Virtual Power Plant for Improving Power System Protection Issues: Solution to the Problem of Power System Reliability under Distributed Energy Resources

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***Abstract*— Modern power system is revolving around three major studies: virtual power plants, power system reliability, and distributed energy resources. The three concepts are interlinked in such a manner, that one can affect the other in either positive or negative way. The involvement of wind and solar systems at distribution level aid to power system generation, but cause a major issue of changes in the conventional protection method of power system. These resources, on the other hand, aid virtual power plants, which give relaxation to the system operators for solving energy and ancillary issues with protection being one of them. In other words, these virtual power plants are both the problem creators, and problem solvers. Literature mostly discusses the reliability issues in power system with the use of virtual power plants. The paper discusses the way these virtual power plants can be utilized for improving the reliability issues due to the high involvement of distributed energy resources on the grid. The paper proposes a model of virtual power plant for the indication and isolation of faults in the power grid, and some test cases in practical scenarios. The model is finally validated using different case studies with the objective of enhancing the TSO and DSO visibility to the faults.**

***Index Terms*--Distributed energy resources, relay, reliability, TSO-DSO, VPP.**

I. INTRODUCTION

Distributed energy resources penetrate the modern distribution grid in a rapid manner, as in [1-2]. These resources cause predictability issues to Independent System Operators (ISO) and Regional Transmission Organizations (RTO) with respect to the quantity and behavior of these resources. Therefore, these additives cause changes in the grid voltages, and currents. Ultimately, the stability and reliability of the grid are disturbed [3-4].

Power system reliability is the core requirement for any system operator. Reliability is to ensure continuous power, with no or very less planned or unplanned outages. The main problem is the unavoidable and random faults, and the next motivation is the detection of these faults to ensure proper operation. This gives rise to the two concepts of power system security, and power system adequacy as in [5-6]. Basic concepts of two terminologies and power system reliability are discussed in [7].

Since faults are unavoidable and probabilistic in nature, the reliability is ensured through detecting, and clearing the fault in as less duration as possible. Literature identifies different indices for the determination of power system reliability. Some of the most common ones are SAIFI (System Average Interruption Frequency Index) [8-9], SAIDI (System Average Interruption Duration Index) [8-9], MAIFI (Momentary Average Interruption Frequency Index) [9] etc. All these parameters emphasize on the restoration time, and the frequency of occurrence of faults. This is the justification for using protection devices in the overall power grid.

II. CONVENTIONAL POWER SYSTEM PROTECTION TECHNIQUES

Power system relay is the most common equipment, which gives signals to circuit breakers for power system protection. It is the responsibility of relay to detect fault, and give indication to the circuit breaker so that the tripping takes place in the shortest possible time. This gives rise to two conditions: tripping of circuit breaker when there is no fault, and this is due to mis-judgement by relay as dependability issue, and no tripping of circuit breaker when there is a fault, and this is due to mis-judgement by relay as security issue [10]. Different types of relay are used for the design of protection schemes for different power system components.

One of the protection schemes is over-current protection,

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which is used for radial distribution networks. Another common scheme is differential protection which is used for transmission lines, bus bars, and transformers. Apart from these two conventional techniques, there are other techniques suggested by market and literature, i.e. distance protection, pilot protection etc. [11]. Irrespective of the type of fault, and the nature of protection scheme, the major principle quantities are voltage and current. These two quantities differ either in magnitude, direction, or angle in order for the relay controller to sense the faults. The next section describes how this behavior is affected due to the presence of additional resources within the power grid.

III. MODERN POWER SYSTEM PROTECTION ISSUES

With the conventional power system, these techniques sense the current and voltage, and gives signals to relays in order for the circuit breaker to trip correctly. Addition of distributed energy resources, and other unplanned components under the umbrella of virtual power plant, can cause these voltages and current to change with respect to the conditions for which they are designed. As an example, consider that an over-current relay is designed to trip the breaker when the fault current at a lateral reaches 15000 Amperes, on the primary side of current transformer. However, the addition of photovoltaic panels, and demand response can cause the current through lateral to vary.

