_{eq}} = \frac{E_S}{X_S + X_{AB} + X_{BC}} \tag{3}$$

E_{eq} is the equivalent electric potential of system power, X_{eq} is the equivalent reactance of line.

I'_{K2} is the fault current flowing through protection 2 after DG synchronization.

$$E'_{eq} = \frac{E_S(X_{DG}+X_T)+E_{DG}(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} \tag{4}$$

$$X'_{eq} = \frac{(X_{DG}+X_T)(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} + X_{BC} \tag{5}$$

$$I'_{K2} = \frac{E'_{eq}}{X'_{eq}} \frac{\dfrac{E_S(X_{DG}+X_T)+E_{DG}(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}}}{\dfrac{(X_{DG}+X_T)(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} + X_{BC}} \tag{6}$$

$$I'_{K2} - I_{K2} > 0 \tag{7}$$

$$I'_{K2} > I_{K2} \tag{8}$$

E'_{eq} is the equivalent electric potential of system power and DG, X'_{eq} is the equivalent reactance of line.

It follows that the fault current flowing through protection 2 is only provided by system before DG synchronization, but it is provided by system and DG after synchronization. Thus the fault current flowing through protection 2 is enhanced by DG, that is DG enhances the protective range of protection 2, it can make protection section I extend to next section.

4.1.2 Decrease of protective range of line

In Figure 1, K_1 is short dot, I_{K1} is the fault current flowing through protection 1 before DG synchronization.

$$E_{eq} = E_S \tag{9}$$

$$X_{eq} = X_S + X_{AB} + X_{BC} \tag{10}$$

$$I_{K1} = \frac{E_{eq}}{X_{eq}} = \frac{E_S}{X_S + X_{AB} + X_{BC}} \tag{11}$$

I'_{K1} is the fault current flowing through protection 1 after DG synchronization.

$$E'_{eq} = \frac{E_S(X_{DG}+X_T)+E_{DG}(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} \tag{12}$$

$$X'_{eq} = \frac{(X_{DG}+X_T)(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} + X_{BC} \tag{13}$$

$$U'_{BC} = \frac{E'_{eq}}{X'_{eq}} X_{BC} = \frac{\dfrac{E_S(X_{DG}+X_T)+E_{DG}(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}}}{\dfrac{(X_{DG}+X_T)(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} + X_{BC}} X_{BC} \tag{14}$$

$$I'_{K1} = \frac{E_S - U'_{BC}}{X_S + X_{AB}} = \frac{E_S - \dfrac{\dfrac{E_S(X_{DG}+X_T)+E_{DG}(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}}}{\dfrac{(X_{DG}+X_T)(X_S+X_{AB})}{X_{DG}+X_T+X_S+X_{AB}} + X_{BC}} X_{BC}}{X_S + X_{AB}} \tag{15}$$

$$I'_{K1} - I_{K1} < 0 \tag{16}$$

$$I'_{K1} < I_{K1} \tag{17}$$

U'_{BC} is the voltage of line BC.

It follows that the fault current flowing through protection 1 is provided by system before DG synchronization, but it is decreased because of the shunting action of DG after synchronization, that is DG decreases the protective range of protection 1 [25-29].

4.1.3 Malfunction of line protection

In Figure 1, K_2 is short dot, there is no fault current flowing through protection 1 before DG synchronization, however, DG provides reversed fault current after synchronization which is called I''_{K1}.

$$E''_{eq} = E_S \tag{18}$$

$$X''_{eq} = X_{DG} + X_T + X_{AB} \tag{19}$$

$$I''_{K1} = \frac{E''_{eq}}{X''_{eq}} = \frac{E_{DG}}{X_{DG} + X_T + X_{AB}} \tag{20}$$

E''_{eq} is the equivalent electric potential of DG, X''_{eq} is the equivalent reactance of line.

If the capacity of DG is large enough, I''_{K1} may lead to the malfunction of protection 1.

4.2 Influence of DG on recloser

For radial distribution network, the power restoration of recloser after transient fault won't bring about severe impact and damage to distribution network and then guarantee the reliability. However, after DG synchronization, once fault happens, protection action can only break down the electric contact between system power and fault point, DG seems likely not to be disconnected from circuit and keeps working, and then a "*electric island*" is generated in which DG is the only power supply. The power and voltage of these "*electric islands*" are close to the rated ones which lead to two disadvantages for recloser [30].

