Mechanism Analysis of Impacts of Distributed Generation Connection on Zero Sequence Current Protection in Small Resistance Grounding System

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Abstract — **Aimed at the impacts of distributed generation (DG) access on zero sequence current protection in small resistance grounding system, the influence mechanism was studied and which was verified combined with the numerical simulation. Moreover, under the precondition of meeting reliable action of relay protection, the relationship between the maximum short capacity accesses to the DG side, allowed by distribution network, and the grid-connected position and the grid-connected transformer neutral point impedance was analyzed. The results show that it may cause protective action lose selectivity, and maloperation, or anti-operation due to the connection of DG; in different grid-connected positions, set the grid-connected transformer neutral point grounding impedance rationally, which could reduce the influence, caused by the connection of DG, on distribution protection, and thus the maximum short capacity accesses to DG side could be allowed to increase.**

Keywords - DG; small resistance grounding; zero sequence current protection; connection short circuit capacity

I. INTRODUCTION

More and more DG has been connected to the distribution network [1], which caused larger impact on relay protection [2-11], power quality [12, 13], and reliability [14] in distribution network. Among them, the home and domestic researchers had made large amounts of valuable studies about the influences of DG on distribution network relay protection, and made deep discussions on problems of power voltage reduction due to connection of DG, such as the photovoltaic energy [15]. The literatures [3-5] analyzed the impacts of distribution network short current distribution and relay protection due to DG connection, and the analysis results shown that the DG connection may lead to distribution network lose selectivity, and misoperation or anti-operation. Moreover, the literatures [6-7] mainly analyzed the impacts on distribution network current protection in aspect of DG connection capacity. Under meeting condition of reliable action of relay protection, the literatures [10, 11] also proposed the new distribution network, which contained DG, protection method. However, these studies only made discussions when the inter-phase short circuit happened, and didn't make relative analysis when the single phase short circuit occurred in small resistance grounding system.

The grounding capacitor current increases due to growth of cable lines in distribution network, and many distribution networks adopt neutral point grounding type via small resistance [16, 17]. Meanwhile, in all types of short circuit, the single phase short circuit accounts the most [18], and which is different with three-phase short circuit and is taken the negative sequence and zero sequence network into consideration, thus it is unable to make analysis simply. Therefore, it is essential to analyze the influence mechanism of DG connection on zero sequence current protection of small resistance grounding system.

The research on influence of DG connection on zero sequence current protection of small resistance grounding system is still primary, and which lacks complete theoretical derivation and mechanism analysis. In the thesis, the rigorous mathematical derivation and simulative analysis of the action mechanisms of DG connection on zero sequence current protection are given, thus analyzes its influences on three sect protection of distribution network zero sequence [19]. Moreover, compared with the connection capacity, the connection short circuit capacity is better to weigh the influences of DG connection on relay protection directly. Therefore, the relationship between the maximum connection short circuit capacity of DG with the grid-connected position and the neutral position grounding impedance of grid-connected transformer is also analyzed.

II. THE EQUIVALENT MODEL OF ACCESSING OF DISTRIBUTED GENERATION TO DISTRIBUTION NETWORK

A. Model of DG Side

The DG model can be equivalent to an ideal voltage source in series with impedance through the Thevenin's equivalent circuit [3]. Among the model, the size of DG short circuit capacity is directly determined by its impedance, and which also represents its injection ability of fault current.

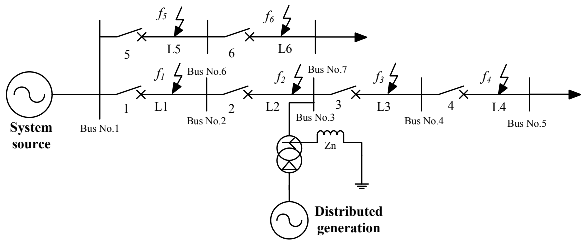
The DG is generally connected to the grid through the grid-connected transformer, and whose main function is not in order to realize voltage conversion, but for needs [20] to avoid the DC current injecting into the grid and prevent 3k (k=1,2,…) times of harmonic from injecting into grid and ensure that the DG observe system fault, and limit system fault current, and avoid resonant overvoltage and frequency overvoltage, etc. For the small resistance grounding system, the grid-connected transformer should adopt "Yg /Δ" connection mode [20,21]. The system side is "Yg" connection, and among it, it's suitable to set the size of neural point grounding impedance of transformer to control the size of zero sequence fault current.

In this paper, the DG connection short circuit capacity is defined the product of short circuit current, supplied by the DG side, and the average rated voltage at grid-connected points, when the grid-connected points (high voltage side of grid-connected transformer) occurs three-phase short circuit.

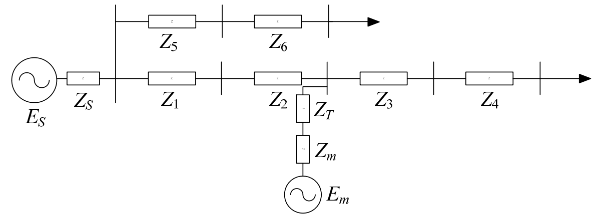
B. Model of System Side

Due to several kinds of connection models in distribution network, then it's necessary to make classification and summary of the influence that the access of DG to distribution network protection. In this paper, the influence is classified into three types [9], that is, influence on adjacent feeder protection; influence on upstream lines protection; and the downstream lines protection. The distribution network model is shown as an example in Fig. 1, in which, the size of system power equivalent impedance Z_S is determined by the size of low voltage bus short circuit capacity of upper level transformer.

