GRID BACKUP PROTECTION ON RENEWABLES SUBSTATION PLANTS: ZONE 3, OVERCURRENT AND OTHER OPTIONS

Carlos Aguilar, GE Grid Automation, Spain
Daniel Patynowski, GE Grid Automation, Spain
Jorge Cárdenas, GE Grid Automation, Spain
Nemanja Vukobrat, GE Grid Solutions, Serbia

SUMMARY

This paper addresses grid backup protection on interconnection lines of renewable plants with transmission network. Renewable plants are characterized by low-inertia generation and they can be considered a weak source. Short-circuit power capability of renewable plants for external faults is limited due to inverter-based generation, which affects to distance protection schemes capability for external fault detections. Overcurrent elements detection capability for external faults will also be limited due to low current fault contribution from renewable plant.

An example of Zone 3 calculation in a real case of a renewable plant will be studied, where a miscoordination based on existing recommendations for Zone 3 protection can occur due to infeed of adjacent lines on remote substations. Expected infeed and high SIR of renewable plant affects also to Zone 2 protection considerations, which will be discussed also on this paper. It will also be explained constraints of phase overcurrent elements usage for grid backup protection on this real case.

To finalize, other options will be considered as remote backup protection. It will be explained overcurrent directional elements with teleprotection schemes based on routable GOOSEs and Wide Area Protection Schemes based on Phasor Measurement Units.

Key words: Grid Backup Protection, Renewables, Zone 3, PMU.

Carlos.aguilar@ge.com

INTRODUCTION

Most common renewable plant configuration is shown in FIGURE 1. Several feeders which comes from Wind Turbine Generators (WTG) or Photovoltaic Plants are connected to a single busbar at Medium Voltage Level. This busbar is connected through a step-up transformer with the High Voltage Grid through a line to closest available substation.

Distances of interconnection line between renewable plant and closest available substation at High Voltage network are generally short, which combined with the low current short-circuit contribution from renewable sources to faults, contributes to have high source impedance ratio at the local relay on renewable plant of interconnection line. This will affect to remote backup protection as explained on following chapters.

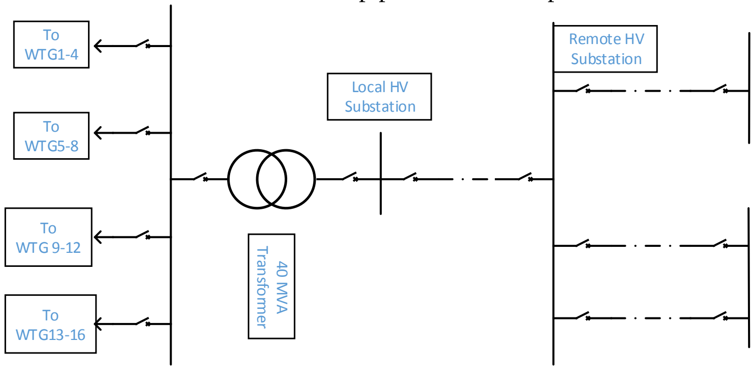

FIGURE 1 – TYPICAL SINGLE LINE DIAGRAM OF RENEWABLE PLANT

BACKUP PROTECTION CONSIDERATIONS

The objective of protection is to remove only the affected portion of plant and nothing else. A circuit breaker or protection relay may fail to operate. In important systems, a failure of primary protection will usually result in the operation of back-up protection. Remote back-up protection will generally remove both the affected and unaffected items of plant to clear the fault. Local back-up protection will remove the affected items of the plant to clear the fault.

Backup protection can, and in many cases does, play a significant role in providing adequate system performance or aiding in containing the spread of disturbances due to faults accompanied by Protection System failures or failures of circuit breakers to interrupt current.

Remote backup requires longer fault clearing times and additional circuit elements are removed from the system to clear the fault. While the latter usually has no worse effect on the transmission system than does local backup relay operation, it does interrupt all tap loads on all lines that are connected to the substation where the relay/breaker fails to operate.

The primary disadvantage of remote backup protection is that it can restrict the amount of load a circuit can carry under emergency conditions. Generally, relays designated as Zone 3 relays provide this remote backup function for phase to phase and three phase faults; however other relay designations may be used to provide the remote backup function.