4.2.1 Random paralleling

After disconnection from system power, DG may operate faster or slower. It will bring about a angle difference which result in out-of-step between grid and "*electric island*". The impulse current caused by non-synchronization paralleling is very large, line protection probably takes action again, and then the input of system power fails.

4.2.2 Persistence of electric arc in fault point

For the protection action only disconnects system power, DG probably keeps on generating short-circuit current to the fault point which will lead to the persistence of electric arc. In this way, transient fault grows to permanent fault, recloser fails.

4.3 Influence of DG on reclosure, sectionaliszer and fuse on branch line

Recloser automatically acts according to the inverse-time protection and recloses many times in accordance with a predetermined delay and order; sectionalizer can remember the action times of recloser, and automatically analyses when there is no voltage or no current; fuse acts when there is a high-current on branch line which is not allowed, thus the fault line can be removed. Based on the fact that, once current protection of breaker acts, the whole line will be power outage, we usually use a kind of protection containing reclosure, sectionalizer and fuse. It can separate the fault area after fault happens, and then decrease the areas of power outage [31]. It will damage the compatibility between each component after DG synchronization, which is mainly embodied in three aspects as below:

4.3.1 Lead to malfunction of reclosure

Figure 4 is the structure chart of protection of reclosure and sectionalizer on branch line. In Figure 4, K_1 is short dot, DG can provide fault current to short dot through this circuit. If this current is high enough it will lead to the malfunction of reclosure R_2.

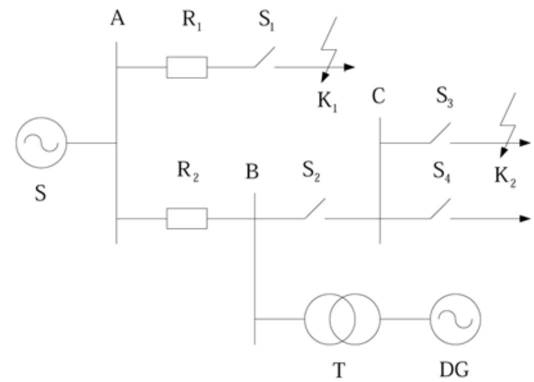

Figure 4. Structure chart of protection of reclosure and sectionalizer on branch line

4.3.2 Lead to abnormal analysis of sectionalizer

In Figure 4, K_2 is short dot, reclosure R_2 disconnects system power, however, DG can still supply power for its downstream lines. In this way, there is still current flowing through sectionalizers S_2 and S_3, and then they can not analyse properly.

4.3.3 Damage on the coordination of each fuse protection

Figure 5 is the structure chart of fuse protection on branch line. In Figure 5, K_1 is short dot, before DG synchronization, the currents flowing through fuses FU_1 and FU_2 are the same, fusing time ofis longer than that of, sofuses beforedoes, in this way fault parts has been separated and fault areas has been minimized; After DG synchronization,is short dot, the currents flowing through fusesandare still the same, however, in this wayis needed to fuse before, that is to say, the fusing time ofshould be shorter than that of, this breaks the coordinating of each fuse protection.

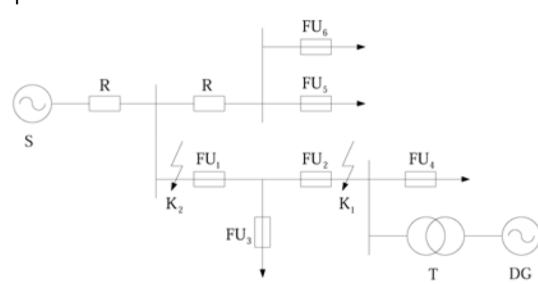

Figure 5. Structure chart of fuse protection on branch line

5. Simulation Examples

It analysed influence of DG on current protection of main feeder through different simulation examples. In Matlab/

Simulink, it constructed a $10kv$ distribution network model with DG as Figure 6.