In Fig. 1, No. 1~6 respectively shows the protection of line L1~L6, and both of them have zero sequence current three sections protection. The E_S is equivalent power phase electromotive force of system, and E_m is equivalent phase electromotive force of DG, in this paper, select E_S=E_m, and in Fig. 1, Z_1~Z_6 are impedances of each line, Z_T is short circuit impedance of grid-connected transformer, and Z_n is neural point grounding impedance of grid-connected transformer, Z_m is equivalent impedance of DG, and neural point impedance in system side is supposed 0; α_1~α_6 the distance proportion that the distance between each line short circuit point and its bus accounts for the total line distance, the above parameters are both selected per-unit values. In addition, in this paper, the positive and negative and the lines zero sequence impedance and electrical sources are respectively expressed by subscript I, II and 0.



(a) Typical distribution network model



(b) Positive sequence equivalent circuit diagram

Fig.1 Typical Distribution Network Model and the Positive Sequence Equivalent Circuit Diagram

III. IMPACTS ON ZERO SEQUENCE CURRENT THREE-SECTION PROTECTION

During calculation of fault current, aimed at single phase fault, it's different from three-phase short fault, which could implement independent calculation or direct superposition on system or power source side, the single phase fault should also consider the negative and zero sequence equivalent impedance, and which couldn't be calculated simply and independently. The faults discussed below are both supposed as the single phase short circuit faults.

A Faults Happen in Adjacent Feeder Lines

1) Impacts on the protections of adjacent feeder lines

The connection of DG plays an improvement role in the fault zero sequence that flows through the protective devices of adjacent feeder lines, which can improve the sensitivity of its protective actions, and expansion of its protective range as well, and may cause the protective actions of each zero sequence current in the adjacent feeder lines lose selectivity.

2) Impacts on upstream lines protection

When the opposite fault direction fault zero sequence current flows the protective devices in upstream lines, which may cause protective misoperation of upstream lines, then leads to the DG in unscheduled islanded operation state, resulting in expansion of power failure.

3) Impacts on downstream lines protection

No fault zero sequence current flows the downstream lines, so the protection of downstream lines aren't be influenced.

4) Example explanation

It's shown in Fig. 1, when the line L5 occurs fault (f5), the zero sequence current flows the No. 5, No. 1 and No. 2 relay is

$$I_{k5.0} = \left| \frac{3E_S}{Z_{f5(I)} + Z_{f5(II)} + Z_{f5(0)}} \right| \tag{1}$$

$$I_{k1.0} = I_{k2.0} = I_{k5.0} \left| \frac{Z_{S0}}{Z_{S0} + Z_{10} + Z_{20} + Z_T + 3Z_n} \right| \tag{2}$$

Where the positive sequence and negative sequence and zero sequence equivalent impedance are respectively

$Z_{f5(I)} = Z_{SI} // (Z_{1I} + Z_{2I} + Z_T + Z_{mI}) + \alpha_5 Z_{5I}$,
$Z_{f5(II)} = Z_{SII} // (Z_{1II} + Z_{2II} + Z_T + Z_{mII}) + \alpha_5 Z_{5II}$,
$Z_{f5(0)} = Z_{S0} // (Z_{10} + Z_{20} + Z_T + 3Z_n) + \alpha_5 Z_{50}$.

However, before connection of the DG and when the fault f_5 happens in line L5,

$$I^f_{k5.0} = \left| \frac{3E_S}{Z^f_{f5(I)} + Z^f_{f5(II)} + Z^f_{f5(0)}} \right| \quad (3)$$

$$I_{k1.0} = I_{k2.0} = 0 \quad (4)$$

Where the positive sequence and negative sequence and zero sequence impedance are respectively
$Z^f_{f5(I)} = Z_{SI} + \alpha_5 Z_{5I}$, $Z^f_{f5(II)} = Z_{SII} + \alpha_5 Z_{5II}$, $Z^f_{f5(0)} = Z_{S0} + \alpha_5 Z_{50}$.

Compared the formula (1)~(4), it's concluded that $I_{k5.0} >$ $I^f_{k5.0}$, $I_{k1.0} = I_{k2.0} > I^f_{k1.0} = I^f_{k2.0}$, and at the time that, 1) the sensitivity of the No. 5 relay will increase, and can cut off the faults correctly; 2) if the current flow the No. 1 and No. 2 relays are both smaller than its zero sequence III section setting current values, then the No. 1 and No. 2 relays are in misoperation, and its feeder lines work normally; 3) if the current flows the No. 1 or No. 2 relay is larger than its any zero sequence current protection setting value, and its action time are shorter than No. 5 relay, then the No. 1 or No. 2 relay will act in maloperation; 4) if the current flows the No. 1 or No. 2 relay is larger than its any zero sequence current protection setting value, and its action time are longer than No. 5 relay, then the No. 1 and No. 2 relay don't misoperate, and its feeder lines work normally. It is same with fault zero sequence current calculation principle of line L5, when the fault (f_6) occurs in line L6, suppose the size of zero sequence current flow the No. 5 relay and No. 6 relay are

$$I_{k5.0} = I_{k6.0} = \left| \frac{3E_S}{Z_{f6(I)} + Z_{f6(II)} + Z_{f6(0)}} \right| \quad (5)$$

where the positive sequence and negative sequence and zero sequence equivalent impedance are respectively
$Z_{f6(I)} = Z_{SI} // (Z_{1I} + Z_{2I} + Z_T + Z_{mI}) + Z_{5I} + \alpha_6 Z_{6I}$,
$Z_{f6(II)} = Z_{SII} // (Z_{1II} + Z_{2II} + Z_T + Z_{mII}) + Z_{5II} + \alpha_6 Z_{6II}$,
$Z_{f6(0)} = Z_{S0} // (Z_{10} + Z_{20} + Z_T + 3Z_n) + Z_{50} + \alpha_6 Z_{60}$

However, before access of the DG, and when the fault (f_6) occurs in line L6, the size of zero sequence current flow the No. 5 relay and No. 6 relay are

$$I^f_{k5.0} = I^f_{k6.0} = \left| \frac{3E_S}{Z^f_{f6(I)} + Z^f_{f6(II)} + Z^f_{f6(0)}} \right| \quad (6)$$

Where the positive sequence and negative sequence and zero sequence impedance are respectively
$Z^f_{f6(I)} = Z_{SI} + Z_{5I} + \alpha_6 Z_{6I}$, $Z^f_{f6(II)} = Z_{SII} + Z_{5II} + \alpha_6 Z_{6II}$, $Z^f_{f6(0)} = Z_{S0} + Z_{50} + \alpha_6 Z_{60}$.