Historically from a security perspective, there have been several cases where remote backup relays (Zone 3) have been involved in significantly expanding system outages by tripping due to unexpected loading during some system contingencies. Less obvious are many times that remote backup (Zone 3) relays have unintentionally operated to remove uncleared faults from the system or to halt cascading outages.

GRID BACKUP PROTECTION THROUGH ZONE 3

Backup protection philosophy for line protection basically has not changed since the time that distance protection was started to be used as main protection for Transmission lines. That means, more than 60 years ago.

When Distance Protection is used, worldwide, it is accepted and standardized the protection scheme shown in the

FIGURE 2.

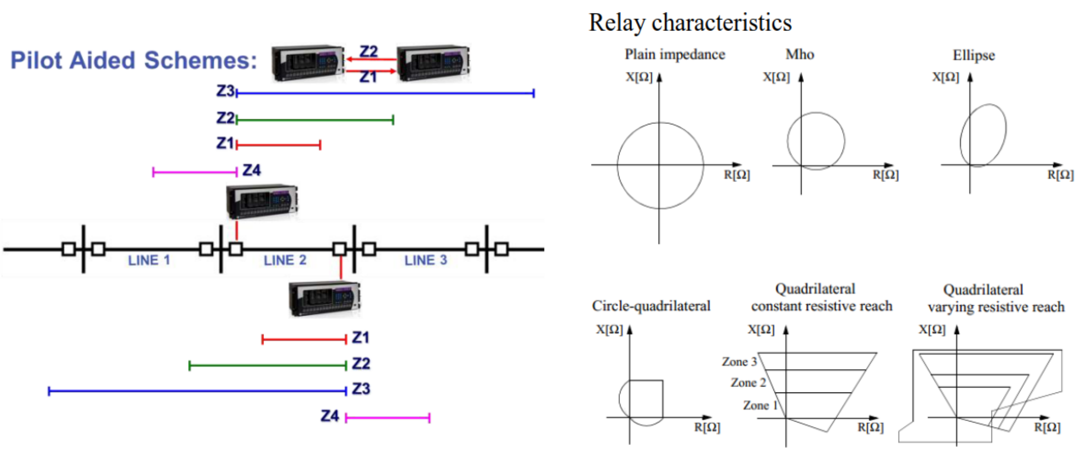

FIGURE 2 – STEPPED DISTANCE COMPLEMENTED WITH PILOT AIDED SCHEMES

Now, any faults that occur on the protected transmission line will be detected by the zones of protection on the relay at each end. These relays will then proceed to open the breaker and clear the fault from their own respective end of the line.

Similarly, each relay will also have ground stepped distance zones of protection, which are identical to that of the phase stepped distance zones. The difference being that the ground distance element is used to detect single phase-to-ground faults.

This scheme is complemented with a Pilot Aided Scheme (POTT, PUTT, Blocking) to cover 100% of the line with fast trip using Z1 and Z2. Z4 is used as complement for Blocking Schemes on in Hybrid Schemes (POTT with weak infeed detection) and time delayed as busbar backup protection.

As an example of grid backup on a renewable plant, it can be seen in

FIGURE 3 current distribution on a fault on an adjacent line on remote substation.

Zone 3 (Z3) protection in relay R_{1-2} is set to over-reach past the end of the longest adjacent transmission line of busbar 2 (remote substation). This third zone is used to act as a remote backup for that next adjacent transmission line, in case the protection on that transmission line fails. To act as a backup and if the impedance of Line 1 and 2 are the same, Zone 3 is usually set to extend to 220%, which is the same point as Zone 2 of the adjacent transmission line. Zone 3 must have a time delay that is longer than the operate time of Zone 2 of the adjacent transmission line. This time delay is typically 1 second.

Limitations of Distance Measuring Criteria:

With only local measurements, and a small-time window, it is difficult to determine fault impedance accurately. For example, if the fault has an impedance ($Zf \neq 0$), then the derivations of previous lectures are no more exact. The impedance seen by the relay R_{1-2} in

FIGURE 3 for fault F also depends upon the current contribution from the remote ends (I_{3-2} and I_{4-2b})

There are infeed and outfeed effects associated with working of distance relays. Recall that a distance relaying scheme uses only local voltage and current measurements for a bus and transmission line. Hence, it cannot model infeed or outfeed properly. Consider the operation of distance relay R_{1-2} for fault F close to remote busbar 2 on line 2-4 in

FIGURE 3.

