Overcurrent Protection Assessment with High PV Penetration in a Distribution Network

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Abstract- This paper investigated the potential protection issues associated to high PV penetration. Impacts of different penetration level (20%, 40% and 60%) on two different network configurations (centralized and distributed) have been modelled and analyzed using PSCAD/EMTDC software. The inverter controller response was assessed under grid faults integrating LVRT capabilities. The presence of PVs in the grid has led to identify nuisance tripping or false tripping in high penetration condition of Solar PV. Moreover, and most important presented in this research is the operational impacts study of PVs on the protection coordination which has been done for a satisfied backup and selectivity protection with a reliable and effective relay setting suggestion. In the simulation results, the most impactful fault is with the centralized case (fault3) causing the protective device to trip faster, which tends to be harmful for high penetration. The severe increase of the available short circuit current due to the proximity of PVs can impact neighbouring overcurrent protection devices, which implies a potential use of protection devices with directional capabilities. Some measures have been recommended as well to mitigate the PV impacts with an acceptable penetration level.

Keywords Distribution network; Photovoltaic; distributed generators; overcurrent protection; protection coordination; relay setting.

1. Introduction

Solar energy utilization is dramatically growing. The main reason which eventually boosted PV penetration is the response to the desire of societies to address the challenges of climate change and contributes to achieve the aim of many countries to enhance energy security as well as several others. One of the most significant global trends is the continued cost decline of PV components and PV-generated electricity, which amongst many others is driving PV adoption by majority of societies today. In [1], Electric power distribution is considered as being the final stage in the delivery of electric power connecting the transmission system to the end-consumers. In passive radial networks, power flows from the main utility downwards to loads [2]. From a single point of power injection configuration (radial distribution system) to a networked or looped architecture, Distribution Systems met a lot of progress in addressing the main concern of the power demand growth [3]. The key to obtain a steady-state operation of electric power systems is the so-called Distribution System Analysis which is getting more and more complex (from a simple drop voltage and short circuit evaluation to calculations of power flow) [4]. Power flow and short circuit analysis represent the two main analyses performed in power system to address failure mechanism [2, 5] and [6] classified the types of DGs and defined them as small (renewable) electrical sources generally connected to the grid and relatively close to loads they supply electrical power as well. Despite its benefits in terms of reliability improvement and as an effective mitigation to shortage risks encountered in the conventional radial distribution network, DGs have raised many concerns that have always attracted the attention of engineers on the fact of integrating Embedded Generation to the Distribution Grid [7, 8].

But to achieve such optimization with positive expected results, deep studies have to be conducted for the sizing and the better location of each small DG units (insuring its good coordination with the existing network) [6,7]: any inconsideration of these two elements can

consequently result to some abnormalities such as increases in power system losses, voltage drop, harmonics and voltage quality degradation [9]. In the paper [10] is proposed a curve optimization approach for the microgrid protection using Directional Over Current Relays (DOCRs). Investigating the possible challenges that may rise due to integration of PVs on the existing distribution networks, the shorts circuit current level with respect to variation in MW integration is presented in [11].

As our study is focused on PV penetration, the impact of PV intermittency represents one of the biggest drawbacks of Distributed Generation with PV [12]. Listed amongst the influencing factors in the change of solar energy production output, the local weather pattern and the structure of the PV panel (centralized/distributed) may cause the grid to experience voltage instability, which will result to overvoltage affecting critical devices involved in the regulation and protection of the entire Distribution System [7].
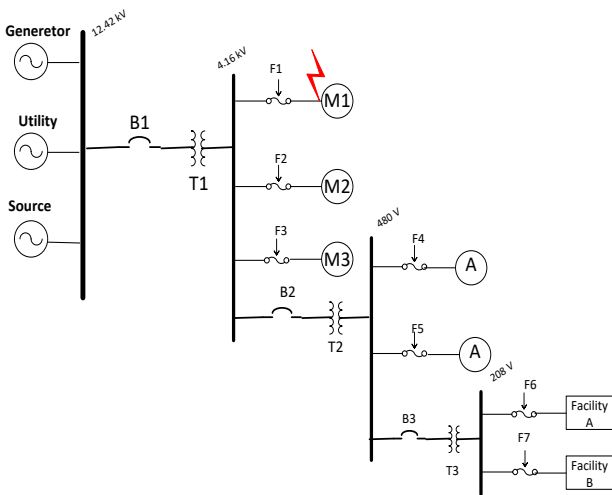

Fig. 1. Coordination protection.

In [13] is defined protective relaying as a "non-productive" item that is not useful during the normal operation of the system till the moment one of the undesirable situation occurs. It involves devices such as relays, breakers, reclosers and other overcurrent protective devices (Fuses) which benefits are to minimize or prevent damage to faulted components, and to minimize the seriousness and duration of the fault interference in normal operation of the non faulted components of the power system. Putting them together in a system raises questions on "Protection Coordination" and "Zone of Protection", highlighting the proper-function characteristics including; sensitivity, selectivity, speed and reliability [14,15]. In [16] is given a review of the protection strategies that are incorporated in microgrids with integrated with DGs.

In power system, protection coordination plays a great role. But what is coordination and why coordinate at all are the major questions to answer. The first thing to bear in mind is the need to reduce exposure and isolate a problem. The coordination can be essentially defined as the concept of minimizing and isolating the problem such a way that the duration of the outage is minimal. This paper is going to firstly investigate the impact that different configuration

of PV penetration may have on the protection of the distribution system and secondly, identify the potential coordination problems that can rise from high penetration of PV. Thirdly fault analysis and a comparison study with and without PV connection under different network configuration. And finally, suggest a protection scheme with a better coordination of protective devices, taking in account the majority of issues encountered in Distribution Networks with high PV penetration (in both centralized and decentralized architecture).

