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# Evaluating Flicker Issues in Power Distribution Systems Due to Distributed PV Generation

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## SUMMARY

This paper discusses the effectiveness of various approaches that power utilities apply to evaluate the severity of voltage flicker caused by photovoltaic (PV) generation connected to power distribution networks. The approaches discussed in this paper can only be used to estimate flicker levels caused by future PV installations, since actual flicker measurement using a flickermeter is not possible at that stage. This paper uses a real-life example to discuss the merits and weaknesses of each approach. The case study includes distributed PV installations planned to be connected to a 34.5 kV distribution feeder in the Northeast of the United States.

## KEYWORDS

Flicker, voltage fluctuation, PV flicker, voltage change.

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## I. INTRODUCTION

The analysis of voltage flicker caused by a PV installation is one of the key requirements in several medium and large sized PV plants interconnection assessments. There are several methods that may be used to evaluate the impacts of PV generation on exacerbating flicker levels of a distribution network. The characteristics of the system and type of PV installation should be considered to decide which method is more suitable for the analysis.

Flicker can be defined as the subjective impression of fluctuating luminance (of incandescent lamp) caused by voltage fluctuations [1]. Mostly, flicker is caused by changes in the power flow (current flow) in an electric network, which in turn causes the voltage to fluctuate. A change in the power flow of a network can be instigated by variations in loading of the system, starting of large motors, loss of a power source, variations in power generation or any other event with a significant impact on power flow.

The perception of flicker is subjective in nature and it is possible that what is irritating to one person may not be noticed by others. However, there is a standardized approach to quantifying flicker levels based on a statistical model of human reaction to incandescent light variability. This approach to quantify flicker levels is based on a 60 W incandescent lamp and the perceptibility of the change in the lamp's luminance by an observer [4].

Historically, flicker has been largely caused by loads with fluctuating power demands. These include arc-furnaces, welders, and large motors during starting operations. The flicker caused by power generation equipment was mostly due to non-uniform rotation of prime movers or imperfections in excitation systems of generators and may not have been perceptible in many cases. With the advent of distributed energy resources (DERs), more unconventional power generation resources are integrated in to the grid and some of these resources are intermittent in their nature. The power generated by PV plants for example depends on the availability of sunlight and should be expected to fluctuate throughout the day based on available irradiance.

PV plants can be the source of flicker when the power output of a plant fluctuates, causing changes to the power system's voltage profile. This change in voltage can be significant enough to cause a perceptible change in the luminance of a light bulb. In the most severe cases, the levels of flicker can be irritating, especially if it occurs more frequently.

High magnitude voltage changes are generally regulated through applicable standards and interconnection requirements. Such regulations are not intended to assess the impacts of a facility on flicker levels. Flicker analysis is concerned with rapid voltage changes of lower magnitudes. Hence, the flicker assessment should involve the determination of the expected voltage change magnitude and some idea of how frequently this change would occur. Based on these estimates, the flicker levels of planned PV installations can be estimated ahead of time. Several utilities and other interconnection partners may use different approaches to estimate flicker levels of future installations. This paper focuses on estimating flicker levels using the $P_{ST}$ equation as recommend by the IEEE Std 1453 [1] and IEC/TR 61000-3-7 [2].

This paper explores the effectiveness of some of the approaches used to evaluate voltage flicker caused by planned PV generation. The merits and disadvantages of each approach are also discussed.

## II. FLICKER CALCULATION METHODOLOGY

The severity of flicker at a given location can be quantified using short-term flicker (Pst) or long-term flicker (Plt) levels. These quantities are measured using a flickermeter at the location of interest. A detailed explanation of the flickermeter is provided by IEC 61000-4-15 [4].