Compared with formula (5) and formula (6), it's concluded that $I_{k5.0} = I_{k6.0} > I^f_{k5.0} = I^f_{k6.0}$, and meanwhile that 1) the sensitivity of No. 5 relay and No. 6 relay will both increase; 2) if the current $I_{k5.0}$ is smaller than the setting current value of zero sequence current protection I section of No. 5 relay, the No. 6 relay can clear the fault correctly; 3) if the current $I_{k5.0}$ is larger than the setting current value of zero sequence current protection I section of No. 5 relay, the zero sequence current protection I section of No. 5 relay and No. 6 relay act in no selectivity; 4) because the zero sequence current III section protection is set in case of avoiding the maximum unbalance current of the outlet of the next line when the interphase short circuit happens, and the selectivity requirement should be in coordination with the current III section of next line in relay mode, thus the current III section sensitivity of No. 5 and No. 6 relay are both increased, and with no case of losing selectivity. The analysis of the influences that may cause disoperation of No. 1 and No. 2 relay is same with the case when the No. 5 line has failure occurrence.

B The Faults Happen in Upstream Lines

1） Impacts on the adjacent feeder lines protection

No fault zero sequence current flows the adjacent feeder lines, so which doesn't influence the adjacent feeder lines protection.

2） Impacts on the upstream lines protection

The fault zero sequence current flows the fault points from the upstream lines protective device will change, which may cause its protection anti-action or acts with no selectivity; the protective devices between the DG access point and fault point will has the direction fault zero sequence current to be flowed, which may cause its protection acts.

3） Impacts on the downstream lines protection

The downstream lines has no fault zero sequence current to flow through, thus no impacts will be generated on the downstream line protection.

4） Example exploration

When the fault ($f1$) is occurred in line L1, the size of zero sequence current flows the grounding point and No. 1 and No. 2 relay are respectively

$$I_{k.0} = \left| \frac{3E_S}{Z_{fS(I)} // Z_{fm(I)} + Z_{fS(II)} // Z_{fm(II)} + Z_{fS(0)} // Z_{fm(0)}} \right| \quad (7)$$

$$I_{k1.0} = I_{k.0} \left| \frac{Z_{fm(0)}}{Z_{fS(0)} + Z_{fm(0)}} \right| = \left| \frac{3E_S}{Z_{fS(I)} B_I + Z_{fS(II)} B_{II} + Z_{fS(0)}} \right| \quad (8)$$

$$I_{k2.0} = I_{k.0} \left| \frac{Z_{fS(0)}}{Z_{fS(0)} + Z_{fm(0)}} \right| \quad (9)$$

Where the positive and negative and zero sequence equivalent impedance on system side are respectively $Z_{fS(I)} = Z_{SI} + \alpha_1 Z_{1I}$, $Z_{fS(II)} = Z_{SII} + \alpha_1 Z_{1II}$, $Z_{fS(0)} = Z_{S0} + \alpha_1 Z_{10}$, and the positive and negative and zero sequence equivalent impedance on DG side are respectively

$Z_{fm(I)} = (1-\alpha_1)Z_{1I} + Z_{2I} + Z_T + Z_{mI}$,
$Z_{fm(II)} = (1-\alpha_1)Z_{1II} + Z_{2II} + Z_T + Z_{mII}$,
$Z_{fm(0)} = (1-\alpha_1)Z_{10} + Z_{20} + Z_T + 3Z_n$, in addition,
$B_I = \frac{Z_{fm(I)}}{Z_{fm(0)}}\frac{Z_{fS(0)} + Z_{fm(0)}}{Z_{fS(I)} + Z_{fm(I)}}$, $B_{II} = \frac{Z_{fm(II)}}{Z_{fm(0)}}\frac{Z_{fS(0)} + Z_{fm(0)}}{Z_{fS(II)} + Z_{fm(II)}}$.

However, before the access of DG, and when the fault (f_1) is occurred in line L1, the zero sequence current flows through the grounding point and No. 1 and No. 2 relay are respectively

$$I^f_{k0} = I^f_{k1.0} = \left|\frac{3E_S}{Z_{fS(I)} + Z_{fS(II)} + Z_{fS(0)}}\right| \tag{10}$$

$$I^f_{k2.0} = 0 \tag{11}$$

Compared with formula (10) and (11), we can conclude that the sizes of $I_{k1.0}$ and $I^f_{k1.0}$ are not determined, $I_{k2.0} > I^f_{k2.0}$, and commonly, the positive sequence and negative sequence equivalent impedance are equal, namely, $Z_{fS(I)} = Z_{fS(II)}$, $Z_{fm(I)} = Z_{fm(II)}$, then

(1) when $\left|\frac{Z_{fm(0)}}{Z_{fm(I)}}\right| > \left|\frac{Z_{fS(0)}}{Z_{fS(I)}}\right|$, namely, $|B_I| = |B_{II}| < 1$, $I_{k1.0} > I^f_{k1.0}$, the fault zero sequence current will increase after accessing of DG, as well as the sensitivity of No. 1 relay increases, and the No. 1 relay can clear the faults correctly;

(2) when $\left|\frac{Z_{fm(0)}}{Z_{fm(I)}}\right| = \left|\frac{Z_{fS(0)}}{Z_{fS(I)}}\right|$, namely, $|B_I| = |B_{II}| = 1$, $I_{k1.0} = I^f_{k1.0}$, the fault zero sequence current is unchanged after accessing of DG, as well as no impact on No. 1 relay, and No. 1 relay can clear the faults correctly;

(3) when $\left|\frac{Z_{fm(0)}}{Z_{fm(I)}}\right| < \left|\frac{Z_{fS(0)}}{Z_{fS(I)}}\right|$, namely, $|B_I| = |B_{II}| > 1$, $I_{k1.0} < I^f_{k1.0}$, the fault zero sequence current will decrease after accessing of DG, the protective range of No. 1 relay lessens, and its sensitivity decreases. If Ik1.0 is smaller than all the setting values of zero sequence three-section protection of No. 1 relay, then the No. 1 relay will anti-act, and the system power will constantly provide short circuit current for the fault points, otherwise, the No. 1 relay will clear the faults correctly.

