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Solar Shading vs. Fault Conditions from a Utility View

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SUMMARY

Photovoltaic (PV) generation is steadily increasing in prevalence within the power system. Higher DG penetration levels provide many inherent benefits, such as clean and local power supply; however, one of the main downsides is the variability of the fuel source – sunlight. Sunlight is unavailable at various times during the day due to shading caused by cloud coverage. PV shading can cause large swings in the power output of solar farms, causing the utility to compensate for the loss of power in a distribution circuit. A distribution circuit may experience a large disturbance if a significant amount of PV power is lost due to shading. The goal of this paper is to examine the utility grid's response to the loss of power caused by PV shading in comparison to a fault on the same circuit. The results show a comprehensive examination of the differences and similarities in voltage, current, frequency, phase shift, and total harmonic distortion(THD), as seen by the grid. This information will be useful to utilities and protection engineers that are experiencing high levels of volatile generation on the distribution circuits in their territory.

KEYWORDS

Faults, Photovoltaic Generation, PV Shading, Utility Grid

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1. Introduction

Utility scale solar installations increased at an average of 72% a year between 2010 and 2016, faster than any other generation type [1]. Utility scale solar plants, capacity > 1MW, make up 2% of utility scale electric generation capacity in the United States [1]. Over 21.5 GW of solar generation capacity was online as of 2016 [1]. Dominion Energy has a capacity of 931.78 MW on the distribution grid. The amount of photovoltaic (PV) generation will only increase as many states, such as California and New York, have developed ambitious goals for penetration in the coming years [2].

The days of radial, predictable networks are far gone due to the mass penetration of photovoltaics (PV). PV penetration creates a diverse array of operating scenarios that the utility grid can see every day. PV generation not only creates this array of options but its volatile nature means that transitioning between operating scenarios can happen in a moment's notice. California has such a large amount of PV generation that 2017's solar eclipse became an expose on how to handle the variability of solar [3]. The grid operators knew when the Moon would block sunlight from the Earth and take GW of PV offline. To ride through this event the grid operators secured 1000MW of reserve power, 650MW more than an average day, for the three hour window when the eclipse's effect would be the greatest [3].

Solar eclipses are a rare and predictable event that makes for a nice story more than a serious threat due to the preparation of the California grid operators. But, most grid operators do not have such foresight when dealing with the everyday grid. Figure 1 illustrates how PV shading can take MW offline without the benefit of gathering reserve power. The PV power, in orange, reaches a maximum of 18MW but experiences high volatility throughout peak sunlight hours. There are various research efforts such as [4] and [5] into the ability of inverters to mitigate the ramp rate of power output in order to cause less fluctuation.

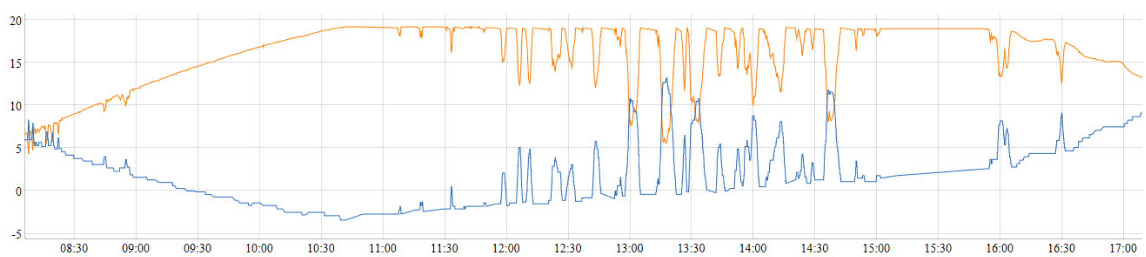

Figure 1. PV and grid power to a load

Certainly this area of research is extremely important but translating these findings to PV inverter control systems is not a simple task for utilities. Therefore the research in this paper was performed to face the current reality of the large volatility of PV generation. RSCAD software is used to simulate a distribution circuit with a grid source, transformer, load, and PV generation. The power output from the PV generation is quickly lowered, such as it would due to PV shading, and the effects on the grid's voltage, current, phase, and total harmonic distortion (THD) are recorded. The same grid quantities are also examined during a 3-phase fault. The results from the two scenarios are compared to better understand how PV variability can affect the utility grid protection schemes.