Flicker measurement using flickermeter is only practical for existing facilities. Other ways of estimating flicker must be used to assess the impact of planned installations. The IEEE Std 1453 and IEC/TR 61000-3-7 provide a procedure for estimating flicker levels at a given location

given that certain parameters of the system are known. This way the severity of flicker due to planned installations can be estimated and appropriate decisions can be made.
The flicker analysis of PV installations discussed in this paper estimates the severity of flicker using the guidelines provided by the IEEE Std 1453 and IEC/TR 61000-3-7. The procedure for estimating flicker levels is based on the use of shape factor, in which the voltage fluctuations are approximated using simplified "shapes" such as step-change or ramp change. Detailed explanation of the use of shape factors and flicker estimation can be found in [1] and [2].
The severity of flicker $P_{ST}$ is estimated using the following equation:

$$P_{ST} = \left(\frac{d}{d_{P_{ST}=1}}\right) \times F$$

Where
F – shape factor
d – relative voltage change caused by the planned installation
$d_{PST=1}$ – required value of relative voltage change to produce $P_{ST}$ levels of 1

The flicker analysis is performed under steady state conditions. The relative voltage change is determined by calculating the voltage change caused by a given change in the power output of the PV plants. The factor $d_{PST=1}$ is a constant that depends on the expected number of changes within a given period of time and is determined using the $P_{ST}$=1 curve [2]. A $P_{ST}$ level of 1 is generally considered to be the threshold for flicker perception. The study considered a $d_{PST=1}$ level of 2.56 (which corresponds to two changes per minute). Shape factor (F) depends on the duration and characteristics (shape) of the expected voltage change and can be approximated using simplified voltage change functions. The quantity is determined using the shape factor curves for pulse and ramp changes [2]. The analysis is performed using a shape factor (F) value of 0.2.
In the equation of $P_{ST}$, the only quantity that is expected to change due to power flow fluctuations is the relative voltage change (d). The other two quantities can be assumed to not be significantly affected by changes in the power flow. Once the rate of the expected fluctuations is determined and the shape of the changes is correlated to a ramp or step change, the rest of the analysis will be mostly limited to determining the voltage change in the system due to changes in the power output of the PV plants. The same approach may also be used to estimate flicker levels due to any other type of generation or load.

## III. DESCRIPTOIN OF CASE STUDY

The The flicker analysis presented in this paper is based on a flicker assessment performed on three PV facilities planned to be installed in close proximity to each other. Each facility is rated at 5 MW and are connected to the same 34.5 kV distribution feeder. The facilities are operated independently and have separate point of interconnection (POI) to the distribution network. However, the three POIs are located so close to each other that it can be considered as having the same POI for all practical purposes. This assumption is based on the fact that there is no meaningful change in all relevant circuit characteristics between the three POIs. The voltage measured at all POIs can be expected to be virtually the same for all practical purposes. The network's averaged equivalent impedance at the POIs is provided in Table 1. A circuit diagram of the distribution network showing the locations of the PV plants is provided in Figure 1.

**Table 1: Equivalent Impedance**

| Location | R (ohms) | X (ohms) | Short Circuit MVA |
|---|---|---|---|
| POI | 4.9 | 14.9 | 76 |

The proximity of the PV plants locations makes it necessary to evaluate the impact of the combined capacity of the facilities on the distribution network. The output power of the plants can be expected to change simultaneously, and the simultaneity of these changes will have an adverse impact on the voltage fluctuations of the system. A cloud cover moving in to the area is likely to cause the power generated by all PV plants to decrease simultaneously. Similarly, when a cloud cover moves from the area, the power output of all facilities will increase again. These changes in power export by all facilities at the same time will have an adverse impact on the voltage fluctuations of the distribution network. The magnitude and frequency (how often the voltage changes) of such fluctuations would determine the severity of the expected flicker. Also, the short-circuit strength of the system would affect flicker levels. In general, a strong network (a network with high short-circuit current levels) is expected to be less susceptible to flicker.

The flicker analysis of the PV plants is performed at the proposed POIs of the PV plants. The fluctuating power output of the PV plants will have the greatest impact at the POI as far as voltage fluctuation is concerned. The impact decreases when moving away from the POI. This trend has also been observed in flicker measurements performed on existing PV installations.

