

INVESTIGATIONS OF THE RESPONSE OF A PHOTOVOLTAIC POWER GENERATOR TO MECHANICAL VIBRATIONS

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ABSTRACT: Mechanical vibrations of a solar module mounting rack cause oscillations in the orientation of the module towards the sun. The resulting intensity oscillations of the incident light originate an a.c. current at the module's terminals. We have investigated this effect in the laboratory by means of a vibration table and outdoors where wind forces induce vibrations of the mounting rack. Although the collected results are specific and restricted to our experimental set up and environmental situation we deduce that vibration induced current transients and oscillations of a solar module's output most often will be the dominant origin of distortion in the low frequency regime.

Keywords: Electromagnetic Compatibility – Silicon Solar Cell – Building Integration

1 INTRODUCTION

The fast increasing capacity of distributed energy resources connected to the grid has recently invoked numerous investigations about the proper interfacing to the grid such preserving power quality and avoiding electromagnetic interference [1, 2]. Only little research has been done so far on distortion caused by a photovoltaic power generator itself and transmitted to the subsequent electric conditioning system [3]. Beside the intrinsic noise of the photovoltaic cells numerous external sources can introduce current transients, spikes and oscillations as illustrated by fig. 1.

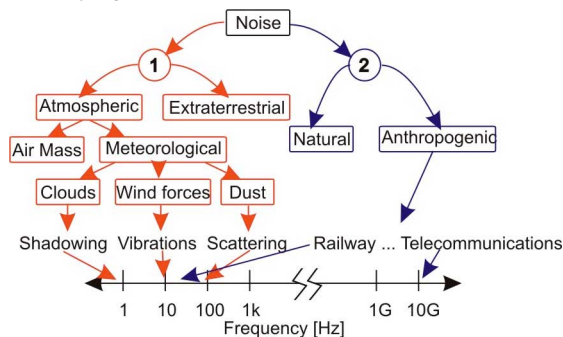


Figure 1: Origin of externally introduced noise in photovoltaic device output (top), examples (middle) and typical frequency ranges (bottom): Light fluctuations (1) are branched in red, radio frequency emissions (2) are highlighted in blue.

These noise sources cover a wide frequency range from below 1 Hz typical for cloud movements up to 10 GHz which is caused by the reception of satellite communication channels. Noise signals originated by light fluctuations are filtered by the internal low pass characteristic of solar cells [4]. Radio frequency signals however can bypass this internal filter. Although the externally introduced current noise at the terminals of a single module may not exceed several mA in amplitude electrical interconnections of an assembly of modules summarises the noise amplitudes which are conducted to the power conditioning unit.

Current distortion in the low to very low frequency regime are extremely hard to remove in the circuitry by a low pass filter without the reduction of the useful d.c.

output. Because of the need to optimise the exposure of solar modules to the incident sun light they are placed on mounting constructions which easily are stimulated to vibrate. These vibrations cause changes of the module's surface orientation with respect to the incident sun rays. As a consequence light intensity oscillations cause current oscillations. Usually the resonance frequency of a mounting construction for photovoltaic applications is in the low to very low frequency range. As previously reported noise amplitudes below 100 Hz sometimes became the major contribution to the observed noise spectra and were attributed to wind induced vibrations of our test module [4].

Currently we investigate the effect of vibration induced current oscillations in detail in the laboratory and under outdoor conditions. In this contribution we present some exemplary results from our measurements in order to highlight the importance of mechanical vibrations as a major source of distortion rather than to present a detailed analysis which unavoidably will be restricted to the specific properties of our experimental set up and ambience.