Consider the Single Line Diagram (SLD) in Figure 1. There is a distribution feeder that serves two laterals at different customer levels. The Thevenin current feed from the distribution end is taken to be I_s. The two laterals draw I_1 and I_2 currents respectively. There is a circuit breaker in between the two laterals for the design of protection for the distribution bus bar, and the two laterals. The breaker receives the signals from the relay in order to trip in case of necessary operation.

Consider the case in Figure 1, where overcurrent relay is used to protect the laterals and line. Consider the relay pickup current to be I_0. I_0 is designed relative to the current through the breaker, i.e. I_s - I_2 OR I_1. Relay operates, and trips the circuit breaker in case I_1 exceeds I_0. In Figure 2, photovoltaic panels are added to the distribution end, and they can generate current of I_p as seen in Figure 2. In other words; Photo-voltaic panels act as a generation source, and thus can generate the current on that part of the system.

These photovoltaic cells generate I_p that causes the current through breaker to reduce to I_1 - I_p from I_1. Since, the breaker current should match with I_s - I_2, the scenario leads to three possibilities. First possibility is that lateral 1 draws more current, which is not seen by the breaker. Second possibility is that lateral 2 draws more current, which is again not seen by the breaker. Third possibility is the back feed from photovoltaic source to the distribution feed, and this causes breaker to sense unusual currents for the line than the ones for which it is designed. As a result, overcurrent protection would fail in this scenario, which requires significant modification in the design of new scheme.

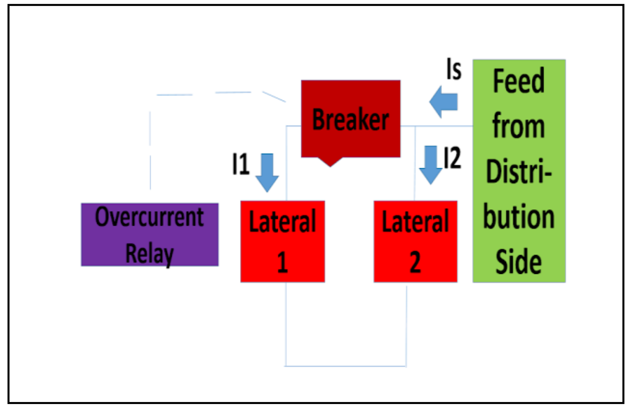

Figure 1. SLD for Overcurrent Relay in Normal Conditions

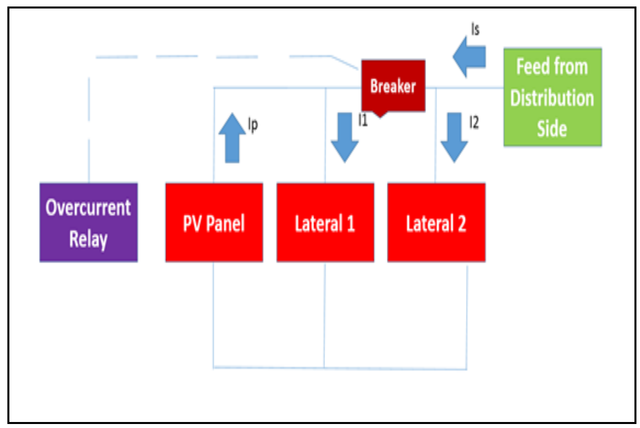

Figure 2. SLD for Overcurrent Relay under DER Conditions

For the case 3, differential protection scheme is designed as shown in Figure 3. For the ease of analysis, ideal case is considered for differential protection with no current transformers mismatches, magnetizing inrush etc. as in [12].