2. Grid-connected PV System Modelling

A Grid-connected PV system is essentially constituted of a set of PV modules which are connected to a converter (converting electrical energy from DC to AC). Here, the irradiance and the temperature are the main factors influencing the electricity power produced by the PV system.
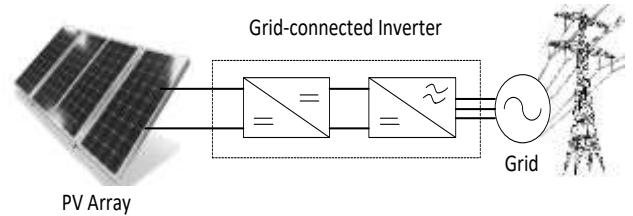

Fig. 2. Grid-connected PV system

As shown in Fig. 2, it has the ability to be connected to the grid and to loads directly reducing the dependency on fossil fuel-based Generator.
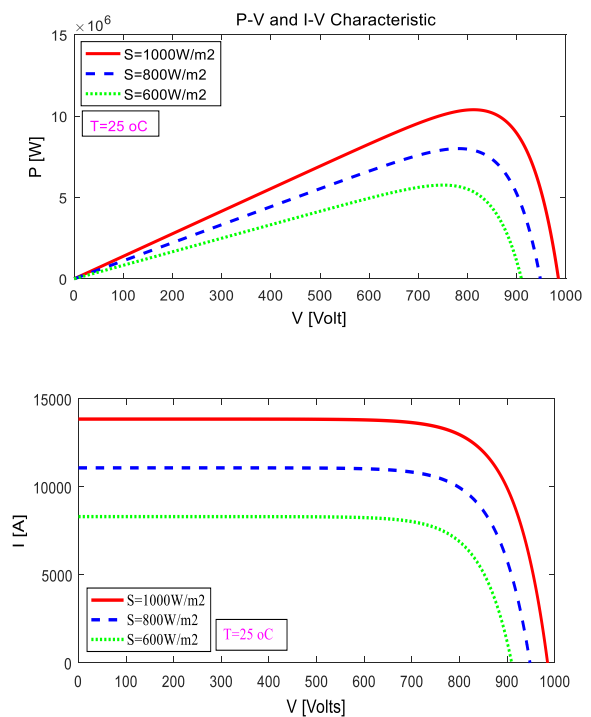
2.1. PV array

Fig. 3. P-V and I-V Characteristics

PV array is the interface capturing the primary energy. Although it represents an important element on the energy conversion it will just be seen as a source of electrical energy.

The characteristic of the PV module is usually provided by the manufacturer and the interconnection of modules used to form an array of PV modules to reach the specified voltage and current compatible with the power inverter. Fig. 3 shows the I-V curve presenting a non-linear characteristic. The most important is the relationship given by I and V expressing the output voltage delivered in function of the current produced.

It can be shown that the maximum power point defines the maximum operating voltage. A PV cell will behave differently, depending on its size or type of load connected to it, and the intensity of sunlight (illumination). The I-V and P-V characteristics of a PV cell are described by the various operating currents and voltages considering different environments [17-18]. Assuming that the cell is exposed to sunlight, but in an open circuit configuration (not connected to a load), no current will possibly be flowing through the cell and the voltage across the PV cell will increase to its maximum.

2.2. PV Inverter

Solar energy reaches the transformer only after being converted by the inverter. This can only be done through some conversion stages and regulations. [9] Gives a descriptive approach of inverter topology choice which can be done or studied according to the application and the scale of PV systems. [8] Introduced different PV configurations including Central-plant Inverter, multiple-string DC-DC converter, multiple-string inverter and module integrated inverter. Based on the power conversion stages, the grid connected PV inverters can be classified into three groups: single-stage inverter, double-stage inverter, and three-stage inverter.
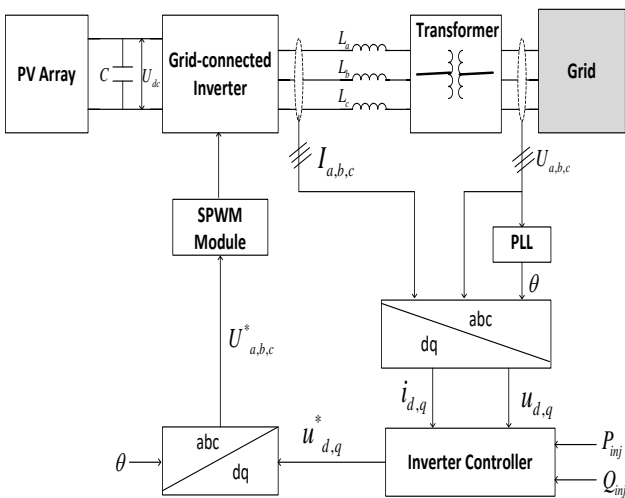

Fig. 4. Inverter control strategy

The structure of the PV grid-connected system under discussion will adopt the single-stage three-phase grid-connected inverter structure, with PV arrays (formed by

several PV cells in serial and parallel connection), inverter, filter and transformer.

A three-phase current is injected to the grid with the help of a rotating "d-q" frame to control the injected current. Operating under a unity power factor insures the synchronism between the injected current and the grid voltage. The signal synchronization has to be done not only with the current and voltage but also with the grid frequency which will contribute to match the reference current and the injected current to the grid [19]. Filters are usually used to attenuate the high frequency harmonics and to avoid any propagation to the power system grid. Fig. 4 shows a structure generally applied with grid-connected inverter based on a simple PQ control.

