

Research on Impact of Solar Power Plants on 110 kV Line Current Differential Protection Operation

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Abstract. The paper presents the research on the impact of renewable energy sources based power plants interfaced to power grids through inverters on differential protection of a line connecting such a power plant to an external grid. The paper considers the case of a weak power grid with a relatively high-capacity solar power plant. An approach to evaluate the IBR impact on differential protection in steady-state conditions under typical inverter control scenarios is suggested. The factors affecting the differential protection operation are revealed. The brief guidance concerning the application of differential protection in such power grids is given.

1 Introduction

Presently the share of renewable energy sources (RES) not including hydro power plants in some local regions of the Russian power system exceeds 10% of the total output generation capacity. In recent years a number of large RES power plants with a capacity of more than 100 MW have been commissioned [1]. The impact of RES on nearby power grids operation is becoming more significant.

In most cases, RES are connected to power grids through electronic power converters (invertors). Behaviour of such inverter based resources (IBR) during normal operation and power system faults is mostly dependant on technical specifications and control algorithms of invertors but not on generator electromechanical characteristics (as for conventional power plants). Typically, RES exhibits: low levels of short circuit currents that exceed rated currents no more than 10-30%, current-voltage phase relationships are different than for conventional power plants, lack of or low negative sequence current response during asymmetrical conditions [2].

The IBR characteristics listed above may have a negative impact on relay protection and automation operation reducing security and dependability of overcurrent and distance protections [3], leading to incorrect operation of negative sequence protection elements [4].

Considering field cases and research results it can be concluded that line current differential protection is the most preferable choice for protection of transmission lines connecting RES power plants to power grids. It is expected that RES have minimal impact on differential protection performance [3, 5]. However, differential protection operation in power systems with IBR may not be sufficiently studied; thus, some papers consider cases of decreased dependability of differential protection (low

sensitivity, delayed operation, failure to operate) due to presence of IBR [6, 7]. It is essential to indicate major issues due to IBR characteristics that challenge differential protection; this will contribute to development of guidance to differential protection application in power grids with IBR and to differential elements settings.

2 Model of power system with IBR

The configuration of the study system is represented by figure 1. It is composed of a solar power plant tied to an equivalent grid source (S) via a 110 kV transmission line (L). The solar power plant includes a single equivalent IBR representing the aggregated capacity of multiple photovoltaic modules, the equivalent transformer 0,69/10,5 kV (T2) interfacing the IBR to the collector grid, the equivalent collector system (CS), the station transformer 110/10,5 kV (T1) with grounded neutral point at a high voltage side. The study system basic specifications are shown in table 1.

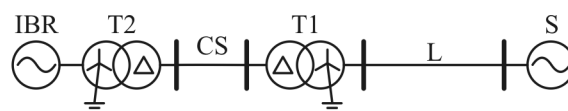


Fig. 1. Configuration of study system with IBR.

Typically, in practice a grid source is much stronger than an IBR source, due to this differential protection operation conditions are almost the same as on a single-feed transmission line. Many papers analyze exactly such cases. Under the scope of this study, considering cases with approximately equal fault current contributions from an IBR and a grid source is of the most interest (weak grid source, long transmission line,

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high-capacity IBR). Considering such a case, an IBR is expected to have a greater impact on differential protection performance.

Table 1. Basic specifications of the study system elements.

Parameter	Value
E.m.f. of grid source S, kV	110
Resistance of grid source S (reactive), Ohm	12,7
Line L length, km	80
Transformer T1 rated power, MVA	120
Equivalent resistance of collector system CS (active/ reactive), Ohm	0,011/0,009
Transformer T1 rated power, MVA	126
IBR rated power, MVA	100

For this study the IBR is represented by a nonlinear controlled current source (Figure 2). The source current is dependent on the algorithms and settings of the inverter control system. The current source is considered ideal; all the constraints on the magnitude and phase of currents come from the control system algorithms. The described model is mainly focused on steady-state conditions allowing for illustrative analysis of the IBR impact on short circuit conditions and for evaluating the quality characteristics of the differential protection performance under the various scenarios of the IBR control system operation. It should be noted that for detailed study of differential protection performance considering operation features of protection's software and hardware functions as well as for relays hardware-in-loop testing it is necessary to use a more detailed IBR model which is suitable for electromagnetic transients analysis in three-phase frame and considering fast transients within an electronic converter and its controls loops.