The No. 2 relay has fault zero sequence current, if $I_{k2.0}$ is smaller than all current setting values of zero sequence current three-section protection of No. 2 relay, then No. 2 relay will not act, and the DG will continually provide short circuit current for the fault points, otherwise, the No. 2 relay acts, and the DG will access into unscheduled islanded operation.

When the fault is occurred in line L2, the impacts of DG on zero sequence protection is same with the above principle analysis of line L1 in fault situation, and the different aspect is when the size of zero sequence current flows through the No. 1relay is smaller than the setting current value of zero sequence protection I section of No. 1 relay, then the No. 2 relay can clear the faults correctly, otherwise, the No. 1 and No. 2 relay will lose action selectivity.

C The Faults Occur in Downstream Lines

1) Impacts on adjacent feeder lines protection

When no fault zero sequence current flow through the adjacent feeder lines, there doesn't have impacts on adjacent feeder lines protection.

2) Impacts on upstream lines protection

The fault zero sequence current that flows through the protective devices of upstream lines will change, and that may cause the protective devices anti-act or misoperate.

3) Impacts on downstream lines protection

The connection of DG will generate an increasing effect on the fault zero sequence current that flows through the protective devices of downstream lines, then its protective action sensitivity will be increased, and its protective range will expand, which may cause that each zero sequence current protective action of downstream lines loses selectivity. It's analyzed like the fault impact analysis of L6 aforementioned, and the detailed example analysis is no longer given here.

4) Example analysis

As is shown in Fig. 1, when the fault (f3) happens on line L3, the size of fault zero sequence current that flows through the No.3, No. 1 and No. 2 relay is respectively

$$I_{k3.0} = \left|\frac{3E_S}{Z_{(I)} + Z_{(II)} + Z_{(0)} + \alpha_3 Z_{3(*)}}\right| \tag{12}$$

$$\begin{aligned} I_{k1.0} &= I_{k2.0} \\ &= I_{k3.0}\left|\frac{Z_{fm(0)}}{Z_{fS(0)} + Z_{fm(0)}}\right| \\ &= \left|\frac{3E_S}{Z_{fS(I)}B_I + Z_{fS(II)}B_{II} + Z_{fS(0)} + \alpha_3 Z_{3(*)}B_0}\right| \end{aligned} \tag{13}$$

Where the positive, negative and zero sequence equivalent impedance is respectively

$Z_{(I)} = Z_{fS(I)} // Z_{fm(I)} = (Z_{SI} + Z_{1I} + Z_{2I}) // (Z_{mI} + Z_T)$,
$Z_{(II)} = Z_{fS(II)} // Z_{fm(II)} = (Z_{SII} + Z_{1II} + Z_{2II}) // (Z_{mII} + Z_T)$,
$Z_{(0)} = Z_{fS(0)} // Z_{fm(0)} = (Z_{S0} + Z_{10} + Z_{20}) // (Z_T + 3Z_n)$, in addition,

$$B_I=\frac{Z_{fm(I)}}{Z_{fm(0)}}\frac{Z_{fS(0)}+Z_{fm(0)}}{Z_{fS(I)}+Z_{fm(I)}},\ B_{II}=\frac{Z_{fm(II)}}{Z_{fm(0)}}\frac{Z_{fS(0)}+Z_{fm(0)}}{Z_{fS(II)}+Z_{fm(II)}},$$

$$B_0=\frac{Z_{fS(0)}}{Z_{fm(0)}}+1,\ Z_{3(*)}=Z_{3I}+Z_{3II}+Z_{30}.$$

However, before the connection of DG, when the fault (f_3) occurs on line L3, the fault zero sequence current that flows through the No. 1, 2 and 3 relay is respectively

$$I^f_{k1.0}=I^f_{k2.0}=I^f_{k3.0}\left|\frac{3E_S}{Z_{fS(I)}+Z_{fS(II)}+Z_{fS(0)}+\alpha_3 Z_{3(*)}}\right| \quad (14)$$

Compared with formula (12)~(14), $I_{k3.0}>I^f_{k3.0}$, based on fault analysis of f_1 and f_2, it's concluded that when the line L3 occurs fault (f_3),

1) when $\left|\frac{Z_{fm(0)}}{Z_{fm(I)}}\right|=C$, among which, C is constant, and its value is larger than $\left|\frac{Z_{fS(0)}}{Z_{fS(I)}}\right|$, there $I_{k1.0}=I_{k2.0}=I^f_{k1.0}=I^f_{k2.0}$, that is, after connection of DG, the fault zero sequence current flow through No. 1 and 2 relays are unchanged, and the No. 1 and 2 relays are not influenced, and the No. 3 relay can clear the faults accurately.

2) when $\left|\frac{Z_{fm(0)}}{Z_{fm(I)}}\right|>C$, there $I_{k1.0}=I_{k2.0}>I^f_{k1.0}=I^f_{k2.0}$, that is, after connection of DG, the fault zero sequence current that flow through the No. 1 and 2 will increase, and if $I_{k2.0}$ is larger than its setting current value of zero sequence current protective I section, the zero sequence current protective I section of No. 2 and 3 relays will lose selectivity, and even the zero sequence I section of No. 1 relay may lose selectivity, otherwise, the No. 3 relay can accurately act to clear the faults.