Active and reactive powers injected to the grid can be expressed as follow:

$$P = u_d i_{d\,inj} + u_q i_{q\,inj}$$
$$Q = -u_d i_{q\,inj} + u_q i_{d\,inj} \tag{1}$$

Where u_d, u_q are the d-q voltages at PCC of the grid side of the transformer. i_{dinj} and i_{qinj} are the d-q injected currents to grid. For computing the reactive power (Q) it can be noticed that the cross coupling of u_q and i_{qinj} but by locking the grid frequency, the uq can be forced to zero resulting to the simplified following equations;

$$P = u_d i_{d\,inj}$$
$$Q = -u_d i_{q\,inj} \tag{2}$$

Under the assumption that the voltage at the PCC is kept constant, the equations above show that i_{dinj} and i_{qinj} are used to control the Active and reactive powers injected to the grid.

2.3. LVRT capabilities

Many incidents like important loads demand connection to the grid, lightning strikes or even short circuits can cause the network to experience voltage drop for a short time. Normally after such short faults DGs can be disconnected immediately and reconnected later after the fault is cleared. But due to some circumstances, especially for the reason that DGs are holding important shares in the Network, such disconnection may result to a blackout. The LVRT will allow large scale Grid-connected PVs to remain connected for that short period supporting the grid for the fault recovery [20-21].

The following expressions are used to govern the LVRT control strategy implemented:

$$I_q = \begin{cases} 0, & 0.9\,p.u \leq V < 1.1\,p.u \\ k\dfrac{V}{V_N}I_N, & 0.5\,p.u \leq V < 0.9\,p.u \\ I_N & V < 0.5\,p.u \end{cases} \tag{3}$$

Most important is the controlled output current during the fault condition,

$$\sqrt{I_d^2 + I_q^2} \leq 1.1 I_N \tag{4}$$

$$k = \left(\Delta I_q / I_N\right) / \left(\Delta V / V_N\right) \geq 2\,p.u \tag{5}$$

Where V and V_N are respectively the amplitude values of the grid instantaneous voltage and the nominal grid voltage, and I_N, I_d and I_q are respectively the nominal current, the active and reactive current.

3. Impact of High PV Penetration on Overcurrent Protection

There are number of issues that one should consider in protection (power system protection in an existing or new feeder) with High PV penetration. Before clarifying each of these faults analysis we should introduce a very important aspect which relies on the behaviour of the PV inverter during the fault; the inverter faults current Characteristic [22-24]. It is a strong function of the controller design of the Inverter [25]. Several assumptions are made in [26] and [27] preventing non-coordination of protection items through some protection techniques [28].

In literature the Fault current is situated in between 110% to 150% of the inverter rated current. This is independent of the PV array rating and solar irradiance. The duration of the Inverter fault current value varies from less than 5ms to 2s (IEEE 1547 limit to disconnect when the Grid fails, to prevent islanding: anti-islanding). Also, per current standard stipulates that, for voltage depth between 0.5 to 0.88 p.u, the inverter can remain connected for 2 seconds. In terms of remote fault, the voltage may not be less than 0.8 p.u so there is a good chance that the inverter remains connected for 2s. The emerging requirements on grid support functionalities (LVRT) typically result in increased duration of fault current and possibly increased magnitude: it makes the inverter to remains connected for longer duration during a fault. To be bear in mind, in most fault cases, 2s is long enough for any protective device to operate.

3.1. Ratings and sympathetic tripping

Ratings violation occurred due to the fact that the PV inverter is injecting current during the fault in the feeder. The amount of current injected in addition to the fault current coming from the source can exceed the current set (re-closers or breakers) especially in a very high penetration scenario. By adding distributed PV and still considering the same rating, those PVs will contribute to the fault current and the total fault current through the Breaker 2 will increase. And the magnitude will be expressed as mentioned in equation (6) and is quite larger than the original set current (I Breaker 2 current magnitude).

$$\left|I_{Breaker2}\right| = \left|I_{2\,Util} + \sum I_{PV}\right| \geq \left|I_{Util}\right| \tag{6}$$

Sympathetic tripping is not that common but consist of an operation for a fault not in his zone of protection but in an adjacent feeder due to the fault current in a reverse direction. This may cause a nuisance tripping because the OCPD blows for a fault in an adjacent lateral.

Fig. 5 illustrates the fault current contribution coming from PV during a fault downstream Breaker 2. Actually, Breaker 2 should be well coordinated with any upstream OCPD and then should blow to clear the fault. A potential nuisance tripping of Breaker 1 can be introduced due to the fault current contribution from PV (in the opposite direction). This scenario will depend on the penetration level and the rating of Breaker 1 because the current coming from PVs is required to be limited. The most probable scenario and mostly invoked in recent researches is the one happening between two adjacent feeders as shown in Fig. 5.
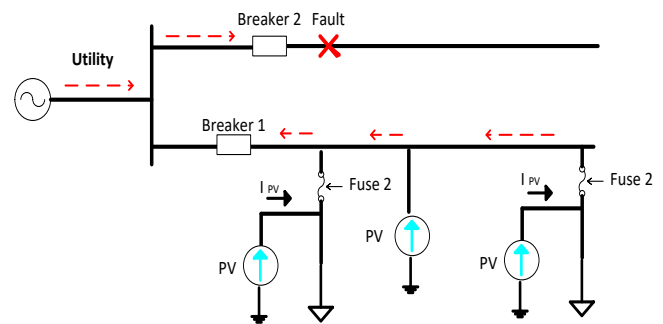