The mathematical equations for the IBR model are derived for a two-phase rotating direct-quadrature "d" and "q" axis; rotating frequency of the axis is the same as the grid frequency. The d, q – current components are dependent on the algorithm and settings of the inverter control. Different control scenarios are considered: active power level is the maximum of the plant power nominal rating; active power and reactive power are adjusted to a reference values; voltage support at the IBR connection point.

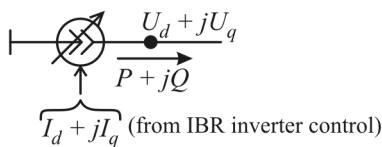


Fig. 2. IBR model.

In many practical cases, during power system normal operation and faults (including unbalanced) inverters contributes only three-phase symmetrical positive sequence currents; however, inverters may also be required to contribute a negative sequence current components during unbalanced events dependent on the negative sequence voltage measured at the inverter connection point.

As follows from the above, the source currents can be generally described by the following matrix equation:

$$\begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d2} \\ I_{q2} \end{bmatrix} = \begin{bmatrix} \frac{U_{d1}}{U_{d1}^2 + U_{q1}^2} & \frac{U_{q1}}{U_{d1}^2 + U_{q1}^2} & \frac{(1-U_1) \cdot U_{q1}}{U_1} & 0 & 0 \\ \frac{U_{q1}}{U_{d1}^2 + U_{q1}^2} & \frac{-U_{d1}}{U_{d1}^2 + U_{q1}^2} & \frac{-(1-U_1) \cdot U_{d1}}{U_1} & 0 & 0 \\ 0 & 0 & 0 & U_{d2} & -U_{q2} \\ 0 & 0 & 0 & U_{q2} & U_{d2} \end{bmatrix} \times \begin{bmatrix} P_0 \\ Q_0 \\ K_U \\ K_2 \cos \varphi_2 \\ K_2 \sin \varphi_2 \end{bmatrix}, \quad (1)$$

where $U_1 = \sqrt{U_{d1}^2 + U_{q1}^2}$ – a module of the positive sequence voltage; I_{d1}, I_{q1} – the d,q-components of the positive sequence current; I_{d2}, I_{q2} – the d,q-components of the negative sequence current; U_{d1}, U_{q1} – the d,q-components of the positive sequence voltage; U_{d2}, U_{q2} – the d,q-components of the negative sequence voltage; P_0 – the reference value of the IBR active power; Q_0 – the reference value of the IBR reactive power; K_U – the droop gain for the reactive positive sequence current component control based on the positive sequence voltage deviation; K_2 – the droop gain for the negative sequence current component control based on the negative sequence voltage; φ_2 – the reference negative sequence current phase angle relative to the negative sequence voltage phase.

To perform further calculations, it is suitable to align the positive sequence voltage phasor at the IBR terminals with the "d" axis; in this case:

$$\begin{aligned} U_{d1} &= U_1; & U_{q1} &= 0; & U_{d2} &= \operatorname{Re} \left(\frac{U_2}{e^{j \arg(U_1)}} \right) \\ U_{q2} &= \operatorname{Im} \left(\frac{U_2}{e^{j \arg(U_1)}} \right), \end{aligned} \quad (2)$$

where U_2 – vector of the negative sequence voltage; $\arg(U_1)$ – initial positive sequence voltage phase (before it aligning with d-axis).

Assuming (2) the initial equation (1) can be defined as the following simplified equation:

$$\begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d2} \\ I_{q2} \end{bmatrix} = \begin{bmatrix} \frac{1}{U_{d1}} & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{U_{d1}} & -(1-U_{d1}) & 0 & 0 \\ 0 & 0 & 0 & U_{d2} & -U_{q2} \\ 0 & 0 & 0 & U_{q2} & U_{d2} \end{bmatrix} \times \begin{bmatrix} P_0 \\ Q_0 \\ K_U \\ K_2 \cos \varphi_2 \\ K_2 \sin \varphi_2 \end{bmatrix}, \quad (3)$$