3) when $\left|\frac{Z_{fm(0)}}{Z_{fm(I)}}\right|<C$, $I_{k1.0}=I_{k2.0}<I^f_{k1.0}=I^f_{k2.0}$, that is, after the connection of DG, the fault zero sequence current that flow through the No. 1 and 2 relays decrease, and if $I_{k2.0}$ is smaller than all of its zero sequence protective setting current values, and the No. 3 relay doesn't act accurately, then the No. 1 and 2 relays will anti-act, otherwise, the No. 3 relay will clear the faults accurately.

Improvement of the stability and dynamic reliability of power system is always a difficult and urgent task [2, 3]. The power system is a complex system with high nonlinearity, and when the operation points of system have large deviation, utilize the approximate linearization procession method to control, but its control effect is discontented, even causes the system losing stability. Therefore, it's of great significance to study the application of nonlinearity control theory in power system, and which has been more and more appreciable [4].

The excitation control of generators has been playing an important role in power system stability control, and which has been thought as the most economic and effective measure to improve the power system stability. Nonlinearity excitation control has been the research focus [5-9]. TCSC which as a member of FACTS family has played a significant role in increasing the transmission capacity, improving the power system damping ratio and improving power system stability [10]. The literature [11] based on dissipative system concept, proposed a robust nonlinearity correlation control strategy between TCSC and generator excitation. The literature [12] based on the optimal objection method designed the nonlinearity correlation controller of generator excitation and TCSC. Moreover, the literature [13] took the single machine infinite bus system model that contained generator excitation and TCSC as Hamilton system form, and the Hamilton structure of system was utilized to realize the correlation between two control strategies directly.

The correlation controllers designed in above literatures both made researches in the single machine infinite bus system, while in multi-machine infinite bus system, the application effects are lack of persuasion. Thus, the direct feedback linearization method in the nonlinearity system differential geometry theory was utilized to implement precise linearization on the multi-machine nonlinearity mathematical model that contained TCSC. The method didn't need complex mathematical derivation, and has advantages of simple design and sharp physical concept, as well as certain superiority in engineering application. Finally, the simulative results also show the accuracy and effectiveness of the optimal control law studied in this paper.

IV. SIMULATION STUDY

A. Simulation Model

The simulation model is shown in Fig. 2, the Simulink was used in the paper to make modeling research. Each parameter of the simulative model is shown as follows.

1) System power source: the output voltage is 10.5kV, and short circuit capacity 100MVA, resistance-reactance-ratio R/X=1/7;

2) Line: the maximum transmission capacity is 14000kVA, and positive and negative resistance 0.01273Ω/km, zero sequence resistance 0.3864Ω/km, positive and negative reactance j0.2933Ω/km, zero sequence reactance j1.2963Ω/km, and positive and negative capacitor 12.74×10-12 F, and zero sequence capacitor 7.751×10-12 F. among them, the length of L1~L4 are both 2km, and the L5 and L6 are both 3km;

3) DG: the output voltage is 0.4kV, and short circuit capacity 10MVA, resistance-reactance-ratio R/X=1/7;

4) Grid-connected transformer: the capacity is 2MVA,

ratio is 0.4/10.5, no-load loss 4300W, and load loss 13000W, short circuit impedance 6%, no-load current 6%;

5) When single-phase short circuit happens on end of line, the zero sequence fault current is maximum, and the normal maximum unbalance current of line is took 50% of the maximum current carrying capacity, and the stability coefficient of protective setting value is took 1.25;

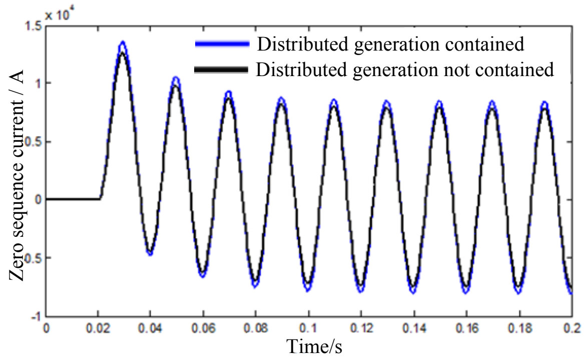
6) Time of fault happens is 0.02s.

B Simulative Comparison of Fault Zero Sequence Current

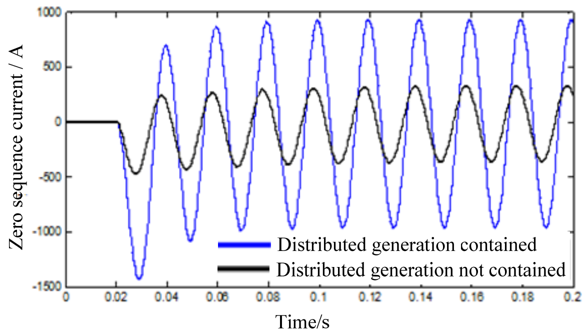
1） Faults happen at head of line L5

The comparison illustration of zero sequence current, which flows through the No. 5 relay, is shown in Fig. 2 (a), and the comparison illustration of reverse zero sequence current, which flows through the No. 1 and No. 2 relays, are shown in Fig. 2(b). It's seen from the two diagrams that the zero sequence currents are increased obviously, and similar to the results of three-phase short circuit [6].

The comparison illustration of zero sequence current, which flows through the No. 1 relay, is shown in Fig. 3, and it's seen from the diagram that the zero seen current is decreased obviously. While when three-phase short circuit happens, the fault current flows through the No. 1 relay is constant [5].