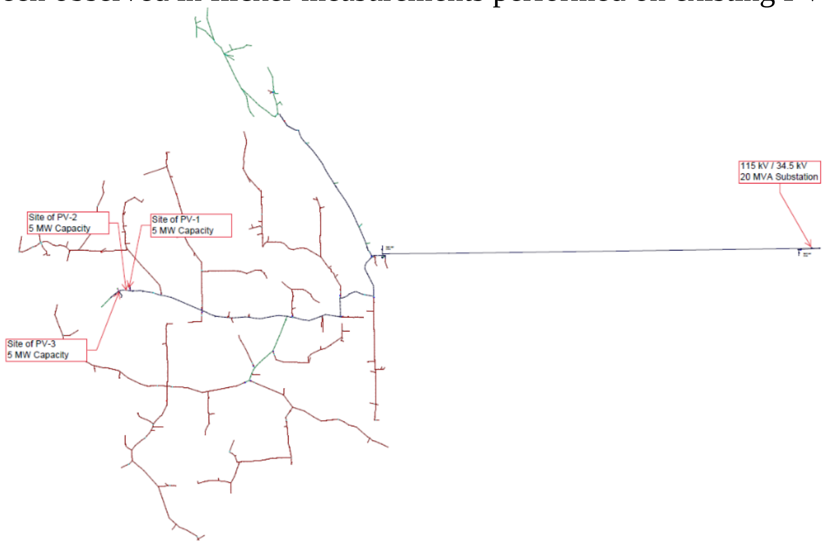


Figure 1: CYME one-line diagram of the system under study

## IV. CALCULATION OF VOLTAGE CHANGE

Three different approaches were used to determine the relative voltage change caused by PV power output fluctuations. The first approach is based on the relative short-circuit strength of the system compared to the power generation capacity of the installations. The second approach is based on the equivalent impedance parameters of the system. The third approach involves a more detailed calculation using a power system simulation software model of the system. A description of the methods used for the analysis along with the merits and drawbacks of each method follows.

### *A. Method 1*

The first method would provide an approximation of the expected voltage change of the system based on the system fault current levels at the POI [1][2].

$$d = \frac{\Delta S_i}{S_{sc}}$$

In the above equation, $\Delta S_i$ is the total apparent power output of the PV plants and $S_{sc}$ is the short-circuit MVA of the grid at the POI. The equation implies that the impacts of fluctuating installations are less pronounced in a strong system, which is commonly defined as one with high short-circuit levels.

The equation can be derived from a simplified model of the distribution system similar to the one provided in Figure 2. Vs is the source voltage and Vo is the voltage at the POI. The distribution system is represented using the Thevenin equivalent impedance as seen from the POI. Using simple circuit analysis tools, the voltage change due to a change in power can be determined. The equation of Method 1 can be derived from the voltage change equation of the network using few mathematical manipulations and certain assumptions. The key assumption is that Xs is much larger than Rs so that the voltage drop due to Rs can be ignored.

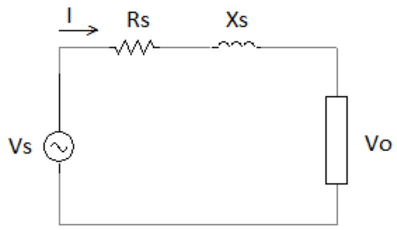

Figure 2: Equivalent Circuit

This approach can be useful for providing a general idea of the impact a new installation may have on voltage fluctuations. Power utilities commonly use this method since its simplicity makes it handy in getting a quick estimate of the severity of voltage changes and flicker levels due to new installations. The drawback of this approach is that the equation oversimplifies the distribution network to only few quantities, that it may not be appropriate to perform an accurate assessment of flicker levels based on this approach alone. The equation fails to provide a reasonable estimate of voltage change, especially when the system impedance has low X/R ratio or the change in reactive power flow is minimal.