2. Model Outline and Formulation

Figure 2 shows the RSCAD model used in this work. An infinite grid with RL impedance is connected to a transformer which leads to the load and PV generation. The RL impedance is low, therefore the grid is considered a strong grid. A resistive load is used to model a load of 5 MW at 480 V. The PV generation is modeled using a voltage-sourced converter (VSC) that is controlled via PQ control. The controls are designed so that the output power of the PV and infinite grid are the same.

Two trials were conducted using the model in figure 2; sudden PV output change and a 3-phase fault. A 3-phase fault is chosen so that each phase is equally affected, as each is when the PV output is lowered. First, the power output of the PV will be reduced from 2.5 MW to 0 MW instantly and kept there for the duration of the simulation. The current from the transformer and system voltage, frequency, phase, and THD will be measured at the load. This process will be repeated with a 3-phase fault. The current, voltage, frequency, phase, and harmonics are then compared side by side to determine the nuance differences between instantaneous PV generation decrease and a 3-phase fault.

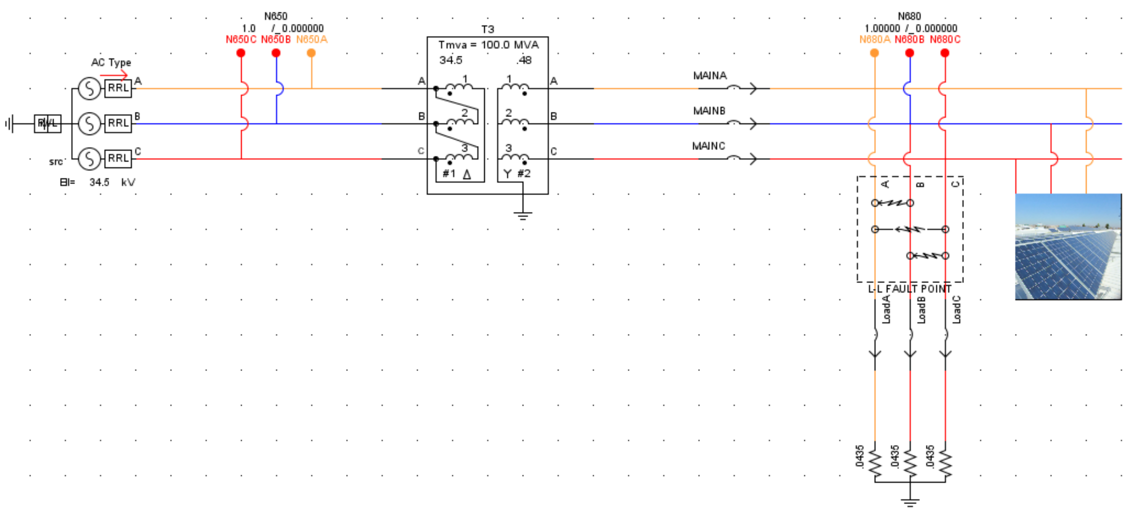

Figure 2. RSCAD Model

3. SIMULATION RESULTS

In separate simulations the change in PV output and the fault are triggered at 0.1 s. Figure 3A shows the power output of the PV and grid as a result of PV shading. The PV output changes from 2.5 MW to -1.87 MW in 17.8 ms during the transient state, which is a ramp rate of 0.25 MW/ms. During the transient, the VSC briefly acts as a load before moving to a steady state value of 0 MW. The infinite grid mirrors this ramp rate, only in the positive direction, as shown in figure 3A. This makes sense as the grid compensates for the power lost from PV shading. The 3-phase fault is applied to the load, and the resulting power outputs can be seen in figure 3B. The output power of the PV briefly goes negative as it did when PV shading occurred, briefly acting as a load. Once stabilized, the PV continued to output its nominal power output of 2.5 MW. The infinite grid experienced a large rise in power output to compensate for the fault.