2 EXPERIMENTAL

The outdoor investigations were done in central Vienna at the roof top of the institute building: Latitude = 48.22165 N, longitude = 16.3558 E and altitude = 202 m determined by GPS. As rack a two axis gimbal mount originally designed for solar irradiance measurements was used which allowed us to vary the inclination manually with a simple lever lock. The horizontal orientation from North, Ψ_0 was kept constant at an angle of 180.7 deg in our experiments. A 10 W_p flat solar module of multicrystalline silicon cells together with an encapsulated three axis geophone from Mark Products Inc. was mounted on the rack. The panel is specified for 17 V operation with an output current of 0.6 A at AM1.5 illumination. The optimally matched load would require an impedance of 28 Ω. We operated the module either with a 21 Ω/25W ohmic resistor as load monitoring the photo-current which remains close to short circuit current at all intensity levels. Alternatively the module was connected to an Agilent Technologies 50V/3A power supply

module (N6762A) inserted in a N6705A frame with integrated measurement and storage capabilities for voltages and currents up to at sample rates up to 10 kHz. The power supply was capable to serve as adjustable sink and allowed us to carry out measurements at different well defined operating points of the module. The specifications of the three geophones are identical and as follows: Sensitivity is 26.9Vm/s, The corner (-3dB) frequency is 4.5 Hz, the slope at lower frequencies is 12dB/oct. Beside these core parameters the following ambient parameters were locally recorded during the measurements: global incident intensity by means of a Kipp & Zonen pyranometer type CM6B, temperature and the wind speed in the range between 1.5 m/s and 15 m/s by an anemometer from Wilh. Lambrecht.

Horizontal and vertical geophone velocities were recorded simultaneously with the light generated current at sample rates of at least 1 kSs⁻¹. The velocities were converted to displacement co-ordinates from the origin, Δx , Δy and Δz by numerical integration. In order to examine the variation of the panel's orientation towards the sun and thus the intensity variations of the incident sun light on the module's surface a transformation in rotation angles in analogy to the yaw-pitch-roll model used in Aeronautics is favourable [5]. The three angles defined by the model are Ψ , Θ and ϕ where Ψ is the horizontal angle from North and is identical to the definition of Ψ_0 above. The pitch angle Θ is the inclination from the horizon and may not be confused with the definition of the tilt angle commonly used in photovoltaic terminology which is defined by the angle between the horizontal plane and the module's plane. The pitch angle Θ equals the angle between the module's surface vector which is oriented perpendicular to the module's surface and the horizontal plane. The tilt angle therefore relates to the pitch angle by (90- Θ) deg. The roll angle ϕ describes a rotation coplanar to the module plane. Therefore at least for flat plate modules ϕ should not contribute to intensity variations caused by the displacement. During our experiments we varied the inclination Θ_0 between 90 deg (tilt angle=0 deg, horizontal module position) and 5 deg (tilt angle=85 deg, steep module position). The transformation is given by the following equations:

$$[x + \Delta x, y + \Delta y, z + \Delta z] = [x, y, z] R_\Psi R_\Theta R_\phi \quad (1)$$

$$R_\Psi = \begin{bmatrix} \cos \Psi & \sin \Psi & 0 \\ -\sin \Psi & \cos \Psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$R_\Theta = \begin{bmatrix} 0 & 0 & 1 \\ \cos \Theta & \sin \Theta & 0 \\ -\sin \Theta & \cos \Theta & 0 \end{bmatrix} \quad (3)$$

$$R_\phi = \begin{bmatrix} \cos \phi & \sin \phi & 0 \\ -\sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Assuming the mounting rack to be a rigid body, solely the horizontal displacement given by Δx and Δy is independent whereas the vertical component Δz is a function of Δx and Δy . Consequently calculating the variation in orientation ($\Delta\Psi$) and inclination ($\Delta\Theta$) further simplifies.

Under laboratory conditions various solar cells were mounted on a vibration table in a vertical position. The device under examination was illuminated by a halogen lamp unit with a focusing mirror which emits a narrow light beam. The angle of misorientation determined by the cell's surface vector and the optical axis of the light source was arranged in a horizontal plane and varied between 0 and 1.2 rad. The vertical Z-axis of the vibration table was displaced sinusoidal at different frequencies without any additional excitation of the horizontal X and Y axis.