(a) The comparison of zero sequence current that flows through the No. 5 relay



(b) The comparison of reverse zero sequence current that flows through the No. 1 and No. 2 relays

Fig.2 The Comparison of Zero Sequence Current When Single-phase Short Circuit Happens at the Head of L5

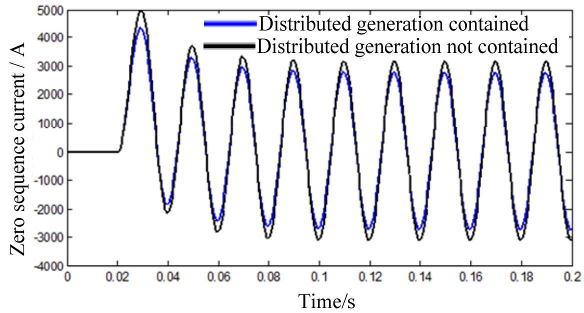
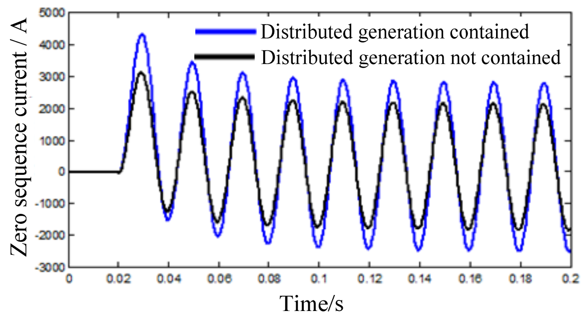
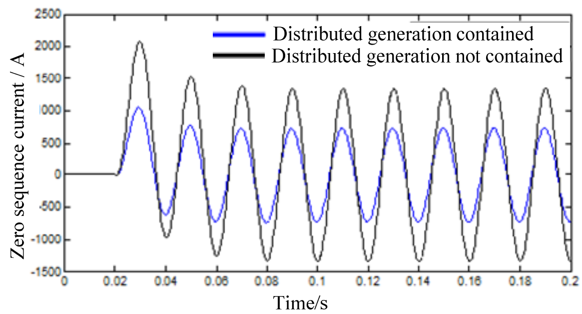


Fig.3 The Comparison of Zero Sequence Current When Single-phase Short Circuit Happens at End of Line L1



(a) The zero sequence comparison of No. 3 relay



(b) The zero sequence comparison of No. 1 and No. 2 relays

Fig. 4 The Comparison of Zero Sequence Current When Single-phase Short Circuit Happens at End of Line L3

3） The fault happens at end of line L3

The comparison illustration diagram of zero sequence current that flows through the No. 3 relay is shown in Fig. 4(a), and the comparison illustration diagram of zero sequence current that flows through the No. 1 and No. 2 relays are shown in Fig. 4(b). It's seen from the Fig. 4(a) that the zero sequence current of L3 increases obviously, and which is similar to the result of three-phase short circuit [6]. Meanwhile, under given parameters, it's can be seen from the Fig. 4 (b) that the zero sequence current that flows through the No. 1 and No. 2 relays decreases obviously.

C Simulative Analysis of Connected Maximum Short Circuit Capacity

It's known from the aforementioned analysis that the connection of DG may cause the protective action of distribution network zero sequence current loses selectivity, and may cause the zero sequence current protection of upstream line in anti-action or misoperation. Moreover, it's concluded based on aforementioned analysis that the factors that influence the size of zero sequence current are mainly the size of equivalent impedance Z_m+Z_T, the size of grid-connected transformer neutral point grounding impedance Z_n and the grid-connected position (the distance from grid-connected point to No. 1 bus). In the paper, it mainly utilizes the connected short circuit capacity to weight the size of Z_m+Z_T.

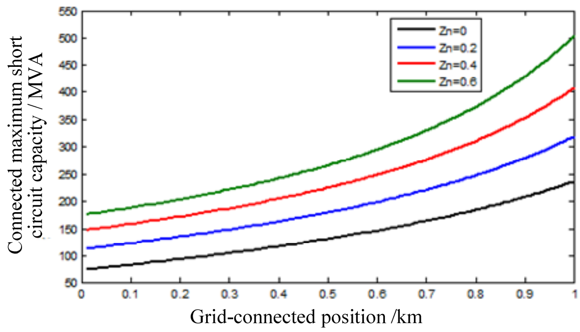
It's similar to the maximum connection capacity that is determined in literature [8], and the determined method of connected maximum short circuit capacity in this paper is show as flows. In case of different grid-connected positions and grid-connected transformer neutral point grounding impedances, the size of connected short circuit capacity is increased gradually until the distribution network zero sequence current protection loses selectivity, misoperation and anti-action.

1) Ensure the protective action loses no selectivity

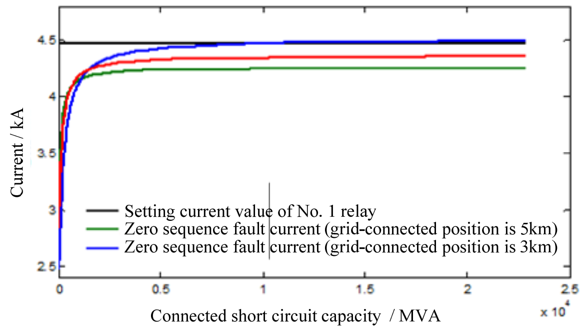
According to the analysis results, in order to make sure the protective action of adjacent feeder lines lose no selectivity, the fault current that flows through the No. 5 relay should be smaller than its protective I section setting value, when the fault (f_6) happens at head of line L6. It's seen from the Fig. 5(a) that the longer the grid-connected position, the larger the connected maximum short circuit capacity, and the larger the grid-connected neutral point grounding impedance, the larger the grid-connected point maximum short circuit capacity, which also explains that the Z_n has a limited effect on the zero sequence current in adjacent feeder lines.

In order to ensure the upstream lines protective actions lose no selectivity, the fault current that flows through the No. 1 relay should be smaller than its protective I section setting value, when the single-phase fault (f_2) happens at head of line L2. It's seen from Fig. 5 (b) that the connected short circuit capacity, in a large range, determines the fault current that flows through the No. 1 relay not larger than its setting value. Also can be seen from Fig. 5 (c) that the Z_n has contribution effect on the zero sequence fault current that flows through the upstream lines, and which is not always kept in an increasing trend with the variation of connected short circuit capacity, but decreases at beginning and increases after.