Due to the configuration of generators and loads, it is seen $\overrightarrow{I_{2-F}} = \overrightarrow{I_{1-2}} + \overrightarrow{I_{4-2b}} + \overrightarrow{I_{3-2}}$

Hence, $\overrightarrow{V_{R1-2}} = \overrightarrow{I_{1-2}} \cdot Z_{1-2} + \overrightarrow{I_{2-F}} \cdot x \cdot Z_{2-4a}$

$$\overrightarrow{V_{R1-2}} = \overrightarrow{I_{1-2}} \cdot (Z_{1-2} + x \cdot Z_{2-4a}) + (\overrightarrow{I_{4-2b}} + \overrightarrow{I_{3-2}}) \cdot x \cdot Z_{2-4a}$$

$$\frac{\overrightarrow{V_{R1-2}}}{\overrightarrow{I_{1-2}}} = Z_{1-2} + x \cdot Z_{2-4a} + x \cdot Z_{2-4a} \cdot \frac{(\overrightarrow{I_{4-2b}} + \overrightarrow{I_{3-2}})}{\overrightarrow{I_{1-2}}}$$

EQUATION 1

Thus, we see that the distance relay at R_{1-2} does not measure impedance $(\boldsymbol{Z_{1-2}} + \boldsymbol{x} \cdot \boldsymbol{Z_{2-4a}})$. If there is an equivalent generator source at busbar 3 and busbar 4, then it feeds the fault current. Thus $\overrightarrow{\boldsymbol{I_{1-2}}}$ and $(\overrightarrow{\boldsymbol{I_{4-2b}}} + \overrightarrow{\boldsymbol{I_{3-2}}})$ are approximately in phase. This is known as infeed effect. From

FIGURE 3, it is clear that infeed causes an equivalent increase in apparent impedance seen by the relay R_{1-2}.

From the relay's perspective, the fault is pushed beyond its actual location and relay R_{1-2} loses sensitivity as remote backup protection. In fact, main problem on renewable plants is that $\overrightarrow{I_{1-2}}$ will be much lower than $(\overrightarrow{I_{4-2b}} + \overrightarrow{I_{3-2}})$ due to low short-circuit capability of the Wind Turbine Generators or Photovoltaic Plants. This itself does not sacrifice selectivity, but relay R_{1-2} perceives fault to be farther away from than its actual location and depending of setting and network topology, fault can be detected or not by backup protection zones.

As per (1), a minimum and maximum infeed factor must be calculated for setting of zone 3. In example shown in

FIGURE 3, zone 3 must be set as follows:

$$\mathbf{115\% \cdot [Z_{1-2} + max\,(Z_{2-3}, Z_{2-4a}, Z_{2-4b}) \cdot k_{max}\,] \leq Z3_{1-2}}$$

EQUATION 2 – ZONE 3 MINIMUM IMPEDANCE

Where $k_{\max}$ is the maximum infeed factor, considering all the infeed currents from adjacent lines on busbar 2 of remote line considered, Z_{1-2} is the line impedance from busbar 1 to busbar 2, Z_{2-3} is the line impedance from busbar 2 to busbar 3, Z_{2-4a} is the line impedance from busbar 2 to busbar 4a and Z_{2-4b} is the line impedance from busbar 2 to busbar 4b.