3 RESULTS AND DISCUSSION

Prior to evaluating data at different weather conditions mechanical vibrations were invoked by applying short manual forces to the mounting rack. This was done by simply pushing or pulling the rack on a clear sunny day during periods where the wind velocity was below detection limits. Knowing the horizontal displacement and the sun's position the effect of varying misorientation of the module's surface relative to the geometrical path of sun rays and thus the variation of the incident light intensity, P_{inc} on the module's surface were calculated as well as the vertical displacement for the rigid body simplification. A comparison between the measured and calculated values of Δz shows that the experimentally observed elongation always was at least one order of magnitude larger than calculation. That indicates that the rigid body assumption is not justified. None the less a comparison of the model calculations of oscillating P_{inc} and the recorded module's current I_{module} qualitatively agree fairly well in several cases. After the application of a short force in North – South direction the rack is horizontally displaced at similar amplitudes as well in N-S as in E-W direction. The magnitude was generally less than 2 mm in one direction. The rack oscillates at frequencies between 4 Hz and 5 Hz. The frequency shifts as the centre of mass of the system changes which depends on the adjusted inclination since the construction is not well balanced in the centre of the gimbal axis. The frequency of the E-W displacement always differed somewhat from the frequency of the N-S displacement resulting in a rather complex horizontal trace of the total displacement. The observed damping time constant typically was about 4 s. Vertical displacement oscillations occurred at much higher frequencies of 16 Hz to 18 Hz. In order to extract the measured photo-current oscillations in time intervals of 2 s in a first step a linear fit accounting for the d.c. value of the photo-current, I_{DC} , and potential slow variations of sun light intensity was performed. The linear response than was subtracted from the original data set. The residual of the photo-current, I_{AC} , was Fourier Transformed and the amplitude spectra were compared with the displacement oscillations. Within the uncertainties due to changing ambient conditions during the various experiments the magnitude of the a.c. photo-current increases linearly with the amplitude of horizontal displacement. At different incident light intensities the relative a.c. photo-current defined as the ratio $I_{rel}=I_{AC}/I_{DC}$ remains roughly constant for similar excitation conditions of the mounting rack.

Model calculations of the variation of the incident light intensity P_{inc} were carried out using the measured horizontal displacement amplitudes and compared with the relative changes in the module's photo-current. Beside the simplifications of the model described above it shall be noted that the calculation accounts solely for direct radiation with a geometrical light pass. Practically a significant but not measured portion of diffuse sun light was present during our experiments due to the hazy air conditions and Albedo reflection.

Since for our load resistor $I_{module} \approx I_{sc} \propto P_{inc}$ is valid under all illumination levels the relative amplitudes as defined below are compared:

$$P_{rel} = \frac{P(\Psi_0 + \Delta\Psi(t), \Theta_0 + \Delta\Theta(t)) - P(\Psi_0, \Theta_0)}{P(\Psi_0, \Theta_0)} \quad (5)$$

$$\Delta\Psi(t) = f(\Delta x(t), \Delta y(t)) \quad (6)$$

$$\Delta\Theta(t) = g(\Delta x(t), \Delta y(t)) \quad (7)$$

Ψ_0 and Θ_0 are the static, undisturbed angles of the module's orientation. The functions f and g are the inverse operations to Eq. 1 with respect to the simplification described earlier.

Subsequent measurements with different module inclination were carried out using manual forces in N-S direction. Measured and calculated magnitudes of the oscillations were compared (fig.2). The measurements were done on the 20th August at about 16:30 in the afternoon where the misorientation of the module to the incident sun rays was between 30 deg and 75 deg depending on the inclination shown in fig.2 as magenta coloured line (right axis). The smallest deviation from optimal alignment in the module's orientation would be for a tilt angle of 20 deg.