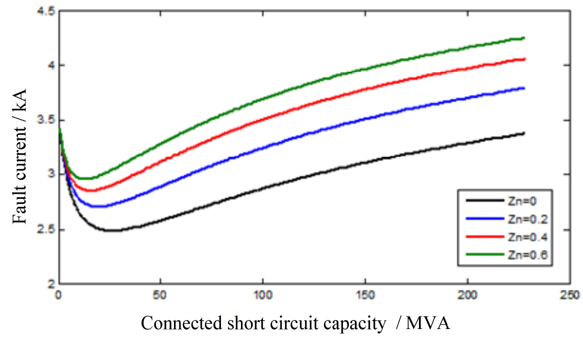
In order to ensure the protective action of downstream lines lose no selectivity, the fault current that flows through the No. 3 relay should be smaller than its protective I section setting value, when the fault (f_4) happens at head of line L4. Moreover, it's seen from Fig. 5 (d) that the longer the grid-connected position, the smaller the connected maximum short circuit capacity, among which, the larger the grid-connected transformer neutral point grounding impedance, the larger the connected maximum short circuit capacity, which also explains that the Z_n has a limited effect on the zero sequence current in downstream lines.



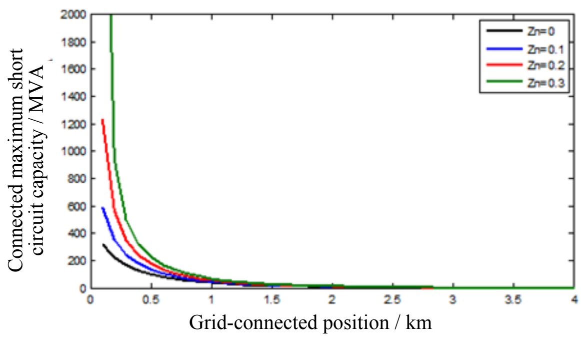
(a) Fault happens at head of L6



(b) Fault happens at head of L2 and *Zn*=0



(c) Fault happens at head of L2 and the grid-connected position is 3km



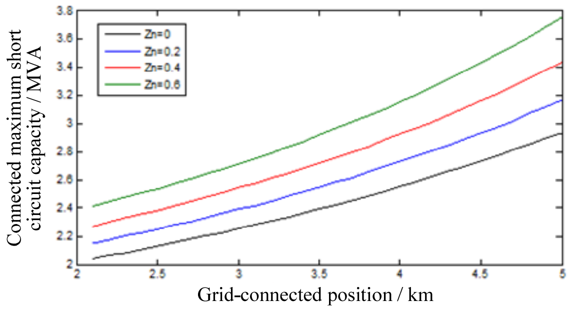
(d) Fault happens at head of L4

Fig.5 Ensure the Protective Actions Lose No Selectivity

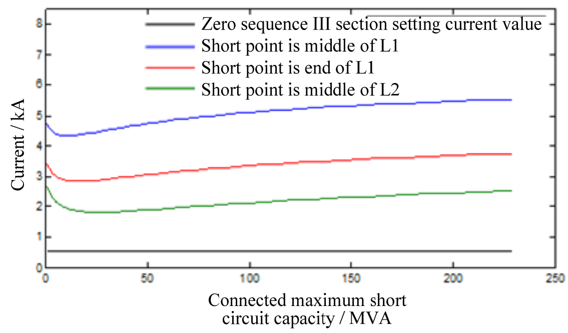
2) Guarantee the protective actions in no misoperation or anti-action

In order to the guarantee no misoperation of protections in upstream line, when the fault (f_5) occurs at head of line L5, the fault current that flows through the No. 1relay should be smaller than its protective III section setting value. We can see from the Fig. 6(a) that the longer the grid-connected position, the larger the maximum short circuit capacity. Moreover, the larger the grid-connected transformer neutral position grounding impedance, the larger the connected maximum short circuit capacity, which also explains that the impedance Z_n plays a limited role in the upstream line zero sequence current.

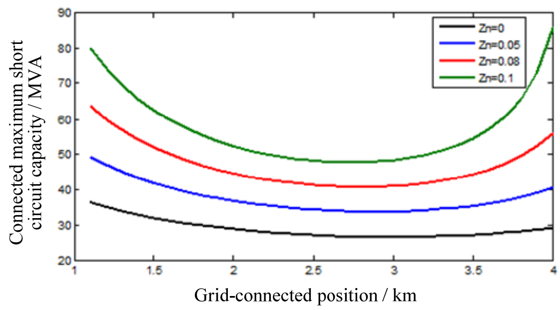
In order to ensure no anti-action of the protections of upstream line, the fault current that flows through the No. 1 relay should be larger than its protective III section setting value, when the single-phase short circuit fault is occurred in the upstream line. It's seen from the Fig. 6(b) that the connected short circuit capacities, in larger range, both make the fault currents that flow through the No. 1 relay aren't smaller than its protective III section setting value.



(a) No maloperations (fault happens at head of L5)



(b) No maloperations (the grid-connected position is 4km and *Zn*=0)



(c) No maloperations (fault happens in middle of L3)

Fig.6 Ensure no maloperations or anti-actions of protective devices

In order to guarantee no anti-action of upstream protective actions, the fault current that flows through the No. 1 relay should be larger than its protective III section current setting value, when the fault happens in downstream lines. We can see from Fig. 6 (c) that the connected maximum short circuit capacity is presented in trend of decreasing at beginning and increasing later with gradually length growing of grid-connected positions, and meanwhile the larger the grid-connected transformer neutral position grounding impedance, the larger the connected maximum short circuit capacity, and which also explains that the impedance Zn has a contribution effect on the upstream line zero sequence fault current.

