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Impacts of the Decentralized Photovoltaic Energy Resources on the Grid

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SUMMARY

The Power Quality and Protection impacts of the Photovoltaic Energy resources on the Distribution System are presented. IEEE standards are addressed and various issues caused by step up transformer configuration, feeder load, capacitor banks and possible adjacent generation are discussed. Solutions are recommended for the identified interconnection issues.

KEYWORDS

Distributed Generation, Photovoltaic, Wind Energy, Synchronous Generator, Sequence Network, Power System Faults, Anti-Islanding, Self Excitation, Power Factor, solidly grounded system, Effectively Grounded System and Impedance Grounded System.

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POWER SYSTEM GROUNDING

Early US 3ϕ power distribution systems were usually ungrounded and used a delta as the most common system configuration. Even though reliability was significantly better on low voltage, delta systems, they have some significant limitations from a system protection viewpoint. First, it was not possible to identify which circuit on a bus had a ground fault without complex switching or interrupting multiple circuits and customers. Secondly, ground insulation must withstand full Φ-Φ voltage which was not a problem in early days when voltages were low (~ 2400). Delta was also an issue in ungrounded systems and as cable lengths/transmission voltages increased, the associated capacitances to ground increased. In these systems, transient grounds no longer self-cleared, arcing grounds became problematic, hazardous high fault voltages were generated, severe damage could occur at the point of the fault, and it was not uncommon to find equipment damage elsewhere on the circuit. Furthermore, if the capacitance (X) to ground is sufficiently high relative to system impedances (R+jX) then unfaulted phase to ground voltage during a ground fault can exceed phase-to-phase voltage and additional charging current on unfaulted phases can distort the voltage triangle making it difficult for protection to operate.

As voltages increased, electric power system designers recognized that grounded systems offered distinct advantages mainly in the area of system protection. In particular, using grounded systems allowed relaying to detect Φ-G faults even at the end of radial lines. They also allowed lower system insulation levels.

As well as system grounding, it’s important to understand transformer grounding before photovoltaic systems are described. In the US there are three different grounding types: A) solidly grounded – grounded through an adequate ground connection in which no impedance has been intentionally inserted. B) Impedance (resistance, reactance) grounded – grounded through impedance (resistance, reactance). C) Effectively grounded – grounded through a connection of sufficiently low impedance such that voltages that exceed established limits cannot be generated during faults. Solid grounding and impedance grounding refer to the transformer neutral-to-ground connection whereas effective grounding refers to the system impedances and fault voltages. Effective grounding is usually defined as the ratio X0/X1 being less than 3 at the location of the fault. This results in a phase-to-neutral voltage of 1.25 PU on the un-faulted phases during a single line-to-ground fault. Meeting the 1.25 PU voltage criterion also requires R0/X1 to be less than 1, but this is rarely a problem unless neutral resistance has been deliberately added. A solidly grounded transformer may or not result in an effectively grounded system and an impedance grounded transformer may or may not result in an effectively grounded system. The transformers ratings determine the type of power system grounding

Figure 1 shows another criterion for an effectively grounded system when the transformer is impedance grounded where XT and X1sys are the positive sequence impedance values of the DG step up transformer and the power system, respectively. X_L represents the impedance of the neutral winding. Figure 1 can be used to analyze the grounding type of the power system when the utility transformer is disconnected from the DG transformer due to the fault. Based on the criteria provided in Figure 1, the proper protection scheme shall be design to ensure the safety and reliability of the distribution system.

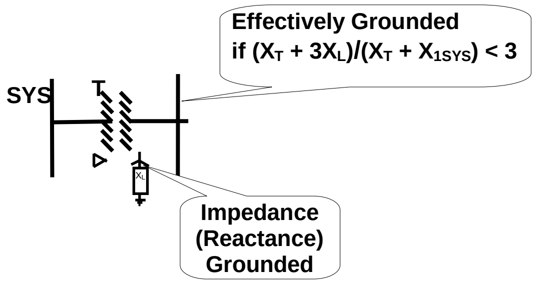

Figure 1. Criterion for an effectively grounded system when the transformer is impedance grounded.

As a result, the transformer size and grounding determine the power system grounding type. Appropriate protection relaying is required for each type of power system grounding related issues during faults.