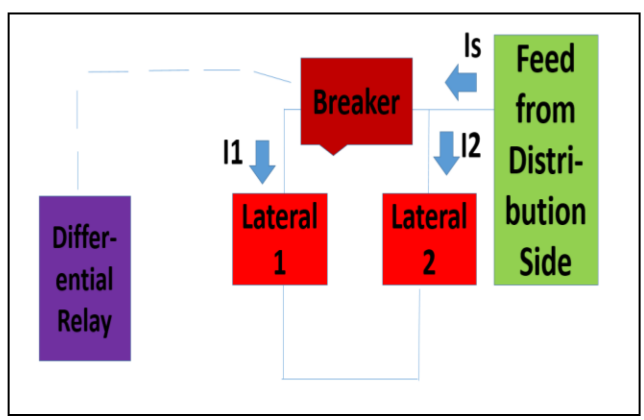

Figure 3. SLD for Differential Relay in Normal Conditions

The current difference is the only signal used for the tap setting of the differential relay. The tap settings are thus defined on $I_{difference}$ equal to I_1-I_s+I_2. After the addition of photovoltaic panel as in Figure 4, the $I_{difference}$ needs to be re-parameterized, and thus changes are required in the existing protection conditions.

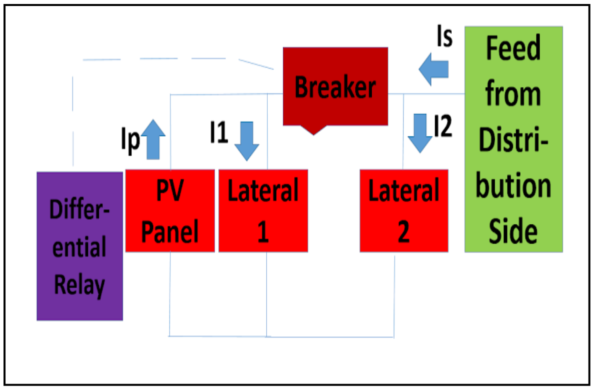

Figure 4. SLD for Differential Relay under DER Conditions

IV. PROPOSAL OF VPP FOR THE SOLUTION OF PROTECTION ISSUES

Virtual Power Plant (VPP) is a common point of discussion in this period of research. Economic analysis for the benefits of a VPP to frequency reserves ancillary service is demonstrated in [13]. [14] It justifies the use of VPP for effective utilization of renewable energy resources. [15] It supports the idea of better reserve market as suggested above. A more elaborative review is presented in [16], with focus on individual VPP components. In the context of this paper, only protection system and its implications are taken in to account.

The idea is to employ the major conventional relays, and communicate them with the major virtual power plants. Two layers of VPP are proposed; one deals with the faults at distribution levels, and the latter with the transmission and generation levels. The idea is illustrated with a layout in Figure 5. There is a centralized VPP master, which has direct communication with TSO. The centralized master is under the direct supervision of transmission level master VPP, and distribution level master VPP. There are chains of VPP operators at both transmission and distribution levels. The idea is that these operators share the operational data with their master controls.

At the distribution level, the main distribution feeders and the distribution transformers are the points of scope for the paper. These feeders and transformers employ digital relays, and ultimately create a VPP for protection purposes. These relays work on the principle of pilot protection. At the level of transmission, the main generators and the most crucial transmission and sub-transmission transformers are emphasized. These subsets are also supported through their protection based VPP, and employ digital relays that are compatible with pilot protection scheme.

It is compulsory for all the VPP platforms to support the pilot protection schemes: Centralized VPP, Transmission Level Master VPP, Distribution Level Master VPP, VPP sub-chains on Transmission Level, VPP sub-chains on Distribution Level, the components' based VPP at Transmission Level, and the component' based VPP at Distribution Level. Table 1 shows the visibility pattern for different participants in the network. Level 0 indicates direct visibility with no further interconnection. Level 1 indicates one, level 2 indicates two, and level 3 indicates three layers of interconnections.

Centralized VPP can access the information related to faults at all the levels of architecture. With the aid of backup protection scheme, the centralized tool can directly isolate a line, transformer, or a generator in case of urgent situations. Since TSO is sharing layer 0 with the centralized tool, it has access to all the VPP providers with the variations in delay. However, the visibility of DSO is limited to pertain network requirements. DSO can communicate with TSO only through the centralized platform. The communication is done when the network at lower level is unable to handle larger amount of faults. In the extreme case when all the VPP platforms fail, and there is a tremendous traffic on centralized controller, TSO can call for a restorative blackout. Next section defines test cases for better evaluation.