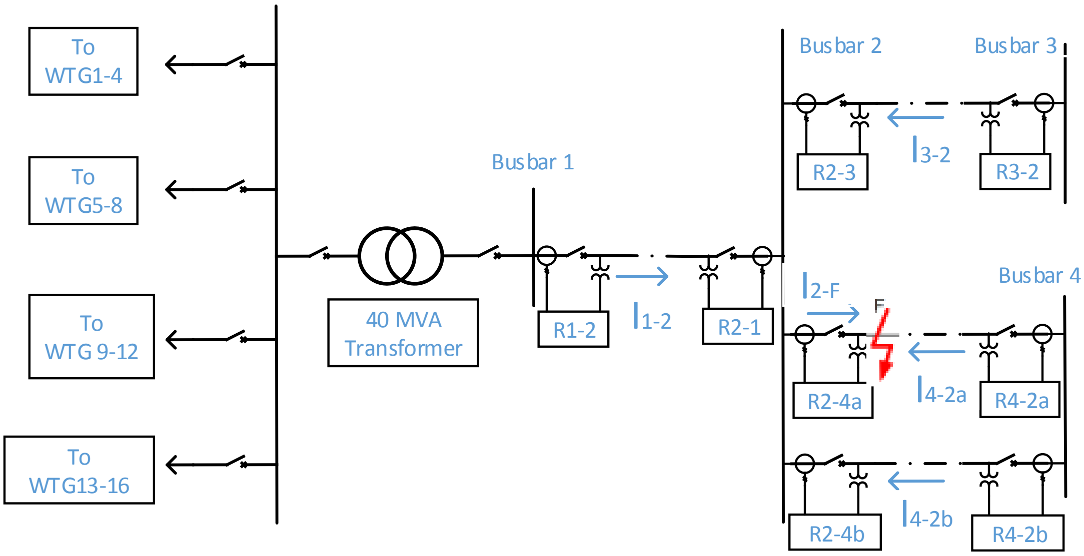

FIGURE 3 – CURRENT INFEED

And with a maximum reach as follows:

$$Z3_{1-2} \leq 85\% \cdot [Z_{1-2} + \min\,(Z2_{2-3}, Z2_{2-4a}, Z2_{2-4b}) \cdot k_{min}\,]$$

EQUATION 3 – ZONE 3 MAXIMUM IMPEDANCE

Where $k_{\min}$ is the minimum infeed factor, $Z2_{2-3}$ is the impedance of zone 2 protection of line from busbar 2 to busbar 3, $Z2_{2-4a}$ is the impedance of zone 2 of line from busbar 2 to busbar 4a and $Z2_{2-4b}$ is the impedance of zone 2 of line from busbar 2 to busbar 4b.

Complying previous equations, it is assured that zone 3 will overreach any of the remote adjacent lines as well as it will not overreach zone 2 of remote adjacent lines, assuring coordination between distance zones.

In (1), it is proposed to calculate maximum infeed factor based on a three-phase fault at 65 % of shortest remote adjacent line. Considering 2-3 shortest line, maximum infeed factor will be $\sum {}^{I_{4-2a}, I_{4-2b}}/_{I_{1-2}}$.

For minimum infeed factor, a similar approach as maximum infeed factor is followed, but considering that remote adjacent line with maximum infeed is disconnected or two lines with maximum infeed are disconnected if substation has more than 5 feeders.

Maximum and minimum infeed factors must be taken into account also for Zone 2 settings on R_{1-2}.

On a real case with a single line diagram as shown in FIGURE **3**, at 45 kV level, a renewable plant had a short circuit current contribution of 439 A to faults at remote end of busbar 2. This value is below the line 1-2 nominal current of 513 A. As well, remote adjacent lines reached up to 9100 A for current infeed on faults closed to busbar 2 on remote adjacent lines. Considering these values, it can be seen that you have easily maximum infeed factors higher than 20 due to low current contribution from renewable plants. Apart from this, if line distance from renewable plant to busbar is short, Zone 3 settings based on EQUATION 2 and EQUATION 3 are even more difficult to comply and considerations based on dependability and security searched with zone 3 must be taken, limiting reliability of zone 3 as remote backup protection.

GRID BACKUP PROTECTION THROUGH OVERCURRENT ELEMENTS

Overcurrent elements can be used as a simple backup for overloading conditions based on thermal ratings of protected line. Nevertheless, this scheme is limited to values above nominal current of protected line, and based on shortcircuit power of renewable plant and fault impedance and distance of remote adjacent lines, fault current of remote backup protection can be easily below the nominal current of protected line. Then, dependability of overcurrent elements is low.

Routable GOOSEs can be used for implementation of teleprotection schemes with remote relays on adjacent lines. Similar approach has been followed in high-speed electric train networks (2).