The equation may be useful to estimate voltage changes due to installations that cause a significantly large change in reactive power flow as opposed to real power flow. The power flow changes caused by arc furnaces or during the start of large motors are expected to draw significant amount of reactive power that the equation may provide a better estimate of voltage change under such circumstances. The equation may provide an even better estimate in such applications, especially if the X/R ratio of the network is relatively high. An X/R ratio greater than 5 is generally recommended [1][2].

A PV plant is expected to operate at unity or near unity power factor under ideal conditions. As a result, the voltage fluctuations caused by PV installations are mostly caused by changes in real power flow. This makes the use of the simplified equation of Method 1 unreliable to determine the voltage change due to PV installations. However, this equation can be useful to make quick calculations in order to get a general sense of the expected impact of an installation on the system voltage. The results of such analysis, however, should be considered as a rough approximation and very conservative.

Another limitation that leads to the inaccuracy of results of Method 1 is that it fails to account for other factors that may impact system voltage. Any change in power flow will impact the response of voltage regulators, capacitor banks, STATCOMs and many other devices in the system. The actual voltage change at any location will be influenced by several other factors and the simplified equation is not adequate to account for these factors.

The $P_{ST}$ levels of the PV plants was calculated using the relative voltage change equation of Method 1. The PV plants output may be reduced momentarily, due to a moving cloud for example. Assuming the total generation changed by 10 MW during this time, the relative voltage can be determined as shown below.

$$d = \frac{\Delta S_i}{S_{sc}} = \frac{10\ MW}{76\ MVA} = 13.2\ \%$$

The relative voltage change calculated above can then be used to estimate $P_{ST}$ due to the proposed installations at the POI. In this case, the $P_{ST}$ level of the sites due to a 10 MW change in power output is estimated to be 1.03. This level of $P_{ST}$ is considered unacceptable in many cases as it exceeds the planning levels threshold specified in IEEE Std 1453.

It should be noted that the choice of 10 MW power fluctuation from the PV plants is arbitrary. It is possible that the actual power fluctuations will be larger (or smaller). A power fluctuation equal to the maximum plant capacity can also be used to estimate the worst-case flicker levels in which the plant output goes from full capacity to no generation or vice versa.

***B. Method 2***

The second method makes use of the system equivalent impedance at the POI to estimate the expected relative voltage change due to power fluctuations. The relative voltage change is calculated using the equation shown below [1][2].

$$d = \frac{R_S \times \Delta P + X_S \times \Delta Q}{V_S^2}$$

Similar to the equation used in Method 1, the equation of Method 2 can also be derived from the equivalent circuit shown in Figure 2 using simple circuit analysis equations and some mathematical manipulation of the equations.

The approach used in Method 2 considers the changes in real power (ΔP) and reactive power (ΔQ) flows of the network to determine the expected voltage change. Compared to Method 1, this approach is better suited for PV installations as it accounts for changes in real power flow of the system, which is the main root of voltage fluctuations caused by PV plants. The relative voltage change of PV installations should be calculated using this method, especially if the X/R ratio at the POI is low, in which case the equation of Method 1 becomes more unreliable.

The drawbacks of this equation compared to Method 1 is that the equation requires more detailed knowledge of the circuit parameters that may not be readily available. In that sense, this equation may be considered slightly complex than the previous method. Similar to Method 1, this method also fails to account for the impact of other devices and network characteristics that may also have an impact on the voltage profile of the system.

The flicker analysis of the PV plants calculated the relative voltage change at the POI using the equation of Method 2 and an assumed power fluctuation of 10 MW from the PV plants as shown below.

$$d = \frac{4.9 \times 10\ MW + 14.9 \times 0\ MVAr}{34.5\ kV^2} = 4.1\ \%$$

Using the relative voltage change calculated above, the $P_{ST}$ level at the POI can be estimated using the $P_{ST}$ equation to be 0.32, which is less than one-third of what was calculated using Method 1. This level of $P_{ST}$ may be considered acceptable in many cases.

