A Practical Setting Method for Over-Current Relay and Automatic Recloser in Distribution Network with Photovoltaic Station

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***Abstract*—Over-current protection in distribution network is easy to be influenced by the additional injected power at the measuring point. In this paper a practical setting method for the over-current relay considering the injected power is proposed. The proposed strategy is based on the bus maximum injected power, and the basic principle of the method is to prevent the over-current protection from mal-operation when there has injection current or branching current. In addition, coordination between Grid Automatic Reclosing Time (GART) and photovoltaic (PV) Low Voltage Ride Through (LVRT) is also studied in this paper. By using exact experimental analysis, the grid maximum automatic reclosing time under common faults is given. Simulation results show that reclosing within the maximum reclosing time can guarantee the successful operation of LVRT for the PV, which would be a guiding value for the safe operation of large-scale Grid-Connected Photovoltaic (GCPV).**

***Index Terms*—injected power, over-current protection, low voltage ride through, automatic reclosing time**

I. Introduction

At present, with the increasing exhausted of energy, Distributed Generators (DGs) have been connected to the power system extensively. Although the renewable energy integration reduces the pressure of fossil fuel energy dramatically, it also results in the less reliability of power system. As a representative renewable energy, PV has been widely used in power system in two modes. One is integrated in large scale, the other is integrated in distribution mode. PV station is different from the conventional power and it has its unique operating characteristic, which may cause the relay mal-protection, and even lead to paralysis of the entire power system [1]-[5].

Nowadays, many researchers have conducted a series of studies for the GCPV system, but most of them focused on the impact on system reliability or security and with little consideration on the specific protection as well as the potential coordination between LVRT and GART which would cause fatal disaster. Reference [6] used the scheme of directional pilot protection to eliminate the influence of the reverse current to the over-current protection due to the GCPV; Reference [7] analyzed the influence on before and after accelerated devices of current protection under the condition of distributed power injected; Reference [8] considered the effect of PV injected power on current protection setting value. While, method proposed in reference [6] is relatively complex; reference [7] was not making quantitative consideration of the protection itself; and reference [8] does not give the specific improvement measures.

For the coordination between LVRT and GART, Reference [9] analysed the effects of DG location to protection's reclosing in the distribution network; Reference [10] presented an automatic safety device based on weak feeder protection methods to solve the coordination with reclosing; Reference [11] discussed a method to guarantee the correct operation of automatic reclosing by cutting the DGs before the reclose. But reference [9] is valid only when the injected power capacity is relatively small; reference [10] is mainly used at substation protection, for the transmission line it is difficult to use; while reference [11] should consider the islanding operation of the DGs which is more complex than itself.

This article mainly studies the influence on over-current protection caused by the injected power of the GCPV system, as well as the coordination between LVRT of the PV and GART. For the influence on over-current protection caused by injected power, this paper revised the current setting value to eliminate the protection's mal-operation, while for the coordination set, the article gives the grid's maximum allowable reclosing time considering the PV LVRT. This study introduced here is to play a guiding role in improving the correct operation of the relay protection and the safe operation of the GCPV in distribution network.

This paper is organized as follows. Section II analyzed the influence of the injected power on over-current protection in distribution network. A practical setting method to avoid the relay mal-operation is given in the section. In Section III, simulations are conducted and discussed when PV is in the LVRT stage coupled with different fault types happened in distribution network, and then the maximum GART to ensure the LVRT correct operation is presented. The proposed maximum GART is also tested in this section. Finally, the Section IV concludes this paper.

Manuscript received July 1, 2015; revised September 17, 2015.

doi: 10.18178/ijoee.3.4.225-229

II. Practical Method for Over-Current Protection Setting

Traditional over-current protection of the line in distribution network is designed only under the background of the single power supply. When the PV system is connected, the injected power would change the power flow's direction of the system, then the original over-current protection which is only suited for the single power flow may be mal-operation. So it is necessary to analyze the influence on over-current protection when there has injected power. In this section, GCPV is chosen to be the injected power to illustrate the effect on over-current protection.