PHOTOVOLTAIC GENERATION

Photovoltaic (PV) generation is a popular type of clean energy generation which is popular in various parts of the US. Efficiency and ease of licensing has helped the technology proliferate in various states with targeted incentives. In Massachusetts, National Grid has seen over 400% increase in requests for interconnections over the past 3 years. One issue with PV generation is that it only can operate during the day light hours and output value is based on the season, clouds, and latitude.

It is assumed that the inverter utilized in the PV system complies with the IEEE-1547 standard for Interconnecting Distributed Resources with Electric Power Systems, listed under UL-1741 by an independent recognized test laboratory and has a built-in active anti-islanding scheme to detect the islanded situation.

Figure 2 shows the Current - Voltage (I-V) curve of a sample PV at a specific temperature for various output power levels. As the temperature increases, the maximum I_{pv} decreases meaning that the output power gets decreased during the hottest parts of the day. Most inverters operate based on the Maximum Power Point Tracking (MPPT) method which is shown in Figure 3. Figures 2 and 3 are related and Figure 3 shows that the maximum power is generated on the knee of Figure 2 curves so the PV is always operating at the maximum power given current conditions for maximum efficiency.

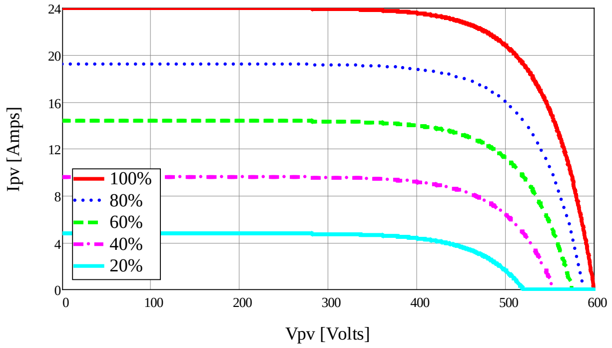

Figure 2. I-V curve of a PV [11]

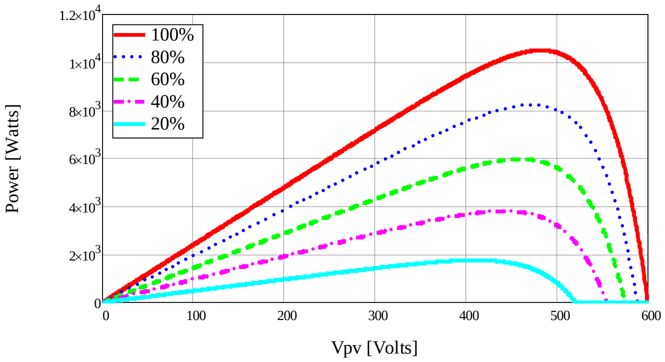

Figure 3. Maximum Power Point Tracking [11]

III. POWER QUALITY AND PROTECTION CONCERNS

What follows are the most important power quality and protection concerns from the utility perspective with regards to PV installations.

A) Voltage and power fluctuations due to the cloud impacts on the generation output will have impact on the distribution system [10]: The impact of the cloud transients on a sample PV active power output is depicted in Figure 4. The power oscillation can be severe enough to create voltage and frequency issues. Figure 5 shows how the cloud transient impacts the voltage at the point of common coupling (PCC). This voltage fluctuation can cause excessive feeder voltage and require regulator(s) on the feeder or at the substation to operate significantly more than designed thereby potentially causing maintenance issues. Hence, in order to reduce the impact of the cloud transients on the regulator operation, it is recommended that the PV regulates the voltage at the PCC. Inverter manufacturers have shown interest on implementing the VAR control feature into the inverters to regulate the PCC voltage by controlling the reactive power flow from/to the inverter.

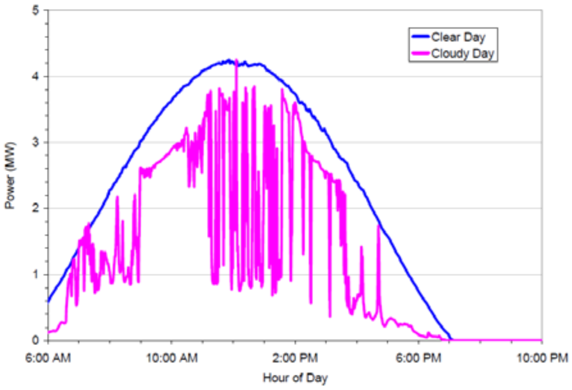

Figure 4. Clear and Partly Cloudy day Solar PV Profile [10]