A remote reverse blocking scheme through routable GOOSE protection scheme is shown in

FIGURE 4, where remote relays R_{3-2} , R_{4-2a} and R_{4-2b} on remote adjacent lines will send blocking signals based on reverse directional ground overcurrent elements to R_{1-2}. If R_{1-2} does not receive any blocking signal, it will trip through forward directional ground overcurrent detection after time delayed defined for backup protection.

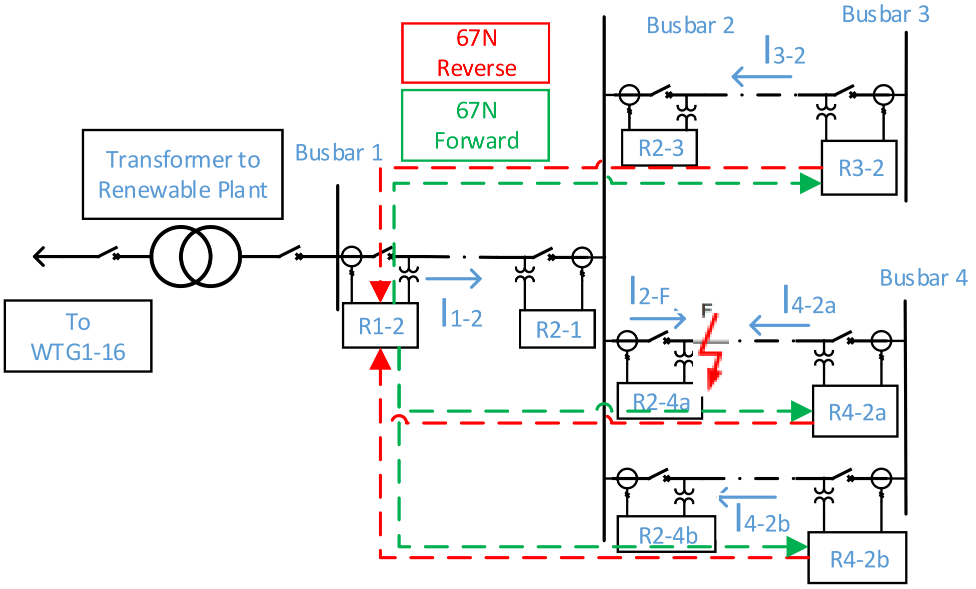

FIGURE 4 – REMOTE REVERSE BLOCKING SCHEME THROUGH ROUTABLE GOOSE

Remote weak infeed scheme through routable GOOSE is shown in FIGURE 5, where remote relays R_{3-2} , R_{4-2a} and R_{4-2b} on remote adjacent lines will send permissive or echoing signal based on forward directional ground overcurrent elements or based on breaker status to R_{1-2}. If R_{1-2} receives a permissive/echo signal from each remote adjacent line, it will trip through forward directional ground overcurrent detection after time delayed defined for backup protection.