Fig. 5. Sympathetic tripping

Considering a high penetration case, the amount of current flowing through breaker 1 and coming from the distributed PVs may exceed breaker 1 rating, causing it to trip unnecessarily instead of a single action from breaker 2. This situation is likely to happen and requires protective devices with directional capabilities especially in a situation of high penetration of PV to the network.
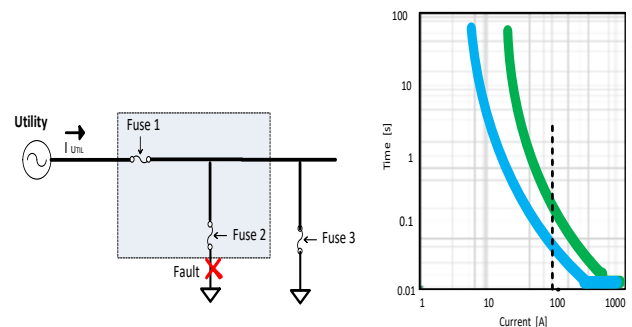
3.2. Loss of coordination

Fig. 6. Fuse-fuse coordination

Protective devices are set to operate in a certain condition including short fault and persistent faults with the aim to minimizing the service outage. The coordination is initiated from the current calculation specially before adding the PV system, so it can happen that the distributed PV inverter added to the grid did not follow a specific

conformity which can lead to loss of coordination because the backup protection may not play its role after the primary and will consequently cause a service outage larger than expected.

Several cases will be discussed in this section. The Fig. 6 shows a fault current of 100 Amps: the same fault current flows through Fuse1 and Fuse2. According to the TCC of both fuses and the coordination applied in this case, it can be observed that it will take longer time for Fuse 1 to start melting, and fuse 2 will rapidly clear the fault before the rest of the installati29on could be affected.

Considering a fuse-to-fuse coordination, When PVs are added to the installations, two cases can give an explicit analysis of fuses behaviour which is mostly function of the location of PVs and the location of faults. In the first case, assuming the position of the PV to be upstream fuse1, the coordination will not be violated (fuse-fuse coordination maintained) because the contribution of PV on the fault current, regardless of the PV capacity, will flow through both fuses and it is essential to make sure that the rating of both fuses are not exceeded due to the addition of the PV. The same analysis is valid if the PV is added after Fuse1 but before Fuse2. In the second case, the PV is located downstream Fuse 2. In this case the location of the fault is very strategic for conducting the analysis because two sub-cases can be studied here;

(1) the case where the fault is located close to the PV (both fault and PV are downstream fuse 2).

(2) the case where the fault is located in between Fuse 1 and fuse 2, and the PV generation downstream the fuse2

Recloser-fuse coordination is another commonly used type of coordination. A proper coordination with the downstream fuses will favourite a reliable functioning of the system. Depending on some configurations, fuse-saving or fuse-clearing, recloser-fuse coordination can be discussed as explained in the following section.

a) Case 1: Fuse-saving strategy

The recloser is characterized by two curves; the fast curve and the slow curve. The superposition of the fuse curve and the two curves of the recloser will determine the region of coordination as shown in Fig. 7.
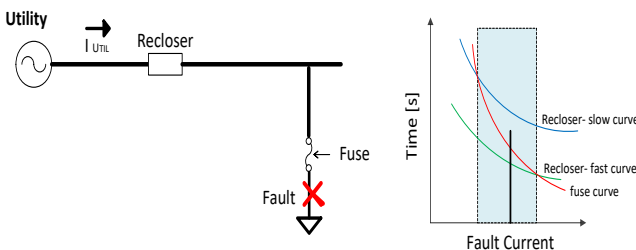

Fig. 7. Fuse-saving strategy (without PV)

Assuming that recloser is programmed for two (2) instantaneous attempts and the zone in blue light is representing the limits where the recloser and the fuse are perfectly coordinated.

This case will be analyzed without the PV penetration where the coordination is well applied and then some observation on the protection coordination will be outlined once PV is added. The graph in Fig. 7 shows a good coordination between the blue, green and red curves representing the recloser-slow curve, the recloser-fast curve and the fuse curve respectively. When the fault indicated by the vertical black line occurs, the recloser will open according to the fast curve (green) of the recloser and then attempts to reclose for the programmed number of times. Depending on the persistence of the fault which can be cleared itself (for a temporary fault) before the fuse blows reclosing the recloser and bringing the system back to the normal operation. In the case the fuse fails to clear the fault after many attempts (for persistent fault for instance), the recloser will simply lock out as its low curve (blue) is indicating and will provide a back-up protection. The fuse-saving strategy can be advantageous for temporary faults avoiding long or total outages but might cause momentary disturbances for a considerable part of the network.

The protection coordination of system can be affected in case of large scale PV integration to the network. By adding a PV generation upstream, the fuse and downstream the recloser can cause (in a certain way) a loss of coordination between the recloser and the fuse. The fact of adding the PV will increase the fault current and this may push the set current out of the region of coordination such a way that the fuse could melt earlier which will see the fault before the recloser as shown in Fig. 8 with the red dashed line.
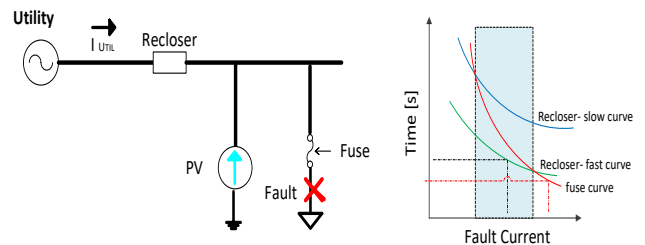

Fig. 8. Fuse-saving strategy (with PV)

$$I_{fuse} = I_{recloser} + I_{PV} \qquad (8)$$

Where,

$$\left| I_{fuse} \right| > \left| I_{recloser} \right| \qquad (9)$$

The potential loss of recloser-fuse coordination in the specific case of temporary fault, will cause an unnecessary blow of fuses and causing outages to an important number of loads unnecessarily. A detailed analysis has to be done on recloser-fuse coordination with high PV penetration especially when the fuse-saving strategy is implemented.