A. Theoretical Analysis

The typical distribution network diagram is shown in Fig. 1, PV is connected to the bus C, the fault occurred at K_1, K_2, K_3 and K_4 respectively. Z_S is the system equivalent impedance.

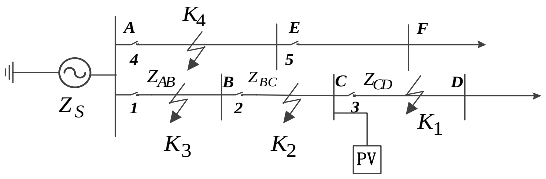

Figure 1. Schematic diagram of a typical distribution network.

1) Fault located at upstream of PV

As shown in Fig. 1, when K_2 is faulted, PV injection current does not affect protection 2 as it only flows the fault current from the system. But when the circuit breaker tripped, the PV system may be in islanding operation.

2) Fault located at downstream of PV

For the protection 3, when the fault occurred at K_1 which is on the 70% of line CD, fault current through C will increase as there is still a close link with the system, moreover, the injection current by PV can also increase the bus C fault current. Then the sensitivity of protection 3 will increase, but it may likely make protection 3 lose its selectivity when external fault occurred (such as location D).

For the protection 2, the backup protection of 3, when the fault occurred at K_1 on the 70% of line CD, as the branching effect of PV, the fault current through the protection would be smaller than no PV connected, and the decreases degree is related with the injected power of the PV [12]. As a result, it may not reach protection 2 current zone II setting value when K_1 faulted, so the backup protection will not operate when protection 3 current zone I failed to act. In this case, the cascading failures may occur.

B. Proposed Practical Method

Compared with the short circuit current, the load current is much smaller, and then it is neglected in this paper. When the fault occurred on the line CD, fault current through protection 3 is:

$$
\begin{aligned}
I_{f3} &= \frac{1}{Z_C + Z_{DG} // kZ_{CD}} \cdot \frac{Z_{DG}}{Z_{DG} + kZ_{CD}} + \\
&\quad \frac{1}{Z_{DG} + Z_C // kZ_{CD}} \cdot \frac{Z_C}{Z_C + kZ_{CD}} \\
&= \frac{Z_C + Z_{DG}}{Z_C \cdot Z_{DG} + k\left(Z_C \cdot Z_{CD} + Z_{DG} \cdot Z_{CD}\right)}
\end{aligned} \tag{1}
$$

$$
I_{f3} = \frac{1}{Z_C \dfrac{Z_{DG}}{Z_C + Z_{DG}} + kZ_{CD}} \tag{2}
$$

$$
Z_C = Z_S + Z_{AB} + Z_{BC}
$$

When there is no PV connected, the fault current through protection 3 is:

$$
I_{f3} = \frac{1}{Z_C + kZ_{CD}} \tag{3}
$$

In the equation above, k is the distance percentage from fault location to bus C, which is between 0 and 1. Z_{DG} is the PV internal impedance which also represents the fault current injection ability of PV.

Comparing (2) and (3), it is obvious to know that when PV is connected, the fault current through protection 3 is larger than the normal condition.

According to the fault current injection ability, a simple and reliable practical method is proposed. In the method, PV injected power is controlled as a variable, and it is checked whether it will affect the nearby protection's correct operation according (2). If the protection is fragile to the injected power, the protection's setting value would be adjusted properly to avoid mal-operation region. Further, limiting the maximum injected power directly to meet the requirements of the protections is also taken if necessary.

By simulation carried out in distribution network with injected power changed from 0 to the maximum, fault current through the protections is obtained. In order to prevent the mal-operation of the protections in all conditions, the over-current settings are considered with the maximum injected power.