The IBR phase currents can be described based on their d,q-components using the following equations:

$$\begin{aligned} \underline{I}_A &= I_{d1} + jI_{q1} + I_{d2} + jI_{q2} \\ \underline{I}_B &= I_{d1} \frac{\sqrt{3}}{2} - I_{q1} \frac{1}{2} - I_{d2} \frac{1}{2} - I_{q2} \frac{\sqrt{3}}{2} + \\ &+ j(-I_{d1} \frac{\sqrt{3}}{2} - I_{q1} \frac{1}{2} + I_{d2} \frac{\sqrt{3}}{2} - I_{q2} \frac{1}{2}), \quad (4) \\ \underline{I}_C &= -I_{d1} \frac{1}{2} - I_{q1} \frac{\sqrt{3}}{2} - I_{d2} \frac{1}{2} + I_{q2} \frac{\sqrt{3}}{2} + \\ &+ j(I_{d1} \frac{\sqrt{3}}{2} - I_{q1} \frac{1}{2} - I_{d2} \frac{\sqrt{3}}{2} - I_{q2} \frac{1}{2}). \end{aligned}$$

If d,q-current components from (4) are calculated according (2), (3), phase current angles will be obtained in a reference frame with positive sequence voltage aligned with d-axis.

There is no zero sequence current components in currents, because the IBR is tied to the grid via “star-delta” connected winding transformer.

3 Analysis of differential protection performance

A number of typical scenarios of the inverter control and anticipated differential protection performance will be discussed further.

The conventional percentage-restrained differential protection algorithm is taken; the criterion for the relay operation is following:

$$\begin{cases} I_{DIFF} \geq I_{DIFF.MIN} \\ I_{DIFF} \geq K_{RESTR} \cdot I_{RESTR} \end{cases}, \quad (5)$$

where I_{DIFF} – the differential current which is a module of the phasor sum of the currents at the line terminals; $I_{DIFF.MIN}$ – the minimum pick-up value of the differential current; K_{RESTR} – the slope coefficient of the protection restrained characteristics; I_{RESTR} – the restrained current.

The restrained current can be calculated in different ways; one of the ways – as a module of the difference of the current vectors at the line terminals. To ensure minimum protection sensitivity (sensitivity coefficient is more than 2 p.u.*) for single-infeed line operation taking into account the protection restrained characteristics, the slope coefficient should be accepted equal to 0,5 p.u.

4 The first control scenario. The inverter contributes maximum active power

In this case the following values describing the inverter control are used in the equation (3): $P_0 = 0,75$ p.u., $Q_0 = 0$ p.u., $K_U = 0$, $K_2 = 0$.

An internal two-phase fault on the transmission line L near the IBR side is simulated. The current phasors at the both line terminals are shown in figure 3. The currents contributed from the IBR for the unbalanced fault are three-phase symmetrical currents; the currents

contribution from the grid is generally typical for an unbalanced event, however, the phase difference of the faulted phase grid currents is significantly less than 180° due to the IBR impact. The phase differences of the currents at the line terminals are 122° for “B” phase and 157,6° for “C” phase; this is not typical for faults in grids with conventional sources where the currents measured at the two terminals are nearly in phase. Because of the larger phase difference of the currents, the differential current becomes smaller, and the restrained current (with the accepted calculation approach) increases. This significantly reduces the protection sensitivity and can eventually results in protection failure to detect a fault.

The differential currents of the faulted phases for the considered case are illustrated by the dotted lines in figure 3; in this case the sensitivity coefficients are 1,16 p.u. for “B” phase, protection elements in “C” phase doesn’t operate. It should be noted that if the IBR source is stronger (with respect to the grid source capacity), the protection elements in the both phases may not trip for the considered event and the inverter control scenario.

5 The second control scenario. The inverter control supports voltage at the IBR terminal

In this case the following values describing the inverter control are used in the equation (3): $P_0 = 0,75$ p.u., $Q_0 = 0$ p.u., $K_U = 6$, $K_2 = 0$.

The current phasors at the both line terminals for the BC-fault on the transmission line L near the IBR side are shown in figure 4. If the inverter contributes to voltage support (coefficient K_U increases), the symmetrical currents contributed from the IBR rotates clockwise. In this case the current phase’s relationships at the line terminals are more suitable to the differential protection better performance. Thus, the phase differences of the currents at the line terminals are 6,9° for “B” phase and 88,5° for “C” phase; the sensitivity coefficients are 12,2 p.u. for “B” phase, 2 p.u. for “C” phase.

6 The third control scenario. The inverter contributes maximum active power with a negative sequence current component in a case of an unbalanced event

In this case the following values describing the inverter control are used in the equation (3): $P_0 = 0,75$ p.u.,

$Q_0 = 0$ p.u., $K_U = 0$, $K_2 = 3$, $\varphi_2 = -90^\circ$ (the negative sequence current leads the voltage by 90°).