Based on above comprehensive analysis of connected maximum short circuit capacity in each kind of case, the maximum short circuit capacity that is connected on DG side can be generally determined, which guarantees the relay protection of distribution network can still act reliably after accessing of DG.

V. SUMMARY

Based on zero sequence current three-section protective principle of small resistance grounding system, the paper made a comprehensive analysis of impact mechanism of DG connection on distribution network zero sequence current protection through a rigorous theoretical derivation, and boundary conditions that no impacts of DG on original distribution network protective reliable action were given, and the concrete conclusions are concluded that

1) the connected short circuit capacity, grid-connected position, and grid-connected transformer neutral point grounding impedance are the mainly factors to determine the impacts of DG connection on distribution network zero sequence current protection;

2) under the case that the original protective configurations of distribution network are unchanged, it's necessary to limit the connected short circuit capacity on DG side, to make sure the reliable action of distribution network relay protection;

3) in approach of setting the size of grid-connected transformer neutral point grounding impedance reasonably, the impacts on distribution network zero sequence current protection can be decreased after the connection of DG, so that the permissible connected maximum short circuit capacity on DG side can be added.

From aspect of zero sequence current protection of small resistance grounding system, the analysis process and results of connected maximum short circuit capacity on DG side can provide the theoretical basis with reference value for the distribution network planning design with DG connection.

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REFERENCES

[1] M M Pan, J F Zhang, "Research on inverter interface of distributed power," The Journal of New Industrialization (in Chinese), vol. 4, no. 6, pp. 60-66, June 2014.

[2] Sukumar M. Brahma, Adly A. Girgis, "Development of adaptive protection schemefor distribution systems with high penetrationof distributed generation," IEEE Transactions on Power Delivery, Sci, vol. 19, no. 1, pp. 56-63, January 2004.

[3] Z C Hu, J P Lu, L H Hu, et al. "Analysis of the impact of DG on the protection of distribution system," Journal of Chongqing University (in Chinese), vol. 29, no. 8, pp. 36-39, August 2006.

[4] W Huang, J Y Lei, X Xia, et al. "Influence of distributed generation on phase-to-phase short circuit protection in distribution network," Automation of Electric Power Systems (in Chinese), vol. 32, no. 1, pp. 93-97, January 2008.

[5] W Zhou, Y Zhang, C J Xia, et al. "Effect of distributed generation on relay protection of distributed system," Power System Protection and Control (in Chinese), vol. 38, no. 3, pp. 1-5, March 2010.

[6] X K Fong, N L Tai, K Song, et al. "Research on the impact of DG capacity on the distribution network current protection and countermeasure," Power System Protection and Control (in Chinese)，vol. 38, no. 22, pp. 156-160, December 2010.

[7] S Tao, J Guo, X N Xiao, et al. "Analysis on allowed penetration level of distributed generation and its grid-connected position based on principles of current protection," Power System Technology (in Chinese)，vol. 36, no. 1, pp. 265-270, January 2012.

[8] J Y Lei, W Huang, X Xia, et al. "Estimation of the shortest radius of power system voltage security region in node injection space," Automation of Electric Power System (in Chinese), vol. 32, no. 3, pp. 82-86, February 2008.

[9] J H Wang, N L Tai, K Song, et al. "Penetration level permission of for DG in distributed network considering relay protection," Proceeding of the CSEE (in Chinese)，vol. 30, no. 22, pp. 37-43, December 2010.

[10] J L Sun, Y L Li, S W Li, et al. "A protection scheme for distribution system with distributed generations," Automation of Electric Power Systems (in Chinese)，vol. 33, no. 1, pp. 81-84, January 2009.

[11] J Ma, X Wang, C Mi, et al. "A new adaptive protection approach for distribution network containing distributed generation," Power System Technology (in Chinese)，vol. 35, no. 10, pp. 204-208, October 2011.

[12] W Pei, K Sheng, L Kong, et al. "Impact and improvement of distributed generation on distribution network voltage quality," Proceeding of the CSEE (in Chinese), vol. 28, no. 13, pp. 152-157, July 2008.

[13] B X Xie, Z Wang, S L Fan, "Influence on harmonic characteristics of distributed network with distributed generations," Power System Protection and Control (in Chinese)，vol. 40, no. 2, pp. 116-120, January 2012.

[14] In-Su Bae, Jim-O Kim, "Reliability evaluation of distributed generation based on operation mode," IEEE Transactions on Power Systems, Sci, vol. 22, no. 2, pp. 785-790, February 2007.

[15] Q Xie, D M Liu, "Study on several problems of distribution network with solar power," The Journal of New Industrialization (in Chinese), vol. 4, no. 8, pp. 22-29, August 2014.

[16] H Y Wang, "Electrical danger to consumer caused by earthing fault in substation of 10 kV network with low resistance neutral grounding and its protective measures," Power System Technology (in Chinese), vol. 22, no. 11, pp. 54-58, November 1998.

[17] X M Li, Y Yuan, Y Pan, et al. "Research on special problems of 10 kV small resistance grounding system," High Voltage Engineering (in Chinese), vol. 29, no. 5, pp. 39-41, May 2003.

[18] Y Z He, Z Y Wen, "Power system analysis (volume 1)," Wuhan: Huazhong University of Science & Technology Press, China, 2002.

[19] J L He, Y L Li, X Z Dong, et al. "Power system relay protection principle," Beijing: China Electric Power Press, China, 2010.

[20] W Y Zhang, S Z Zhu, J H Zheng, et al. "Impacts of distributed generation on electric grid and selecting of isolation transformer," In: Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005.

[21] H Zhang, S Z Zhou, W Y Zhang, et al. "Study on grounding project of distributed generation connecting electric grid," Journal of Shenyang Institute of Engineering (Natural Science) (in Chinese), vol. 2, no. 3, pp. 198-202, March 2006.