TABLE I. VISIBILITY PATTERN FOR PROTECTION SCHEME

Name of Component	**Pattern Description**		
	Visibility to:	***DSO Visibility Chain***	***TSO Visibility Chain***
Component VPP Distribution Level	Distribution feeders, laterals, and trans-formers	Level 2	Level 3
Component VPP at Transmission Level	Generators/ transformers	NO VISIBILITY	Level 3
VPP sub-chains on Distribution Level	Component VPP at Distribution Level	Level 1	Level 2
VPP sub-chains on Transmission Level	Component VPP at Transmission Level	NO VISIBILITY	Level 2
Distribution Level Master VPP	VPP sub-chains on Distribution Level	Level 0	Level 1
Transmission Level Master VPP	VPP sub-chains on Transmission Level	NO VISIBILITY	Level 1
Centralized VPP	Transmission Level Master-VPP, Distribution Level Master-VPP, Component VPP at Transmission-Level, and Component VPP at Distribution Level	NO VISIBILITY	Level 0

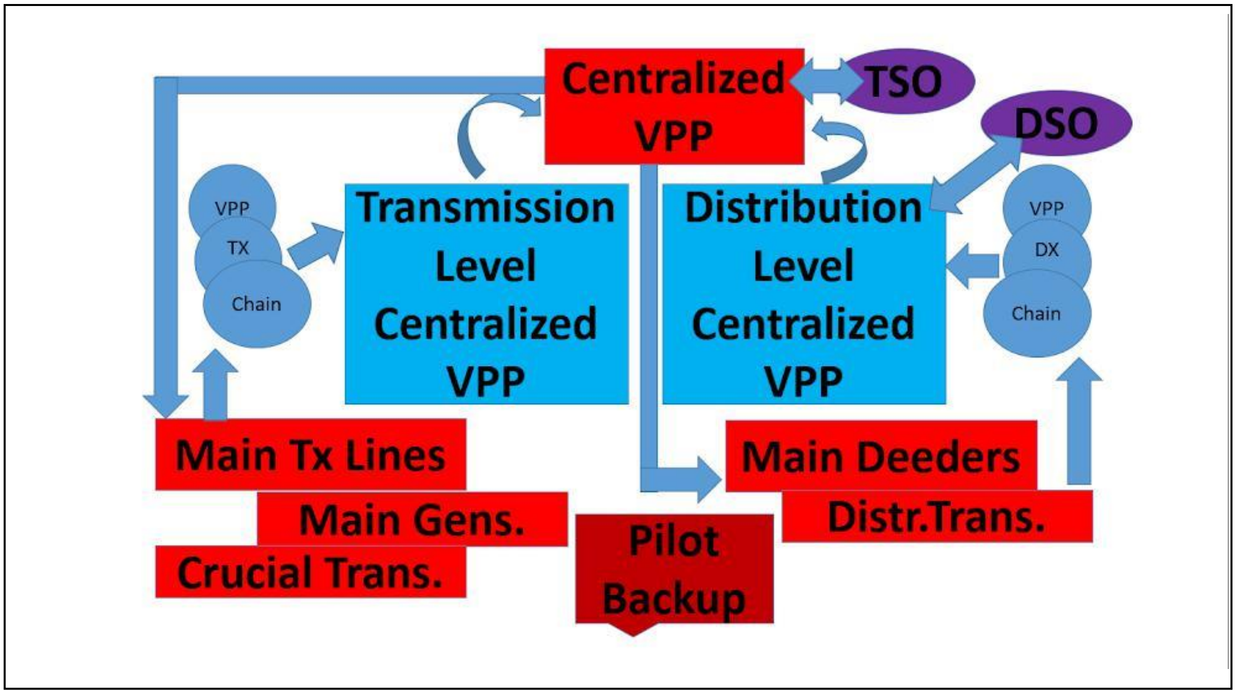

Figure 5. Proposal of Virtual Power Plant for the solution of protection issues

V. TEST CASES

The architecture can be utilized for a number of case studies. The first case is to analyze the fault at one of the MV transformer under transmission network. For the primary protection, differential relay is used. In case of failure of which the Component VPP at transmission level can provide a primary backup protection through any recommended technique (let say over-current technique here). The primary backup is not always present for the proposal. The centralized controller, through pilot scheme, provides the main backup. The centralized VPP can observe this fault, and can manage the issue efficiently and in a timely manner. In fact, the controller can communicate with TSO, and they can provide flexibility for each other in terms of managing the faults.