The current phasors at the both line terminals are shown in figure 5. As previously, the BC-fault on the transmission line L near the IBR side is simulated. The currents contributed from the IBR are nonsymmetrical due to the negative sequence current component injected by the inverter; in this case the IBR currents look more

* calculated as the ration between actual differential current and protection pick-up differential current

typical for an unbalanced event. In comparison with the first scenario the line terminals currents phase relationship are more suitable for protection effective performance (the phase differences: $81,4^\circ$ for “B” phase

and $117,9^\circ$ for “C” phase), the “C” phase differential current also increases due to current magnitudes difference. The sensitivity coefficients are 2,3 p.u. for “B” phase, 1,8 p.u. for “C” phase.

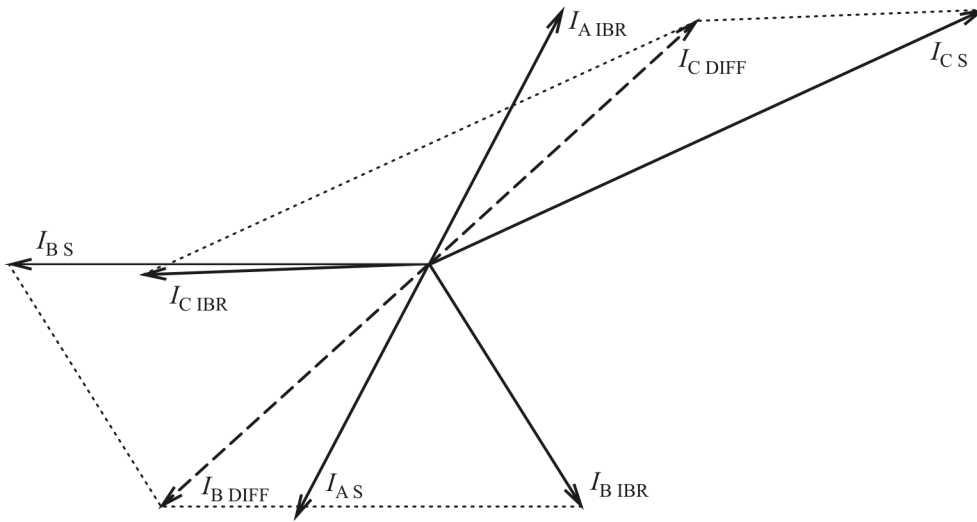


Fig. 3. The current phasors for two-phase fault (scenario 1).

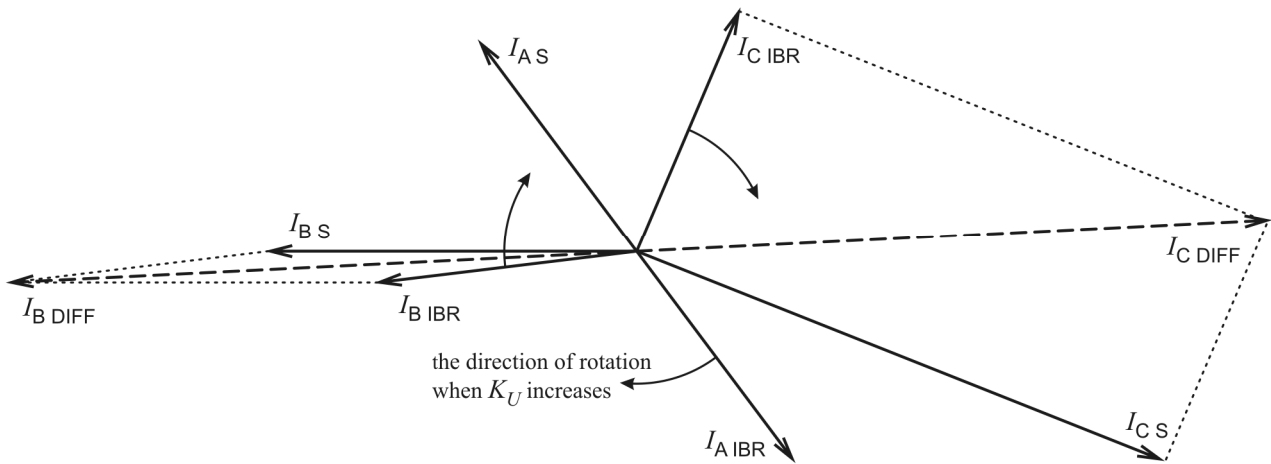


Fig. 4. The current phasors for two-phase fault (scenario 2).