The figures below show the results of the two simulations. The results from PV shading are shown on the left and the results from fault are shown on the right, for comparison. The load voltage, grid current, system frequency, voltage phase shift, and grid current THD that result from the scenarios are shown in figures 4, 5, 6, 7, and 8, respectfully.

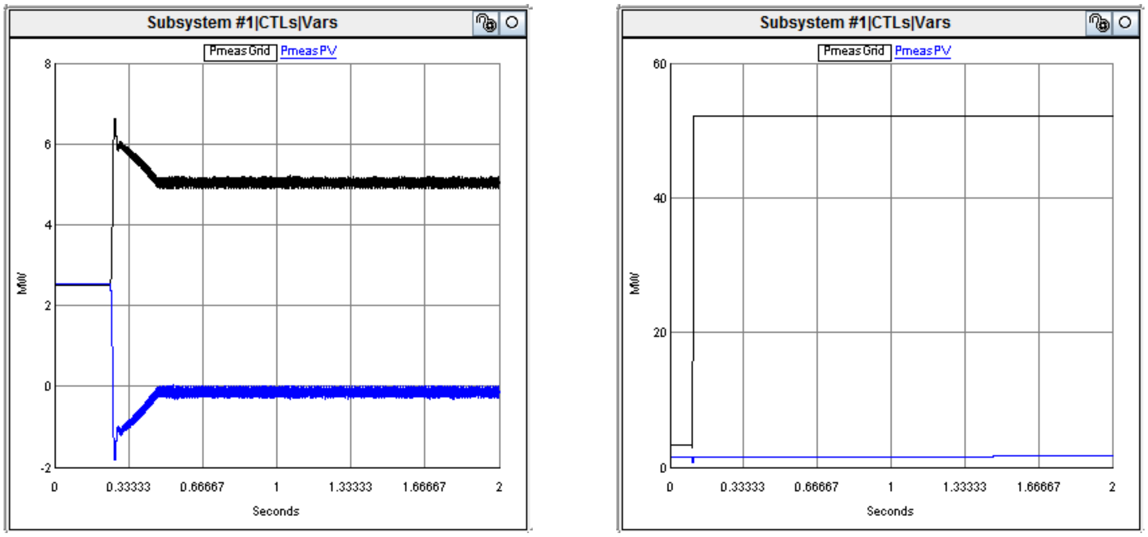

Figure 3. Power output of the infinite grid and PV A) PV shading B) 3-phase fault