C. Simulation Verification

The simulation model is simplified as shown in Fig. 1. Here only takes the faults occurring in the downstream as an example to illustrate the methods of reducing the influence on over-current protection in distribution network when PV system is connected (when the fault occurred in the upstream, the analysis process is similar).

In the model, the 10kV system's equivalent impedance $Z_S = j0.4248\Omega$, the unit impedance of the transmission line is $(0.27 + j0.35)\Omega / km$, bus D and F are with 3MVA and 1MVA constant impedance loads respectively, and the power factor operates at 0.95.

1) Over-Current protections setting value without considering the injected power

Table I shows the over-current protection's setting value which does not consider PV injected power. In the table, scope of the zone I is 80% of the full-length to the corresponding faulted line, and the scope of zone II of protection 2 is extended 75% to the next transmission line.

TABLE I. OVER-CURRENT PROTECTION SETTING WITHOUT CONSIDERING THE PV INJECTED POWER

Protection No.	I	II
2	2.75（80%）	1.778（75%）
3	1.75（80%）	\

When fault occurred at D and the 70% of the line CD, the fault current through protection 2 and 3 are as follows:

TABLE II. FAULT OCCURS AT D

P/MW	I_B/kA	I_C/kA
0	1.640	1.637
0.5	1.631	1.655
1	1.623	1.671
1.5	1.619	1.680
2	1.616	1.689
5	1.582	1.754

TABLE III. FAULT OCCURS AT 70% OF THE LINE CD

P/MW	I_B/kA	I_C/kA
0	1.809	1.794
0.5	1.803	1.829
1	1.796	1.847
1.5	1.793	1.857
2	1.79	1.866
5	1.769	1.902

From Table II, it shows that the sensitivity of protection 3 is increased along with the increase of GCPV injected power, but when external fault occurs (location D), the fault current is 1.754kA (PV injected power capacity is 5MW) which is greater than the setting value 1.75kA, so it will mal-operate; As seen in Table III, when the internal fault occurs (at the 70% of the line CD), the fault current though protection 2 is 1.769kA which is smaller than the zone II setting value 1.778kA, then the backup protection will refuse to act if protection 3 zone I failed to operate. Measurement data obtained from Table II and Table III showed the correctness of the part *A* above.

2) Over-Current protections setting value considering injected power

For the impact on over-current protection as PV connected, in this part, an improved current protection's setting value is shown in Table IV, in which the value considered by GCPV maximum injected power.

TABLE IV. OVER-CURRENT PROTECTION SETTING CONSIDERING THE PV INJECTED POWER

Protection No.	I	II
2	2.673（80%）	1.757（75%）
3	1.801（80%）	\

After reconsideration of the over-current protection's setting value, when external fault occurs (location D), the fault current though protection 3 is 1.754kA which is smaller than the setting value 1.801kA, and when internal fault occurs (at the 70% of the line CD), the fault current though protection 2 is 1.769kA which is greater than the zone II setting value 1.757kA. So it can prevent the mal-operation of protection 3 and 2 effectively.

But in this article the new over-current protection's setting value is mainly considered by PV maximum injected power, so the setting values may be conservative. The ideal method is using adaptive characteristics. And related researches will be conducted along this thought in the future.

III. COORDINATION BETWEEN LVRT OF THE GCPV AND THE GART

LVRT of the GCPV system means that the inverters connected the grid cannot separate from the power grid when the grid's voltage or frequency varies in a certain range (especially in the condition of low voltage), and that it also can provide reactive power supporting according to the requirements of the system.

A. Significance of the Coordination

Fig. 2 shows the typical LVRT operation curve. When a fault occurs in the distribution network with the PV just in the LVRT process, the grid inappropriate reclosing time may lead to the voltage of the gird-connected point enters the line under AB, which would cause LVRT failure easily. Such running state may cause accidents of large-scale PV off the grid. Thus, it will influence the reliability and security of the islanding area's power supply, and even affects the power balance of the whole system.