b)   Case 2: Fuse-clearing strategy

In the previous case, the miscoordination might result to a momentary outage for a very large number of customers for a temporary fault and to avoid this, another method known as Fuse-clearing strategy is used. The recloser is set only with its slow curve and that curve is always above the fuse curve (for the fuse to clear the fault first). PV generation integrated to the system will simply improve the situation under the fuse-clearing strategy. Because the contribution of the PV on the fault current will make the fuse to operate faster (no need for a separate investigation for a High penetration).
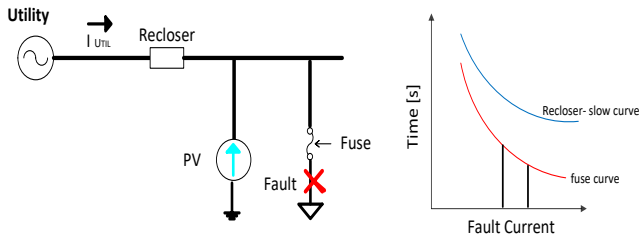
Fig. 9. Fuse-clearing strategy

When a PV system is placed downstream to the recloser, the fault current seen by the recloser for a remote fault actually decreases and therefore the reach of the recloser reduced.
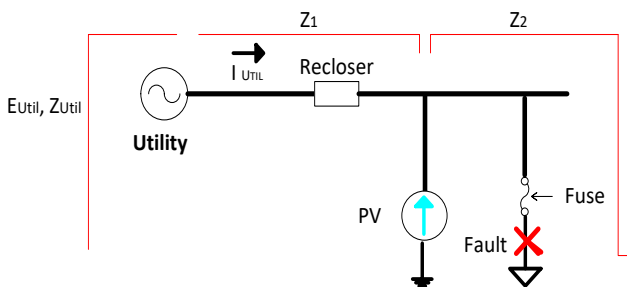

Fig. 10. Recloser reduced reach analysis

It can sound surprising but Fig. 10 can clearly explain that by modelling the simple feeder as follow: - Utility (Thevenin representation: E_{util}, Z_{util}) – the PV (as a current source). The current before adding the PV is calculated and after adding the PV, it can be noticed a decrease in value (the calculation of fault current seen by the recloser). The same analysis can be done with a relay replacing the recloser.

$$I_{recloser\_without\_PV} = \frac{E_{Util}}{Z_{Util} + Z_1 + Z_2} \quad (10)$$

$$I_{recloser\_with\_PV} = \frac{E_{Util}}{Z_{Util} + Z_1 + Z_2} - \frac{Z_2}{Z_{Util} + Z_1 + Z_2} I_{PV} \quad (11)$$

When a recloser is selected and its settings determined, it is done such that the recloser pickup current is less than the minimum fault current due to fault at any of the remote end in its zone of protection causing the reduction of the zone of protection the recloser is supposed to cover as shown in the Fig. 11. But for this type of high penetration problem, a solution would be to change the

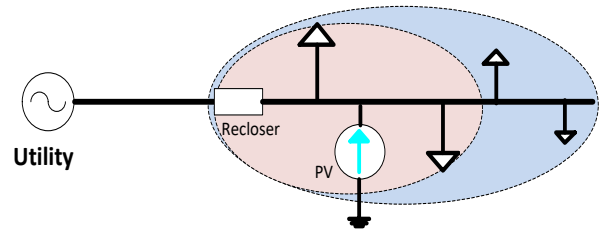recloser settings, or alternatively to think of adding another recloser.

Fig. 11. Recloser reduced reach illustration

4. System Simulation and Overcurrent Protection Coordination Fault Analysis

The design of a good control strategy for PVs helps to limit the current contribution during fault situation. But once dealing with large scale PV, especially when they are equipped with LVRT capabilities which allow the inverter to be connected to the grid during voltage sag, the current contribution from the grid-connected inverter (reactive current support for the grid fault recovery) during the voltage drop might be troublesome [29]. This fault current contribution from the grid-connected PV in high PV penetration can have impacts on the main grid protection devices [30]. Relays and other devices such as recloser are sometimes designed and set for a specific faulty current value (dictated by the short-circuit analysis without PV penetration). Adding PV with an important capacity to the distribution network may request new settings because the fault contribution may reduce the reach of the upstream protective devices or cause them not to operate properly.
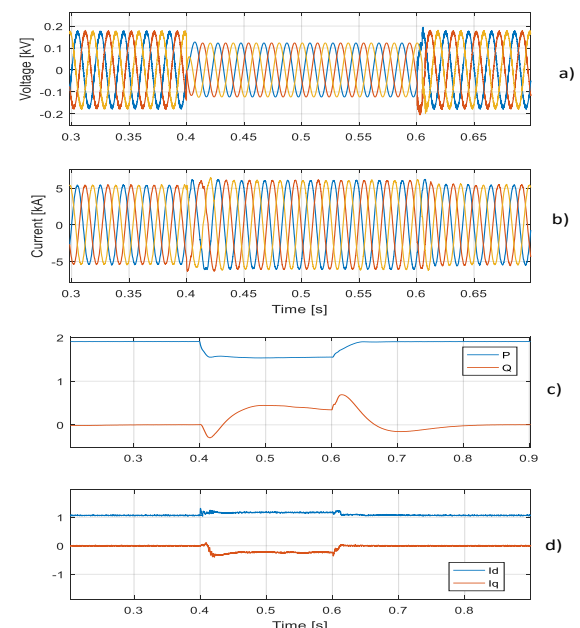
4.1. VRT control response