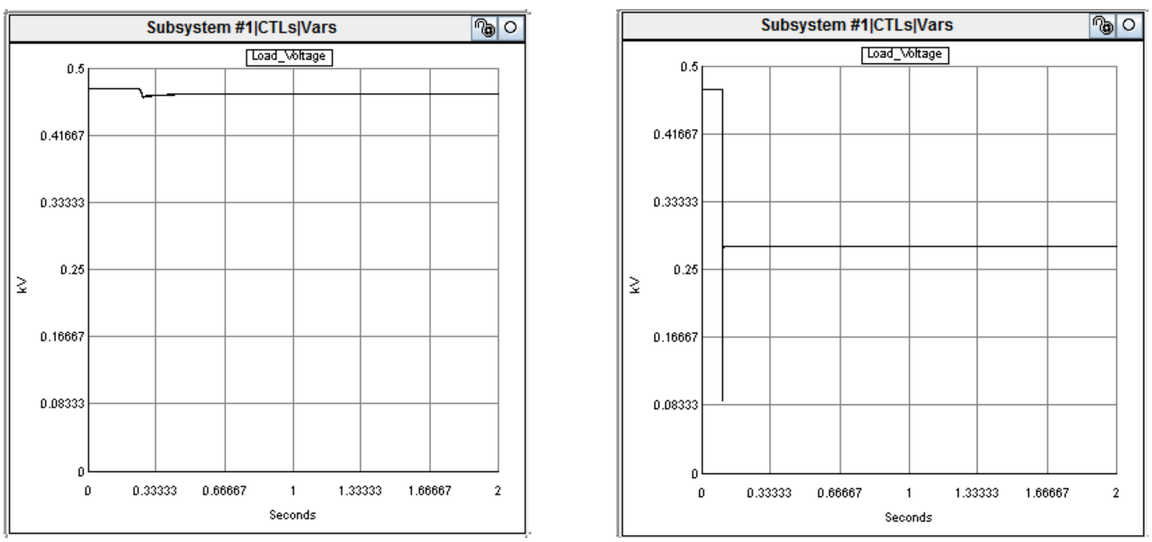

Figure 4. Load voltage response A) PV shading B) 3-phase fault

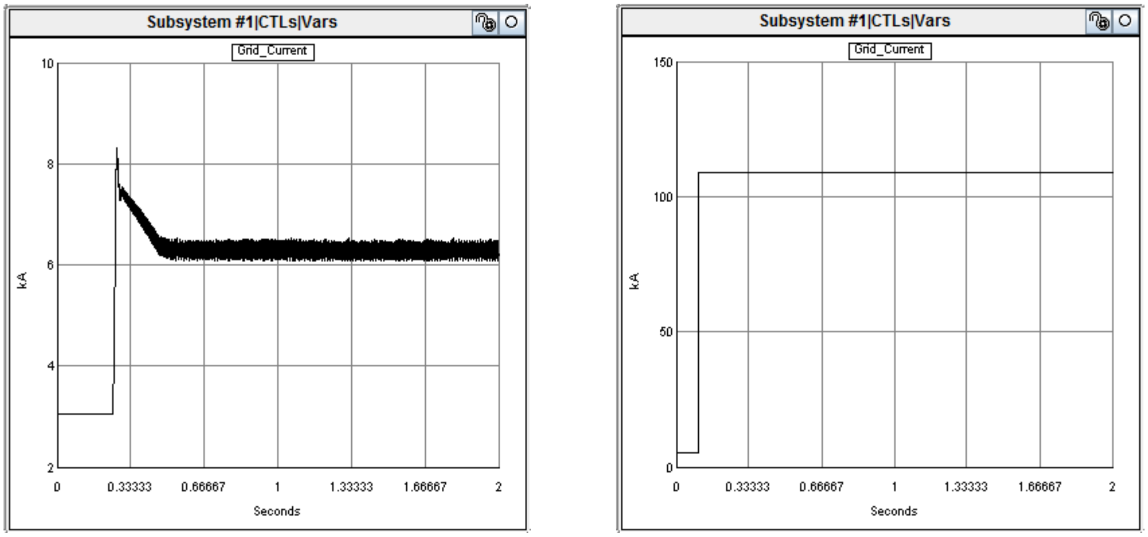

Figure 5. Current through transformer A) PV shading B) 3-phase fault

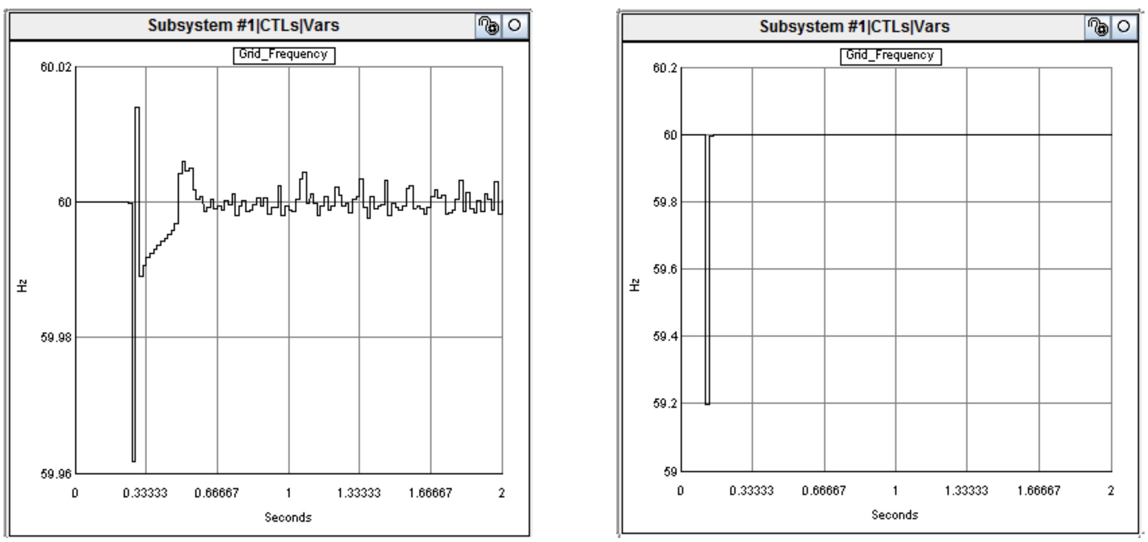

Figure 6. Grid frequency A) PV shading B) 3-phase fault

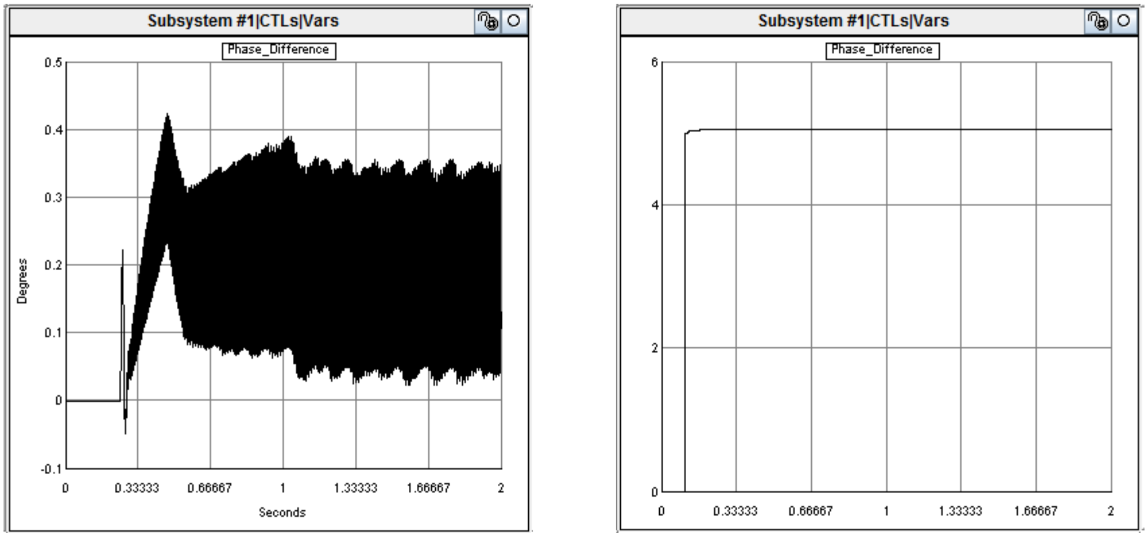

Figure 7. Phase shift A) PV shading B) 3-phase fault

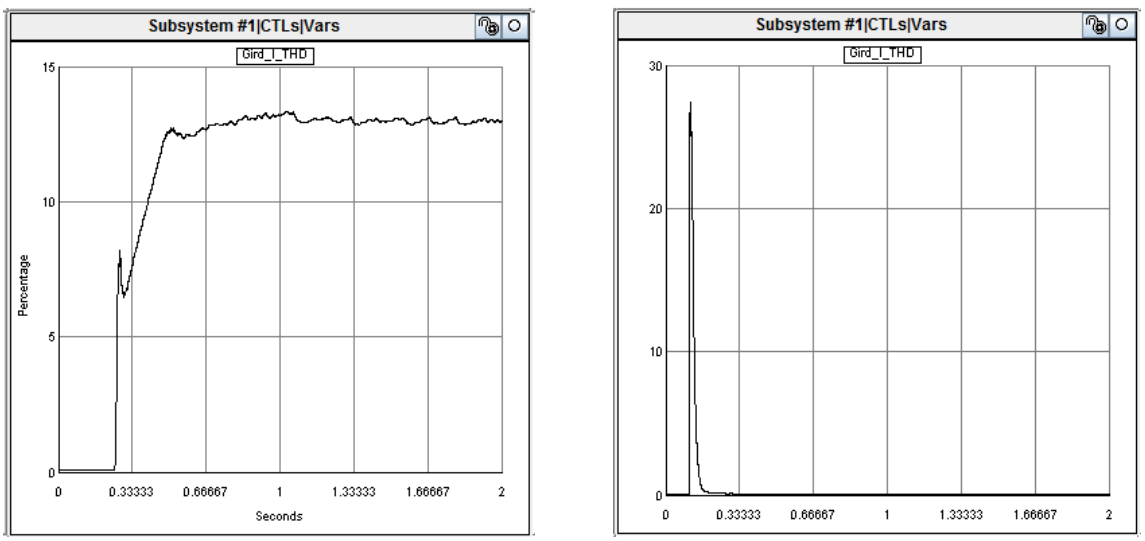

Figure 8. Grid current THD A) PV shading B) 3-phase fault

4. Analysis

This work shows that there are key differences between a 3-phase and PV shading. Most notably is the load voltage, which drops significantly for a 3-phase fault but the reduction in PV output power only causes a voltage drop of 1.25%, figure 4. This is fairly intuitive for grid operators as undervoltage is a common symptom of faults. Also, the grid can compensate for the power lost from the PV generation, stabilizing the voltage at, or near, the nominal value. Undervoltage is a common indication of a fault and protection schemes using undervoltage should not be compromised by PV shading.

The change in grid current is also a noteworthy difference between the two scenarios. Both scenarios produce a very sharp rise in grid current but the steady state current during the events is significantly higher for a fault than loss of PV generation, figure 5. The fault induces grid current 20 times greater than that of the PV generation loss. Certainly losing a greater amount of PV generation