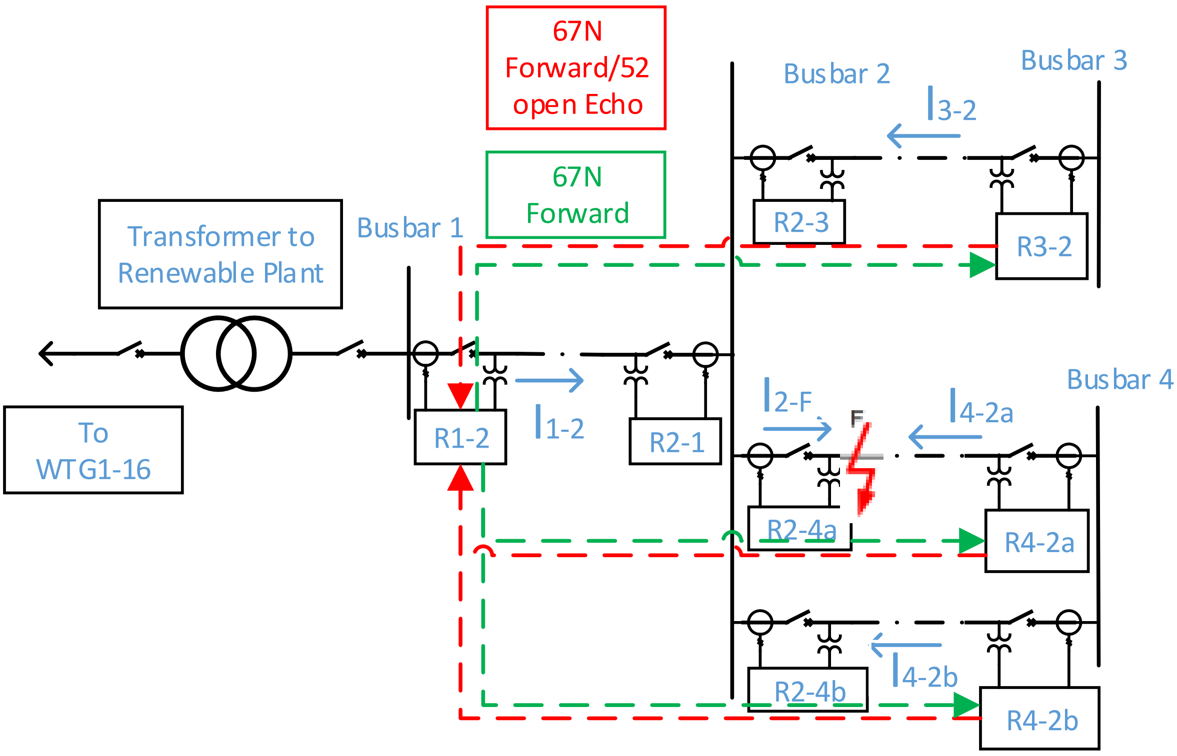

FIGURE 5 – REMOTE WEAK INFEED SCHEME THROUGH ROUTABLE GOOSE

Special care must be taken with direction identification, as suppression of negative sequence components on inverters of renewable generation affect to directional elements and can provoke maloperations of these elements. Some solutions based on flexible directional elements or disabling direction independencies based on negative or zero sequence components has been already presented (3) for proper direction identification. In the coming future and as per new regulations influenced by European Union Network Code Requirements (4), where it is given the TSO the possibility to specify asymmetrical current injection requirements during faults, designs of inverters can be affected and identification of direction based on zero and negative sequence components would also be improved with these new requirements. This is also highlighted in Migrate Project deliverable 1.6 with latest Grid Code implementations on different countries (5).

GRID BACKUP PROTECTION THROUGH PMU

PMU backup protection (6) is a combination of differential protection elements using information from PMU´s combined with a rational use of the inherent characteristics of the electric network. Differential criteria works well with high infeed during faults on remote adjacent lines of the renewable (wind and solar) plants.

Differential (Active Power) time delayed with PMU can be as fast as 200 to 300 ms, which is enough for a backup protection element. Other criteria as current differential or directional comparison elements can also be included. Active Power is preferred because it is inherent non-affected by line charging or inrush current from transformers.

Grid Super nodes are defined with the corresponding overlaps, extending the coverage that normally exists for bus protection in Nodes, as seen in FIGURE 6. A Super Node is perfectly balanced during normal operation (in a first stage it will not be considered the charging line effect), so differential criteria can be used to detect any internal fault in a similar way as it is done with a Node but in this case, using PMU´s as sensors. The main difference is in the operation time that in case of Super node will be time delayed because it is implemented as backup protection.