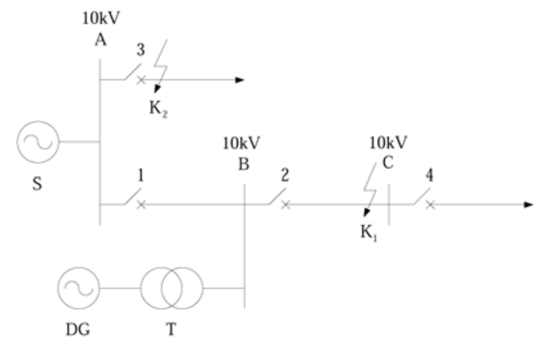

Figure 6. 10kv distribution network model with DG

Reference capacity $S_B = 100MVA$, reference voltage $U_B = 10.5kV$, system short-circuit capacity $S_K = 280MVA$, line reactance $x = 0.4\Omega/km$, the line length of AB segment and BC segment are 7 km and 6 km, DG and transformer T have the same capacity, whose series reactance is $X_* = 100$. Setting coefficients $K_{rel}^{I} = 1.3$, $K_{rel}^{II} = 1.1$, $K_{rel}^{III} = 1.2$, $K_{ss} = 1.5$, $K_{re} = 0.85$, maximum load current $I_{L-max} = 250A$, settings of protection section I and protection section III are I_{set}^{I} and I_{set}^{III}.

$$I_{set-2}^{I} = K_{rel}^{I} \frac{E_S}{X_S + X_{AB} + X_{BC}} \tag{21}$$

$$I_{set-1}^{III} = \frac{K_{rel}^{III} K_{ss}}{K_{re}} I_{L-max} \tag{22}$$

$$I_{set-1}^{I} = K_{rel} \frac{E_S}{X_S + X_{AB}} \tag{23}$$

Table 2 provides the settings of protection 1 and protection 2. The followings analysed influence of DG capacity and synchronization position on current protection.

Protection segment	I_{set}^{I} / A	I_{set}^{III} / A
Protection 1	2467	529
Protection 2	1409	

Table 1. Settings of Protection 1 and Protection 2

5.1 Influence of DG capacity on current protection

Figure 7 shows the variation curve of fault current flowing through protection 2 when K_1 is short dot. Figure 8 shows the variation curve of fault current flowing through protection 1 whenis short dot.

Figure 7 and Figure 8 show that along with the increase of DG capacity, it influences current protection of main feeder as follows:

(1) Fault current flowing through the lower lines of DG increases gradually. DG enhances protective range of protection 2. When $S_{DG} > 3.63MVA$, it can make protection section I of protection 2 extend to next section, the selectivity is lost.

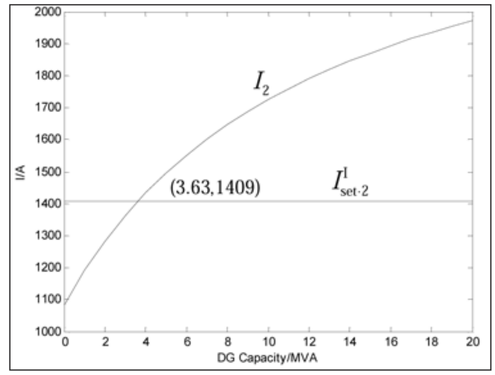

Figure 7. Variation curve of fault current flowing through protection 2 when K_1 is short dot

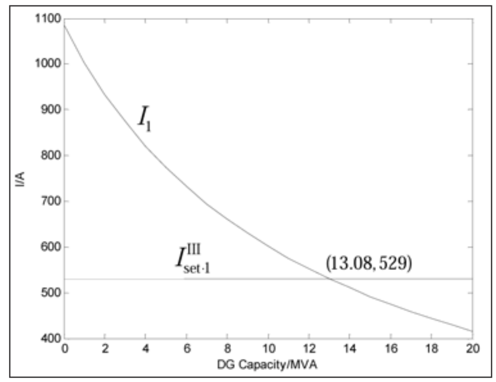

Figure 8. Variation curve of fault current flowing through protection 1 when K_1 is short dot

(2) Fault current flowing through the upper lines of DG decreases gradually. DG narrows down protective range of protection 1. When $S_{DG} > 13.08MVA$, protection section

5.2 Influence of DG synchronization position on current protection

Figure 9 shows the variation curve of fault current flowing through protection 1 when K_2 is short dot. It can be seen that when $S_{DG} = 16MVA$, that is DG synchronization capacity holds constant, and K_2 is short dot, the shorter the distance between DG and system, the higher the reversed fault current flowing through protection 1. When the distance between DG and system is shorter than 49.6% AB, it may lead to the malfunction of protection section I of protection 1.