Next case is to analyze the fault at one of the LV feeder laterals under distribution network. For the primary protection, over-current relay is used. In case of failure of which the Component VPP at distribution level can provide a primary backup protection through any recommended technique (let say differential protection technique here). The primary backup is not always present for the proposal. The centralized controller through pilot scheme provides the main backup. The centralized VPP can observe this fault, and can manage the issue efficiently and in a timely manner. In fact, the controller can communicate with DSO as well as TSO, and they can provide flexibility for each other in terms of managing the faults.

Last case is to analyze the efficiency of backup protection by the centralized controller. The pilot protection scheme is compared with the conventional backup scheme, for example, over-current relay. Then, the performance for both the backup schemes are compared for the fault parameters described in previous section. Overview of the basics of backup protection is available in [17].

VI. RESULTS AND CONCLUSION

For the analysis purposes, the software called Coordinaide S&C [18] is used. The three test cases are analyzed, and the results are verfified. The software aided in selecting the relay parameters. The paper gives an idea that protection system can be improved (and less changes are needed in the conventional protection schemes), if the virtual power plants are coordinated in an efficient manner with TSO and DSO. The analyzed results for each case is discussed one by one.

Analysis for case 1 is shown in Figure 6, where the fault is assumed to be at a MV transformer. The fault occurs at time = 2 seconds, and it is indicated by the blue line. The primary protection is reflected by the orange line which activates with the indication of the fault at the specified time. The primary protection clears the fault in 4 seconds, where it is assumed that it suffices with the protection criteria.

In the event of failure of backup protection, centralized VPP manages to provide the backup in 4 seconds, with total fault clearing time of 8 seconds. The region for TSO visibility is marked in the figure; however, DSO has no role to figure