would cause a larger current but it would be rare to see the grid current reach the levels produced by a fault from PV shading. The sharp rise in grid current means that protection schemes using dI/dt need to be calibrated properly, or the circuit could mistakenly trip for PV shading instead of a fault.

The grid frequency experiences a brief dip in both scenarios but the dip caused by PV generation loss is 0.05% of the nominal frequency and can therefore be considered negligible, figure 6. Underfrequency is a common indication of a fault and protection schemes using underfrequency should not be compromised by PV shading.

Like the other variables being examined, the voltage phase shift has a similar behavior in both scenarios but the fault scenario produces a greater effect, figure 7. When PV generation is lost the phase shifts ~0.2 degrees, while the fault causes a shift of 5 degrees. Like undervoltage and underfrequency techniques, phase shift should not false trip for loss of PV generation. Though the phase shift caused by loss of PV is not extremely large, PV shading is a repeatable scenario, potentially causing issues on the grid.

The grid current THD is the one quantity that has a different characteristic for each case. When PV shading occurs the THD rises to ~12.5% and stays there but when a fault is placed on the system the THD spikes to ~27% then returns to 0%, figure 8. This is most likely due to the VSC's filter, as the output of the VSC compensates for it when active but cannot when PV shading occurs. This works to the advantage of protection engineers as this distinct characteristic is a way to distinguish between PV shading and faults.

5. Conclusion

The growth of PV generation has prompted utility companies to consider PV generation behavior when planning grid protection. The results and analysis in this paper detail certain variables that are important to consider when designing circuit protection. Throughout the comparisons it can be seen that loss of PV generation mirrors the effect of a 3-phase fault, only with lesser consequences. Common protection techniques, such as undervoltage, underfrequency, and phase shift will most likely not be in jeopardy of false tripping due to loss of PV generation. Protection schemes that incorporate dI/dt could be at risk for false tripping due to the rapid increase in grid current in both scenarios. But, the greatest difference between the two scenarios is the grid current THD produced. While the fault caused a spike in THD, PV shading caused a distinct rise and hold in the value. Therefore, THD can be used as a way to differentiate between PV shading and faults. The grid is changing and protection techniques need to evolve with it. As the regularity of PV generation on distribution circuits grows, information on the effects of PVs and their various operating scenarios, such as the findings presented in this paper, will grow in importance to those tasked with protecting the grid.

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