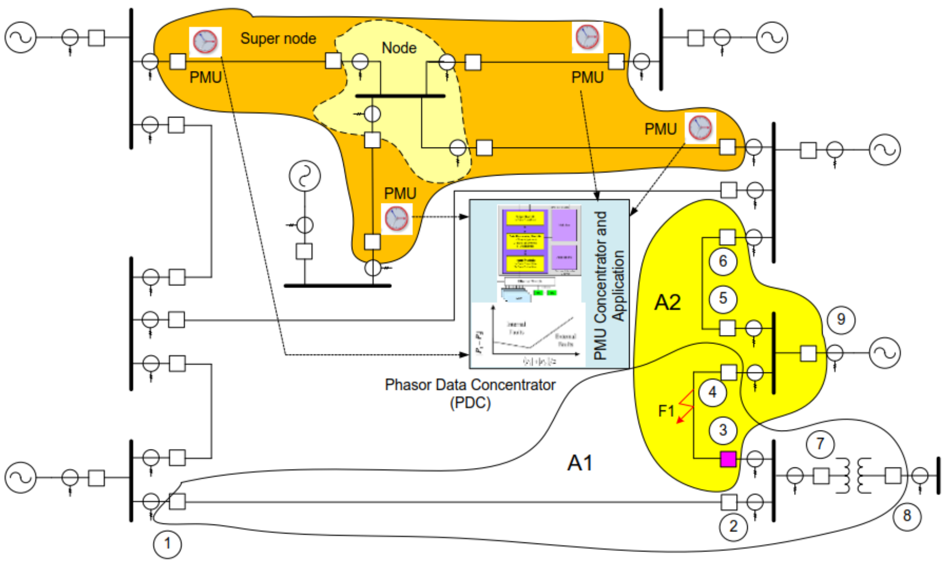

FIGURE 6 – GRID BACKUP PROTECTION WITH PMU

In FIGURE 6 example, in case of fault in F1 and breaker 3 fails to open, Area A1 will trip time delayed (breakers 1, 7, 8 and eventually 2). If breaker 4 is open correctly by primary protection, a signal to remove in the PDC the PMU signals from breaker 3 in A2 is given preventing this area to trip. This is a similar technique used for tripping breaker coupler in bus protection (double bus arrangements). In this case, it can be combined with remote breaker open criteria used in line pilot schemes.

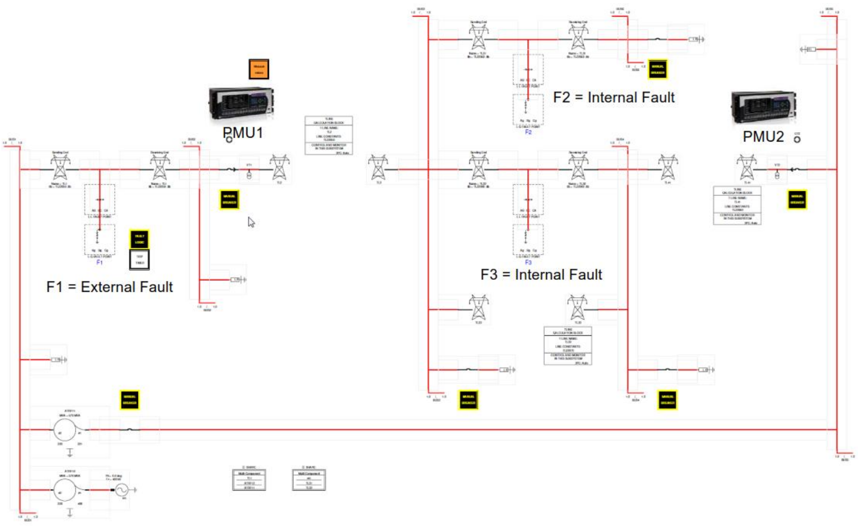

FIGURE 7 - RTDS MODEL FOR SYSTEM UNDER TEST

In order to minimize the impact of charging current and transformer inrush (during energization), it was decided to analyze a Power Differential Protection (7). Power differential protection tripping characteristic is based on power differential in function of restraint power calculated for the super node. As the most sensitive in the case of solidly-grounded system the positive-sequence power was selected.

The adequate criteria are as follow:

$$P_{Diff} = \frac{\left|\underline{P_{1,1}} + \underline{P_{1,2}} + \cdots + \underline{P_{1,n}}\right|}{n}$$

$$P_{Rest} = Max\left(\left|\underline{P_{1,1}}\right|, \left|\underline{P_{1,2}}\right|, \ldots, \left|\underline{P_{1,n}}\right|\right)$$

where:

$\underline{P_1} = \underline{U_1} \cdot \underline{I_1}$ Positive sequence power in per unit

n n-th PMU of the super node

The above algorithm has been combined with a power directional algorithm to discriminate internal from external faults. Results can be observed in FIGURE 8, with fault locations from the model in FIGURE 7.