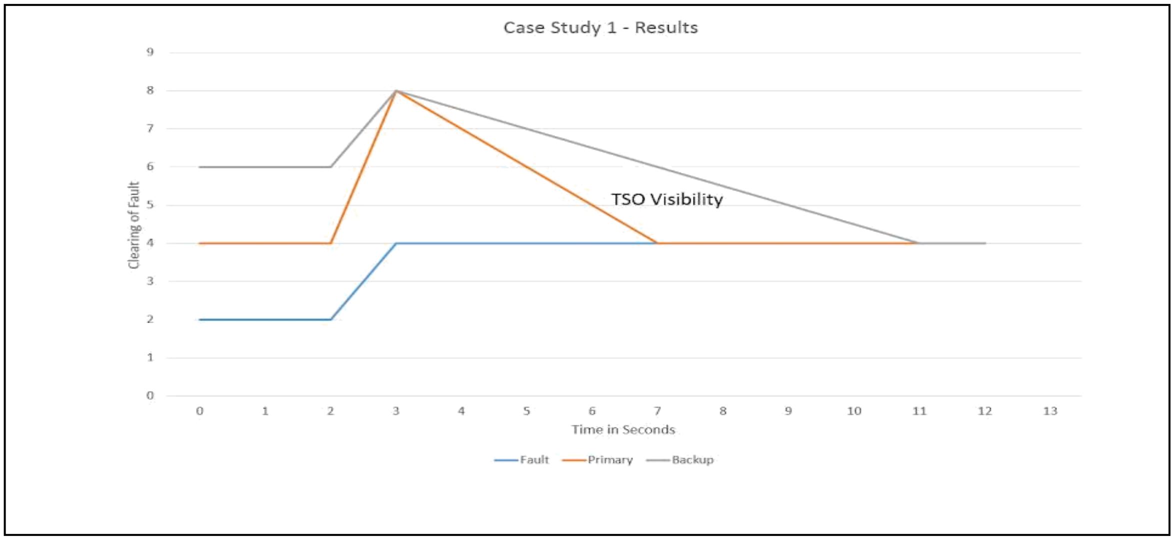

Figure 6. Analysis for Case Study No. 1

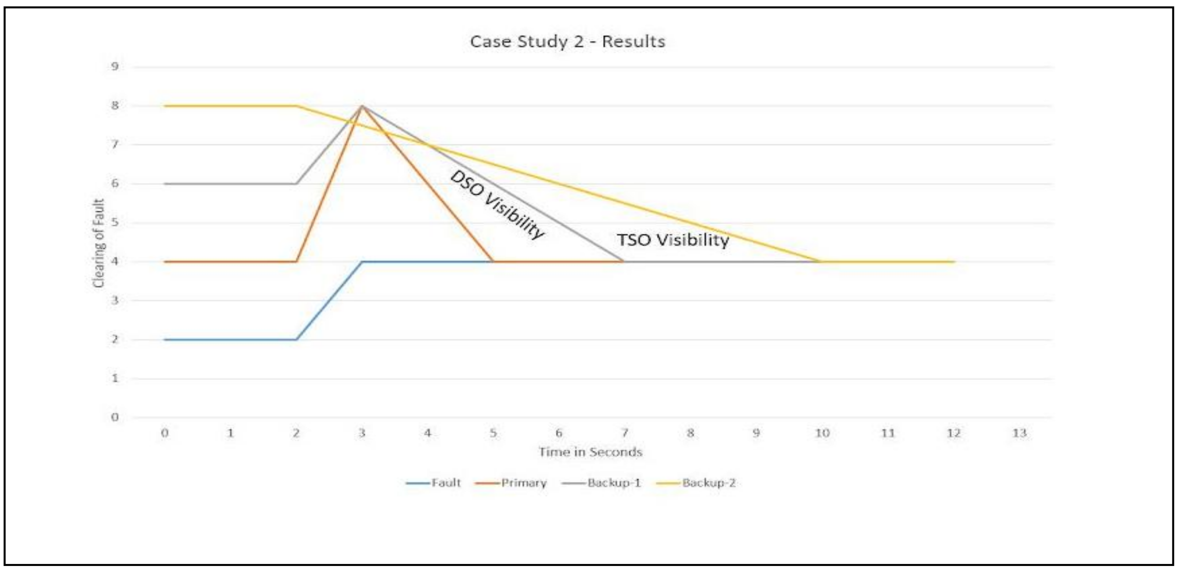

Figure 7. Analysis for Case Study No. 2

out these faults. The analysis for case study 2 is presented in Figure 7. For the same scenario as in case 1, the fault is cleared by primary protection in 2 seconds.

The secondary backup can have two possibilities here. DSO can access the fault through master VPP, and can clear the fault in a margin of 2 seconds. In case, DSO misses the fault, or manages TSO for the purpose, TSO can provide the backup in three additional seconds. DSO and TSO operational areas are marked in the Figure 7.

For the analysis of case 3, the assumptions are taken for the communication times, and the relay operational times. The communication requirements for the pilot protection are mentioned in [19]; SONET (Synchronous Optical Network) communication protocol is considered here for analysis over Ethernet as in [20]. For the comparison, overcurrent back up protection scheme is considered. The IDMT (Inverse Definite Minimum Time) type over-current relay is chosen as in [21]. For the overcurrent backup, the advantages are in terms of fast operation as IDMT operational delays are less than overall SONET communication and the protection relay operating time. However, backup fails in case of any further addition of distributed energy resources in the loop.

In brief, virtual power plants are considered in the paper to analyze their effects on the power system protection. It starts with the problems faced by power system due to the high integration of distributed energy resources. Emphasized issues are the power system protection methods (i.e. issues with radial configuration, and use of over-current protection), and effects on the working of protection devices (i.e. fuse, relays etc.). Presentation of test cases where faults in the system are visible to TSO, DSO, or both of them. Then the presentation of an architecture for communication between TSO-DSO-VPP, and then the examination of the visibility of faults to the common controller for the defined test cases.

The idea is to utilize the existing VPP controller, and to communicate (deliberately) it with TSO and DSO controllers for the purpose. Finally the analysis for the impacts on protection system, before and after the involvement of common controller is done. The results justify the statement of using VPP for solving the issues of power system protection.

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