Fig. 12. Inverter response upon voltage sag

The simulation assessing the LVRT control under different voltage sag is presented in this section. As

indicated in Fig. 12, the inverter is initially injecting a power of 2 MW and the reactive power is set to zero. At t = 0.4 s, a three-phase short circuit is applied resulting to a voltage sags down to almost 85% of the nominal voltage value. In Fig. 12 c) the active power references is reduced to almost 1.5 kW during the fault and the reactive power reference is increased to almost 0.5 kVAr. The fault is cleared at t = 0.6 s. The performance of the proposed controller during 85% voltage sag is shown in Fig. 12 d). Its transition when the fault is cleared shows a need of soft switching techniques. It can be observed that in all cases, transitions are occurring with an accurate powers tracking.
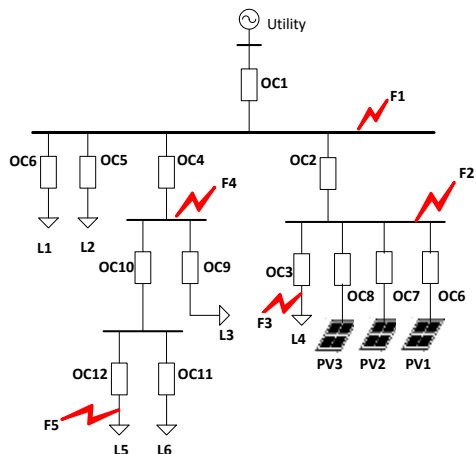
4.2. Centralized architecture

Fig. 13. Centralized PVs

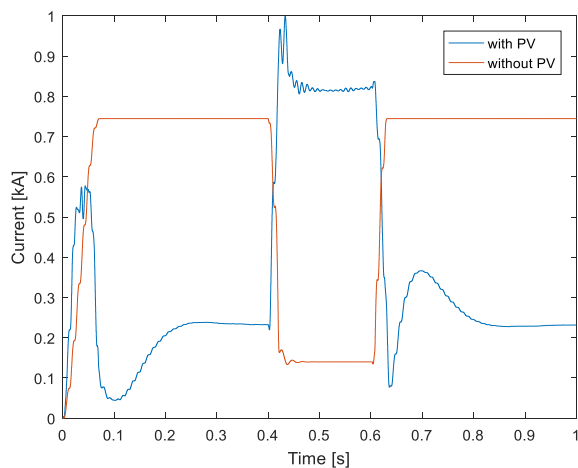*Fault1*: For the observation of fault1,

Fig. 14. OC2 observation under fault1

The consideration of the PV penetration level case of about 60% (very high penetration) with three PV arrays (6 MW of capacity each). Fault1 is applied upstream the concentrated PVs and downstream the overcurrent protective device OC1 from t=0.4s and it is cleared at

t=0.6s. But most important is the behaviour of OC2. Fig. 14 shows the available short circuit current with and without the PV penetration. The blue curve is clearly showing a fault current contribution from PVs.

The trip does not appear to be dangerous enough to result to a miscoordination or a nuisance tripping, but one should pay attention at OC2 which will experience a reverse power flow from the PVs which can unnecessarily trip OC2. OC6, OC7 and OC8 have to be carefully set in order to avoid any undesirable trip.
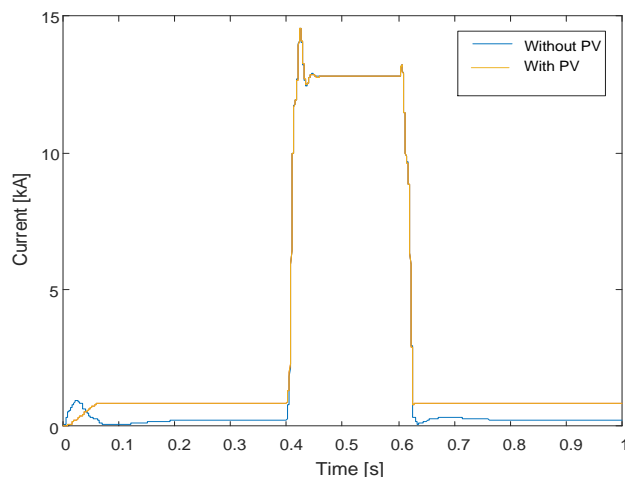

Fig. 15. OC2 behaviour under faultt2

Still, the protection coordination is not affected. The biggest concern here is the power flow design before adding PVs. If the load L4 is design to absorb the entire power coming from PVs, then there is no worry with OC3, if not then power from the photovoltaic generators might totally flow to L4 after OC2 has cleared F2 which might result to a tripping of OC3. An attention has to be paid on OC6, OC7 and OC8 in this case too to prevent any potential rating violation.

The third case is the most interesting case for it shows some very pertinent results. Let us consider the case where the three-phase fault is applied on load L4 located 4km away from the PV generators. A slight increase of the fault current is noticeable but will simply cause OC3 to trip a little faster than in a case of no penetration. Moreover, once considering a fault occurring on a load located close to PVs (hundred meters), a severe increase of the available short circuit at the faulty point can be perceived. This is due to the proximity of the PV generators which are contributing more than a quarter of fault current value when there was no PV penetration. The fault will be cleared after faster for the closest fault applied on load L4, leading to almost an instantaneous trip. This instantaneous trip can be reflected on OC2 because after OC3 clears the fault instantaneously, the power might not find a path to flow and will establish a reverse power flow through OC2 which is not set for such scenario and finally result to a trip of OC2. Directional capabilities in OCPD will be necessary.
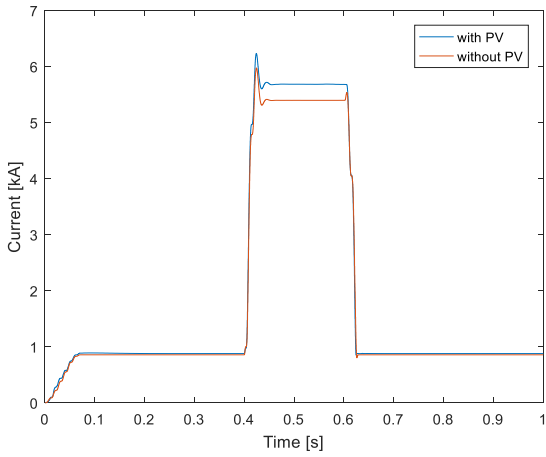
Fig. 16. OC3 observation under fault3