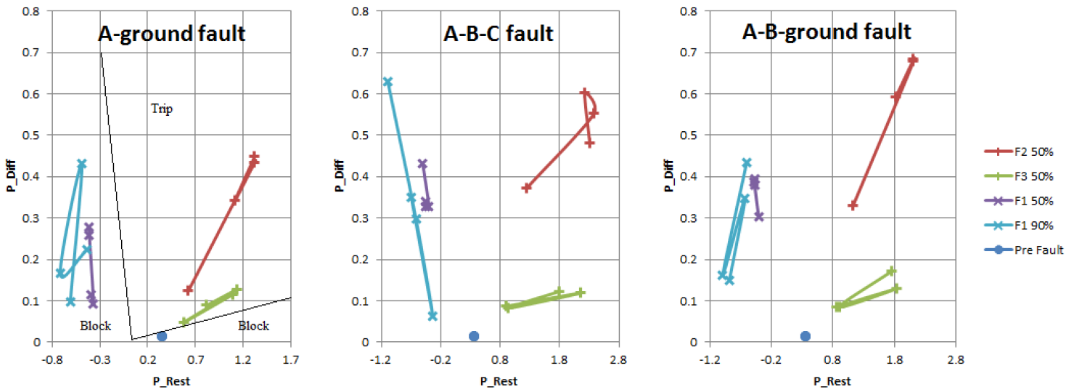

FIGURE 8 - RESPONSE WITH DIFFERENTIAL ALGORITHM ASSOCIATED WITH DIRECTIONAL CRITERIA

Tripping times are shown in FIGURE 9, including operating time of RTDS simulator with amplifiers and GOOSE massage sending time between PLC Logic and PMU relay.

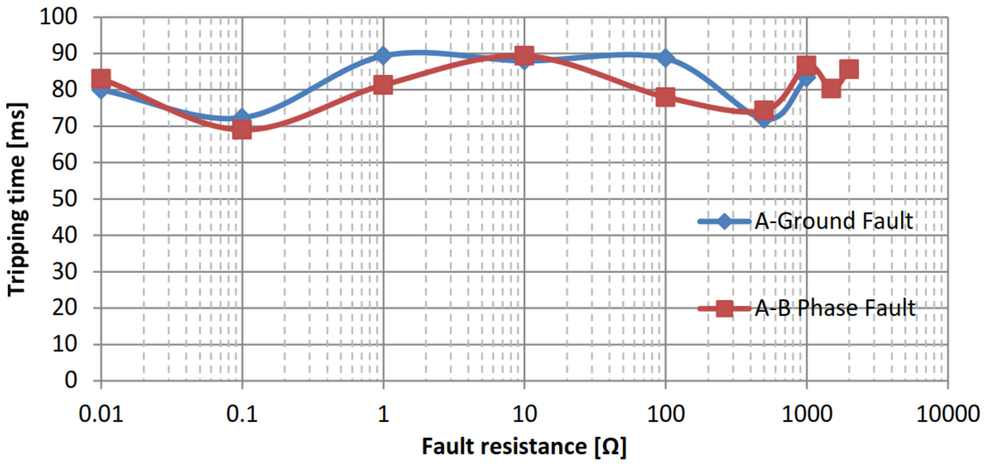

FIGURE 9 - TRIPPING TIME OF PMU BACKUP PROTECTION

CONCLUSION

Main challenges of grid backup protection on renewable substation plants have been detailed. As conclusion from existing implementations of grid backup are summarized below:

- Zone 3 usage is the standard practice, but this philosophy presents limitations as it works only with local information.
- Zone 3 have been involved on cascading effect on several blackouts due undesired operations during line overloads.
- Remote Teleprotection schemes can be implemented through Routable GOOSE with low latency requirements due to long delays for remote backup protection. Special care must be taken due to possible directional improper maloperations due to negative sequence removal on inverters during faults.

- Power Differential Algorithm combined with power directional criteria through PMU gives a very good response and correct fault discrimination for all type of faults.

- Tests were made using only two PMU´s sending information at 50 values per second. We can observe the minimum operating time in FIGURE 9. This time is much smaller than typical delay for Zone 3.

- Phasor Measurement Unit (PMU) technology provides phasor information (both magnitude and phase angle) in real time. The advantage of referring phase angle to a global reference time is helpful in capturing the wide area snapshot of the power system. Effective utilization of this technology is very useful in mitigating blackouts and learning the real time behavior of the power system.

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