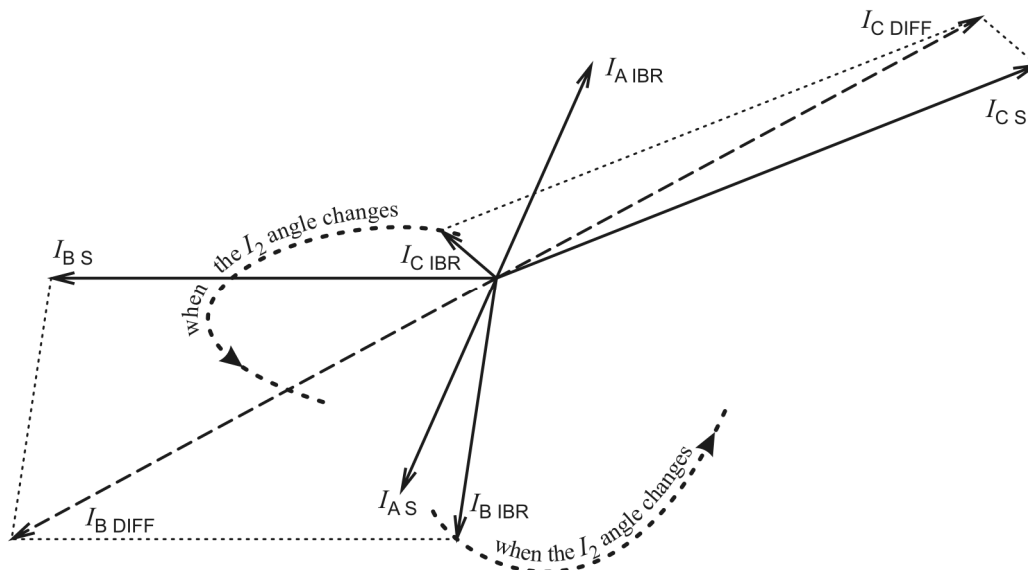


Fig. 5. The current phasors for two-phase fault (scenario 3).

It should be noted that the negative sequence current contributed by some inverters can have a different frequency than the negative sequence voltage [5]. In this case, the negative sequence current phase angle φ_2 in the equation (3) becomes variable. The faulted phase current phasors rotations due to φ_2 variations are illustrated in figure 5 by dotted bold lines. For a certain value of the φ_2 angle, the phase currents become close in magnitude and the phase difference between their phasors becomes large. Such a feature of the inverter injected negative sequence current can result in protection delayed operation (throughout φ_2 angle variations in the range of the unsuitable values) as well as in protection blocking elements activation, assertion of additional restriction algorithms activating secure protection settings and protection failure to operate.

7 Recommendation on the application of the transmission line differential protection

In the case, if grid source is much stronger than IBR source, the inverter control scenario doesn't significantly impact; differential protection operation conditions are almost the same as on a single-infeed transmission line.

In the case, if with the fault current contributions from IBR and grid source are approximately equal, it becomes necessary to perform faults studies considering inverter control algorithm and inverter control settings to evaluate differential protection performance and to pick up protection settings. For that, it is enough to perform steady-state short circuit analysis on one or a series of time intervals; the related calculations can be performed using engineered methods based on the math equations provided in the paper.

The research results presented in the paper revealed that the most unsuitable operation conditions of the differential protection occur when the inverter control is configured to contribute maximum real power and doesn't inject negative sequence current in a case of unbalanced events. The protection sensitivity may be significantly less than for single-infeed transmission line operation; in some cases, protection may even lose dependability. It should be noted, that the task of ensuring differential protection effective performance may be as well addressed in the other way – by assigning the requirements to inverter control.

The possible combination of the various factors (capacities of the IBR and grid source is close, inverter control scenario is unsuitable for ensuring protection sensitivity, there is no possibility to change inverter control and protection settings) can cause the need for solutions to improve the differential protection algorithm.

8 Conclusion

This paper presented the approach to evaluate IBR impact on differential protection in steady-state conditions under typical inverter control scenarios. By

using the math equations provided in the paper, the differential protection operation is studied in the case of the power system composed of the IBR and the grid source of equal capacities; the factors affecting the differential protection operation are revealed and estimated; the case examples are given that illustrates the loss of protection sensitivity and protection failures to trip. The brief guidance is given concerning application of differential protection and considering IBR operation features to study protection operation and to pick up protection settings.

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