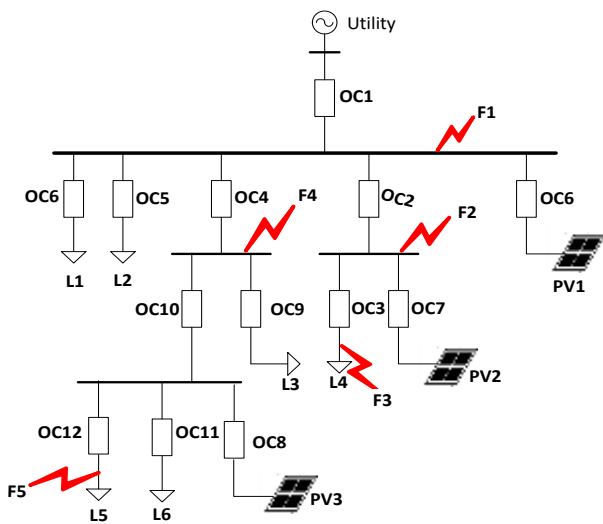### 4.3. *Decentralized Architecture*

Fig. 17. Decentralized

Fault2 is typically demonstrating the impact of the impedance between the fault location and the total sources of the grid. As from now, in the case PVs are dispatched in the network, the total fault current is expected from the grid, PV2 and a very small quantity of current coming from PV1.
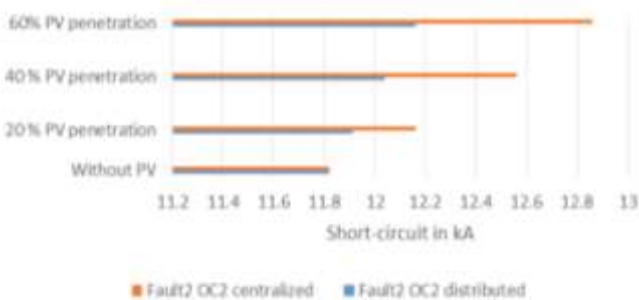

Fig. 18. Fault 2 centralized and decentralized

Fault 2 is very significant with the increase of the level penetration in the centralized case and it may request some setting modifications in a situation of High penetration.

In the present investigation (Fig. 19), the previous case remarks are quite similar and taken in account here.
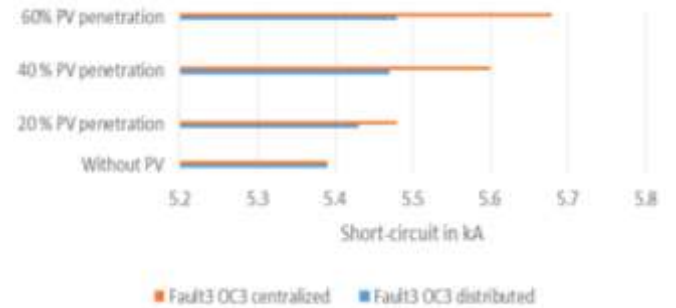

Fig. 19. Fault 3 centralized and decentralized

It can be seen that the huge fault current contribution from the three PVs when the network was configured with centralized PV sources gradually increases with the increase level of PV penetration which clearly imposes some changes in protection settings.

In fault 5, the graph in Fig. 20 is showing an important fault current contribution from once PV3 is connected in a dispatched way.
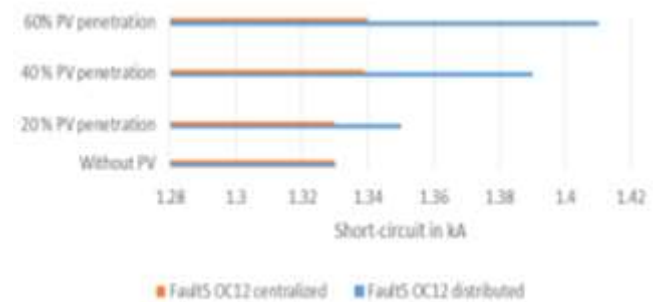

Fig. 20. Fault 5 centralized and decentralized

The more the fault location is getting downstream the main source (close to PV3) higher is the fault current contribution. Here, not only the rated value of the protective device upstream the PV (OC8) have to be carefully set to avoid any sympathetic trip, but two other aspects have to be clearly investigated. The former arrangement of TCC is showing a possible miscoordination between OC12 and OC10 (for they belonged to the same line) which instantaneously trip at the same time when the 2kA fault is sensed.