Therefore, it is very necessary to research the influence of the GART on LVRT.

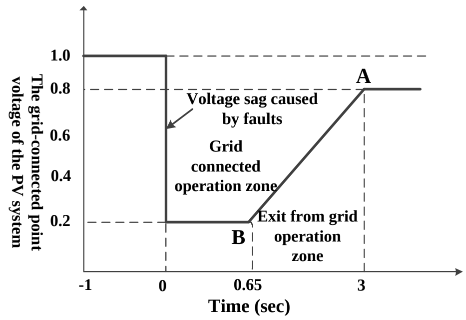

Figure 2. LVRT operation curve of PV station.

B. Proposed Method

As seen in Fig. 2, if the grid automatic reclosing time escaped the minimum voltage time during the LVRT, the probability of LVRT failure can be reduced to the minimum. Based on this, by utilizing PSCAD, a large number of simulation experiments are carried for the coordination problem between LVRT and GART, then the grid's maximum allowable reclosing time for common faults form is given finally in Table V, which is under the premise of ensuring the success of LVRT.

TABLE V. THE MAXIMUM GART

Fault Location	*Fault Type*	*R*	*F*	*Maximum GART*
At middle point	Three-phase to ground	R=0	1	No limit
At middle point	Three-phase to ground	R=0	2	1.05s
At middle point	Three-phase to ground	R=0.1	2	1.1s
At middle point	Three-phase to ground	R=1.0	2	1.2s
At the beginning	Three-phase to ground	R=0	2	0.86s

(In the Table V, F represents fault level, 1 and 2 represent transient and permanent fault respectively and R represents transition resistance)

The acquisition data of maximum allowable reclosing time is calculated when transient faults and permanent faults occurred in the distribution network during the LVRT stage. Results showed that when the GART is within the maximum allowable reclosing time, the voltage curve of the grid-connected point will not enter the LVRT running curve, thus the GCPV is not easy to occur LVRT failure.

C. *Simulation Verification*

Fig. 3 shows the simulation schematic diagram of GCPV system. In the diagram, PV station is connected to the C bus, all faults occur at 0.5s, the circuit breaker tripped by 0.1s delaying, and the reclosing starts by T_{delay} delay. If reclosed on a permanent fault, the breaker would trip again by 0.1s delaying.

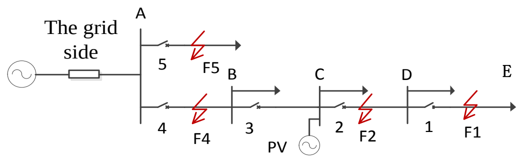

Figure 3. Schematic diagram of a typical distribution network.

This section only analyses the fault located at downstream of PV. Set three-phase transient fault, permanent fault at middle point of transmission line CD and three-phase permanent fault at the beginning terminal of line CD respectively, in which the transition resistance R is 0. The simulation results are shown as Fig. 4, Fig. 5 and Fig. 6.

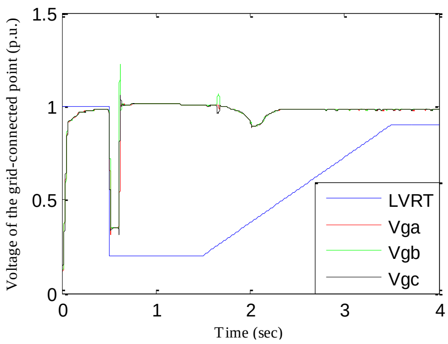

Figure 4. Simulation result of reclosing on three-phase transient fault at middle point of line CD.

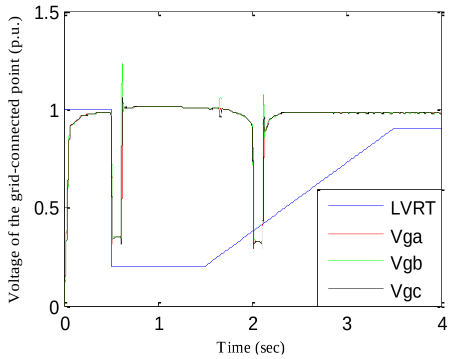

Figure 5. Simulation result of reclosing on three-phase permanent fault at middle point of line CD.