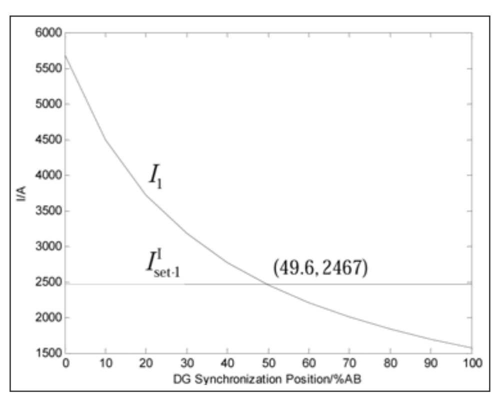

Figure 9. Variation curve of fault current flowing through relay protection 1 when K_2 is short dot

6. Improvement measures

The malfunction and failure to trip caused power supply interruption in normal area when distribution network goes wrong, and fault area can not be isolated. According to the distribution network with DG, it can meet the requirements of relay protection such as selectivity, sensitivity, speed and reliability through the improvement measures.

(1) Set the starting current of every protection device after considering DG, at the same time install the power directional component on the protection 1, this component ought to act when the direction of short-circuit power flows from bus A to bus B, and it does not act when the direction of short-circuit power flows from bus B to bus A, therefore malfunction and failure to trip can be avoided. But this measure only applies to the parallel operation state of microgrid with DG, because when DG supplies the power alone, it need to set the starting current of the protection device again.

(2) In order to eliminate the influence of DG on recloser, it need to install low-voltage and low-frequency separation device on the side of DG, disconnect DG from short dot before switching on through extending the action time of recloser appropriately, and check no voltage on the side of system, check the corresponding period on the side of *DG*.

(3) Retrofit Fault Current Limiter (*FCL*) on DG, *FCL* is evolved on the basis of the limiting series resistance, it is the same with the other controllers of Flexible *AC* Transmission Systems (*FACTS*), and improves its traditional technology relying on the power electronics technology. *FCL* principle diagram is shown in Figure 10.

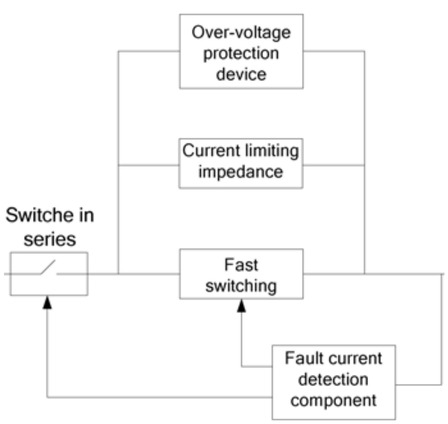

Figure 10. FCL principle diagram

FCL shows the high impedance when line short-circuit is inspected, which restricts the fault current at a low level through rapidly changing impedance parameters of the fault circuit. Conversely, its impedance is zero in normal load condition. Table 3provides the protection parameters of a system before DG synchronization, Table 4 provides the protection parameters of a system after DG synchronization and Table 5 provides the protection parameters of a system after DG synchronization with *FCL*, which can be seen that the installation of *FCL* after DG synchronization can make the system parameters remain unchanged basically.

Line name	I_{set}^{I} / A	I_{set}^{II} / A	Sensitivity of protection section II
Line 1	5122	2377	1.45
Line 2	5232	2540	1.39
Line 3	2139	1142	1.31
Line 4	4850	2461	1.33

Table 3. Protection Parameters before DG Synchronization

Line name	I_{set}^{I} / A	I_{set}^{II} / A	Sensitivity of protection section II
Line 1	6249	2900	1.30
Line 2	5232	2540	1.39
Line 3	3594	1920	0.97
Line 4	5820	2593	1.21

Table 4. Protection Parameters after DG Synchronization

Line name	I_{set}^{I} / A	I_{set}^{II} / A	Sensitivity of protection section II
Line 1	5260	2441	1.44
Line 2	5232	2540	1.39
Line 3	2267	1210	1.30
Line 4	4976	2524	1.32

Table 5. Protection Parameters after DG Synchronization with FCL

Thus the problem that the infeed current from DG influence the current protection in distribution network is solved [32,33] , at the same time as the low fault current, branch line protection based on reclosure, sectionaliszer and fuse can work normally.

7. Conclusion

The parallel operation of DG influences the fault current of distribution network, makes the original protection settings no longer applicable, leads to disadvantages for recloser, and disrupts the branch line protection based on automatic electric components such as reclosure, sectionaliszer and fuse. It theoretically analysed the influence of DG when it is operating parallelly on current protection in distribution network, used Matlab/Simulink to build distribution network model with DG, proved the correctness of theoretical analysis and put forward improvement measures according to the above problems.

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