5. Proposed Network Protection Coordination with High PV Penetration

Having identified issues that can be potential causes of false tripping, sympathetic tripping and eventually miscoordination during the high PV penetration to the network, it sounds suitable to suggest accurate relay

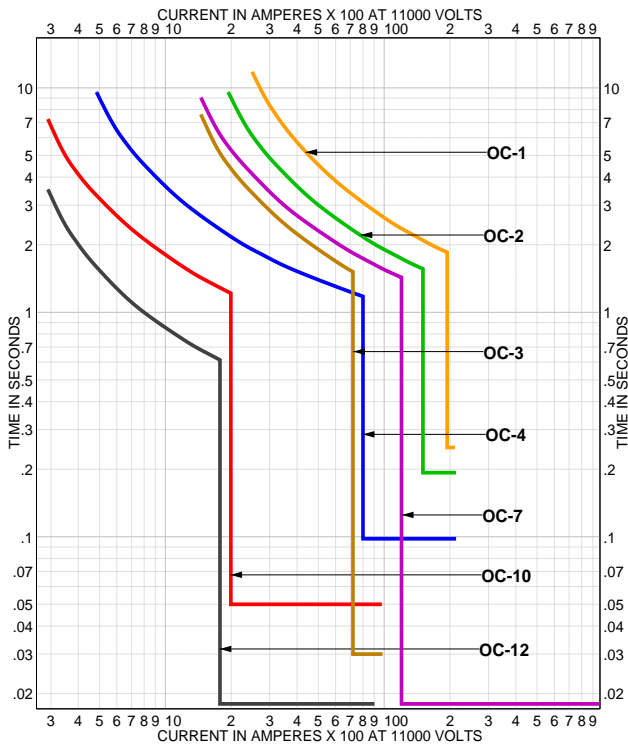settings to ensure a good grid and PV protective devices coordination.

Fig. 21. Time Current Curves

The arrangement of the TCC makes clear the independent operation of each OCPD without any interference with other different branches (feeders).

Two values are interesting for the rating of each Protective device: The operating or nominal current (In) and the highest available short-circuit the protective device can handle (Isc).

$$t_{OC_{i-1}} < t_{OC_i} < t_{OC_{i+1}} \tag{12}$$

$$I_n \leq \frac{2}{3} I_r \tag{13}$$

$$I_{sc} \leq I_{IR} \tag{14}$$

Only RMS values are considered for the relay setting analysis. Integrating the PVs to the grid brought a lot of changes requiring the protective setting values to be carefully chosen. To help the grid-connected inverter to ride through a low voltage fault, The LVRT controller is dictating values to be taken in account for the system to remain well coordinated.

The single line diagram in Fig. 21 shows that the system is well coordinated for the indicated line on the figure at the left, and no miscoordination or other protection issue can be recorded since other aspects have been considered including under/overvoltage protection and under/over frequency. Those modifications will not be necessary in the situation where the network is dealing

with decentralized PV sources. In addition, less OCPD will be needed for changes, as with sources concentrated in the adjacent branches to OC3, not only OC3 will require to be readjusted but OC2 will also request an enhancement due to the possible reverse power flow which can be harmful can mislead the backup protection.
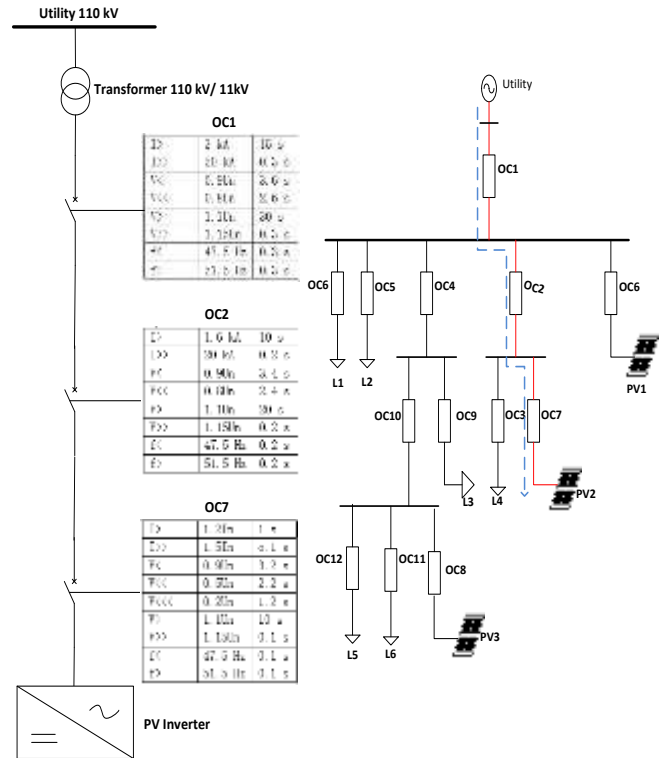

Fig. 22. Proposed protection coordination settings

6. Conclusion

The main focus of this work was to study the impacts of high PV penetration on the overcurrent protection system. The current limitation has been effectively considered in this work. The important amount of the inverter output current is due to large scale of the PV and the primary transformer voltage limited to almost 0.3 kV.

The operating time of circuit breakers, selectivity and coordination with other protective devices have been analyzed with the consideration of photovoltaic generators presence. This short-term voltage drop analysis for different level of penetration has been investigated in order to assess the inverter low voltage ride through capabilities and evaluate the current contribution impacts on the original protection system arrangement. Two network configurations have been subjects of this protection device performance analysis; the centralized arrangement of PVs had the most impactful fault current contribution from PVs with many cases indicating potential false or sympathetic tripping due to the grouped presence of PVs in high penetration. Most important that has been done was the choice of interrupting current ratings corresponding to each circuit breaker after the short circuit analysis. Finally, a distribution network and PV protection coordination has been suggested with the consideration of LVRT controller

function. The inverter controller is responding correctly under fault situation, the level of PV penetration that has acceptable impacts on the distribution network protection is within 20% to 40%. Objectively, coordination protection scheme for system with PV penetration considering the new grid-code requirements considerably improved OCPD performances. The paper points out the difference as compared to the traditional current protection which coordinates the current magnitude and time delay only. Even though they are not commonly used the inverse-time property of fuses are advantageous for a fast operation in a coordination configuration.

Acknowledgements

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