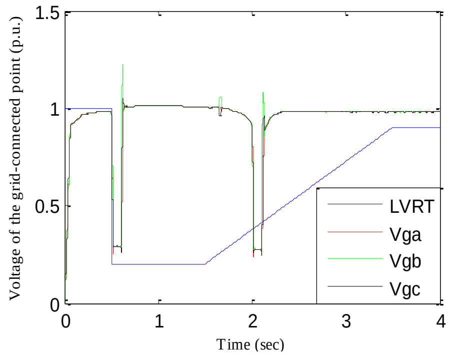

Figure 6. Simulation result of reclosing on three-phase permanent fault at beginning terminal of line CD.

As seen in Fig. 4, for a transient three-phase fault occurs at 0.5s on the middle point of line CD, the grid-connected point voltage drops to 35% of the rated voltage. Line reclosing starts after 1.5s delaying, the voltage recovers to normal condition basically, which cannot enter into the PV system's LVRT curve, so no special maximum GART is required.

If the fault is a permanent fault, the grid-connected point voltage would be within the LVRT curve in the reclosing stage, as shown in Fig. 5. This condition will seriously affect the successful operation of LVRT.

As shown in Fig. 6, if the fault occurs at the beginning terminal of line CD which is closer to the PV power, it is observed that the grid-connected point voltage drops more serious than the middle point of line during the period of reclosing, which is more liable to lead the LVRT failure.

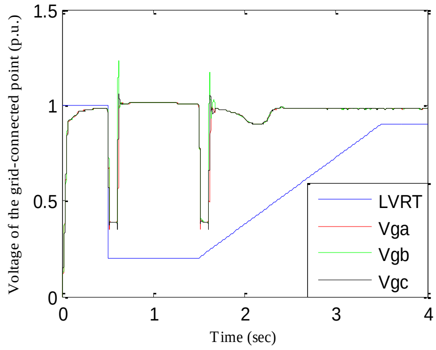

Figure 7. Simulation result of reclosing on three-phase permanent fault at middle point of line CD when the GART is within maximum GART.

Take the fault occurred at the middle point of line CD as an example, the GART is 1s which is within the maximum GART (1.05s). As seen in Fig. 7, the grid-connected point voltage drops to about 35% of the rated voltage during the reclosing period, which is not into the LVRT curve.

Compared with Fig. 5, using the proposed maximum GART can ensure the synchronous operation of the PV system with the grid reliably.

Through the above analysis in this section, the following conclusions are obtained:

- The fault location is farther from the DG, the maximum GART is longer, namely the reclosing time has a larger margin;
- The fault is more serious, the maximum GART will be smaller, namely the reclosing time margin is not sufficient;
- The transition resistance also affects the maximum GART. The greater the transition resistance is, the longer the maximum GART will be.

IV. Conclusions

This paper analyzed the influence of injected power on over-current protections in the distribution network. Then a practical setting method for over-current protections is proposed, which is based on the maximum injected power of PV. Simulation results showed that this method can eliminate the influence of the injection current or branching current on over-current protections brought by GCPV injected power. But further development and optimization of the over-current protection is needed for the realization of adaptation.

In addition, the cooperation between LVRT of the GCPV and the GART is also studied in this paper. When the emergence of grid's faults happened synchronized with the LVRT of the GCPV, it may cause the LVRT failure if the GART value is unreasonable. In order to ensure LVRT succeed, this paper gives the grid's maximum allowable reclosing time for different fault types. Case study and simulation results showed that the proposed maximum GART can strengthen cooperation between GART and the LVRT successfully. Moreover, it is possible to apply this method to the power system with large-scale penetration of PV station.

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