The flicker level estimated using Method 2 is much lower than calculated in Method 1. Given the merits of Method 2 for PV installations explained above, flicker levels presented using this approach are considered a much better estimation of flicker at the POI of the planned PV plants.

***C. Method 3***

The third method of estimating $P_{ST}$ levels makes use of a power system analysis software to determine the expected relative voltage change of the system. The flicker analysis study is performed using a software model of the distribution network to calculate the relative voltage change at the POI due to power fluctuations caused by PV plants. To determine the voltage change, a power flow study was performed using CYME Power Engineering software while changing the output power of the PV plants to simulate the effect of power fluctuations. The change in voltage measured at the POI, caused by a specified change in power output of the PV plants, was used to determine the relative voltage change (d) in the $P_{ST}$ equation.

It should be noted that the results of the power flow analysis only indicate the steady state voltage changes. The transient response of the PV inverters and other circuit components cannot be captured using this method and requires applying electromagnetic transient (EMT) analytical tools.

This approach will provide a much better estimation of the expected flicker levels due to PV installations compared to the previous two methods. A power flow simulation of the distribution network will include the overall response of the system to power fluctuations and accounts for the impacts of other devices that have a direct influence on system voltage. This would provide a more accurate voltage profile of the network, which is more likely to estimate the actual behavior of the system.

The drawbacks of using the approach proposed in Method 3 to estimate flicker levels is that a detailed model of the system in a power system simulation software is required. A network model may not be readily available, or it may require a considerable amount of time and other resources to create one. Furthermore, the analysis of the voltage profile of the system using power flow simulations takes more time than the previous two approaches.

In general, Method 3 is preferred for estimating flicker levels if a software model of the system is available or can be created with minimal effort. The results of the approach are more likely to determine the behavior of the power system accurately.

The flicker analysis of the PV plants under investigation was also performed using Method 3. Power flow simulations of the distribution network determined that the relative voltage change at the POI will be 2% when the power generation of the PV plants changes by 10 MW. The $P_{ST}$ associated with the measured voltage change is calculated to be 0.16 using the $P_{ST}$ equation, which is considerably lower than what was calculated using previous methods. This level of $P_{ST}$ is mostly acceptable and is not expected to cause any irritation to an observer.

## V. SUMMARY AND CONCLUSION

Estimation of flicker levels on distribution networks can be performed using the $P_{ST}$ equation provided by the relevant IEEE and IEC standards [1][2]. A key quantity in the flicker equation is the relative voltage change. The relative voltage change can be determined using several methods which can range from a simple power ratio to running a full power flow simulation of the system.

The paper presented the results of flicker study performed on a 34.5 kV distribution network to which three PV plants with a total capacity of 15 MW are planned to be connected. Flicker levels are calculated using the $P_{ST}$ equation. The relative voltage change required to determine $P_{ST}$ is determined using three different methods.

The first method, Method 1, uses the ratio of the expected power change to the short-circuit MVA of the network to estimate voltage change. The results of Method 1 are too conservative for this application. Also, based on the assumptions used to derive the equation for voltage change, Method 1 may not be appropriate for calculating voltage changes due to PV installations.

The second method, Method 2, uses the equivalent impedance of the system at the POI to estimate voltage change. This approach provides a more reasonable estimate of the voltage change and can be a useful tool if other options are not available.

The third method, Method 3, determines the relative voltage change of the system using power flow simulations. This method is expected to provide a more accurate estimate compared to the other two. However, a detailed software model of the system is required which may not be

available in many cases. If a software model of the network is unavailable, Method 2 may be used as the next best option.
This paper was prepared based on authors experience working on a real-life project in the Northeast of the United States. The proposed PV projects initially failed the local utility's interconnection criteria based on applying Method 1 for flicker evaluation. Authors could demonstrate that the flicker issues identified by the utility were only due to over-simplification and assumptions made in applying Method 1 and is not expected to be reflecting actual operation of the projects. This resulted in meeting flicker requirements and approval of the projects by the local utility.

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