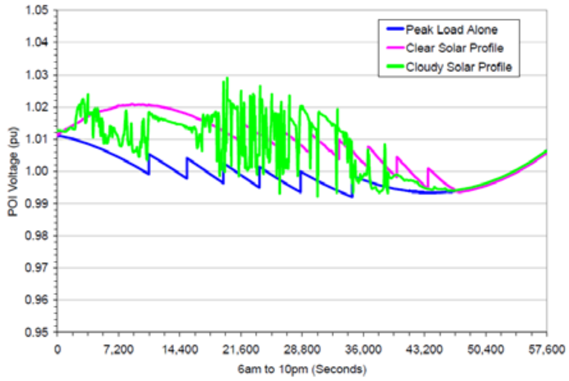

Figure 5. The impact of the cloud transients on the Point of Interconnection Voltage [10]

B) Impact of PV with step-up transformer configuration [8]: If the utility side of the step-up transformer is configured as a delta, there will not be any fault current contribution from the inverter to a single line to ground fault (SLG) on the delta side. Normally, the feeder side of the utility transformer is grounded wye to provide ground reference to end-users' premises wiring. Because, the utility transformer is much larger than the generator step-up (GSU) transformer, the system is effectively grounded and a SLG fault will not create high over voltage (OV) on the unfaulted phases. This is true until the utility interrupting device opens. An inverter's active anti-islanding scheme is capable of detecting the islanding in most cases except: 1) when active and reactive power match. 2) there is a reciprocating generator (Wind turbine, Synchronous generator, etc) connected to the feeder which tends to hold the frequency after islanding due to its inertia. The rule of thumb is if the synchronous generator size is larger than 25% of the inverter size, there is a chance that inverter will have longer run-on time than what is indicated in IEEE-1547 (2 sec). 3) multiple inverters from different manufacturers connected to the same circuit: As inverter manufacturers use different anti-islanding methods, the interaction between the anti-islanding schemes might delay the islanding detection. The only solution for this problem is Direct Transfer Trip (DTT). If the inverter has provided an effectively grounded system at PCC, a 51C relay is a good option to detect the fault because of the limitation on the inverter's fault current contribution. Inverters do not contribute to the fault current more than 120% of the nominal current rating; hence, it would be difficult to set a regular overcurrent relay to distinguish between fault and normal situation. 51C relay is an overcurrent relay that the Over Current functionality is controlled by the system voltage.

C) PV generation for non-faulted islanded situation [8]: If the utility breaker opens for any reason (no fault on the feeder) and feeder load is much lower than the generation, there will be OV on all three phases regardless of the step up transformer configuration. If the customers cannot sustain the OV until it is cleared by regular system relays or inverter's built-in protection scheme, DTT should be initiated from the utility breaker to the interrupting device at the DG side to ensure equipment is not damaged on the customer side.

D) Multi-inverter Generation [7]: For inverters that rely on a deliberately-injected perturbation (positive feedback), the fact that the inverters are not synchronized means that these perturbations "wash out" when large numbers of uncorrelated inverters are used. Thus, the aggregate does not see a significant perturbation, and the anti-islanding performance deteriorates as the number of inverters rises. For inverters using one of the standard positive feedback-based methods, increasing the number of inverters serves to dampen the effect of the positive feedback of any one inverter in a sense, there is an "inertia" consisting of the other inverters in the island, and this inertia again slows down the detection of an island, with run-on times increasing as inverter numbers increase. This effect is minimized by manufacturers by using relatively high gains, but it still exists.

CONCLUSION

DG is and will continue to be an important part of the system as the 19th century grid transitions to the 21st century grid. Understanding and mitigating power quality and protection issues will be essential as the systems continue to mature and two-way power becomes the norm on distribution systems.

In this paper, the impact of the photovoltaic energy resources on the power quality and protection of the distribution system is discussed. As expected, rotating generators (i. e. wind turbine) can cause longer run-on times on PV's relaying. Multi-inverter generation has become another concern as the number of PV installations grows fueled by incentives across the US. The most recent anti-islanding scheme which is the combination of Sandia Frequency Shift Method (SFS) and Impedance method is also discussed. DTT is recommended for the islanding. Due to the cost of the DTT, the authors recommend thorough research on new techniques to detect the islanded conditions locally at the PCC

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