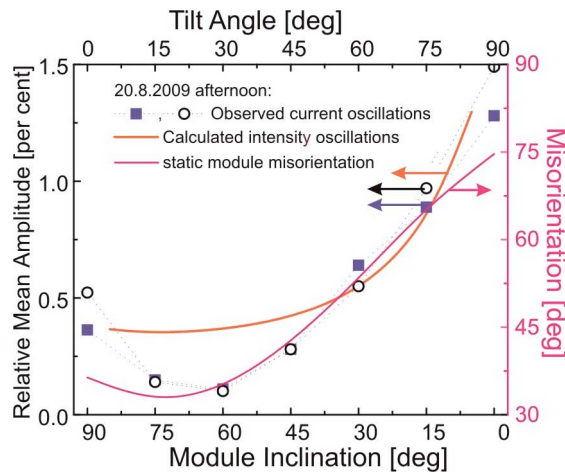


Fig. 2: Dependence of the magnitude of vibration induced current oscillations on the module's inclination

For $\Theta_0 < 45$ deg calculations (orange coloured line in fig.2) and experimentally observed current oscillations (symbols) are in fair agreement. However calculations result in values significantly too high at low misorientation angles most likely due to the simplifications in the calculation. Although a correspondence between misorientation angle and the magnitude of distortion can be

clearly seen by comparing the tendency of the symbols with the magenta line in fig.2. Obviously it is not a simple linear dependence. A little surprising is the circumstance that the smallest current amplitudes do not occur at minimal misorientation. The minimum in the first case was experimentally observed at an inclination angle of 60 deg, whereas the least misorientation would be around 70 deg of inclination. For larger misorientation the distortion increases stronger than linear.

On several days with different weather conditions as by means of wind speed and cloud cover current oscillations, vibrations and wind velocities were monitored during the day at sampling rates of 10 kSs⁻¹. In the period of observation the highest recorded wind speeds were a little more than 15 ms⁻¹. The cloud cover ranges from dense rain clouds to clear blue sky. On average the observed displacement amplitudes and corresponding photo-current oscillations with respect to the panel orientation towards the sun scale directly with the average wind speed. Since we assume that vibrations are preferentially introduced by a sudden change in wind speed we tried to correlate the acceleration obtained from the wind speed recordings with the appearance of high displacement and photo-current oscillations. The response time of our anemometer was determined to be 0.75 s which seems to be sufficiently fast enough to obtain acceleration in real time. However only in a few out of many examined cases we could resolve a doubtless coincidence between wind acceleration and rack vibrations. One major reason for the unsatisfactory resolution presumably is the distance between the location of the rack and the position of the anemometer of more than 5 m which could not be reduced because of the limited cable length between anemometer head and its electronic unit which is placed in house. Therefore we currently restrict our observations on statistical data evaluation. A typical example is given in fig.3 which shows the number of occurrences where the amplitude at a distinct frequency in the monitored frequency range of 2.5 Hz to 5 kHz is the largest. Two results are shown for similar ambient conditions but different inclination angles, namely 45 deg and 15 deg. In order to ease the comparison the occurrence count was normalised to the total number of samples taken. Although the average and peak wind speeds remain low during the whole observation period for about 50 per cent of all events the largest amplitude was seen at the typical vibration frequency of 5 Hz. The additional peaks above 100 Hz with two orders of magnitude lower probabilities were identified to arise from electromagnetic distortion caused by a large cooling unit nearby. Although both distributions are similar the magnitude of the largest oscillations differ significantly. For an inclination of 45 deg a peak value of 0.76 mA or 0.13 per cent was recorded. During the observation with an inclination of 15 deg where the module was mounted steeper than before the largest current amplitude was 6.29 mA or 1.37 per cent. The increased amplitude for the steeper module orientation is in agreement with our experiments on the inclination dependency of the vibration effect.

Laboratory investigations widely confirmed our outdoor results. However several small additional effects were resolved which potentially arise from the cell's or module's surface topology causing locally shadowed areas. A more detailed analysis is currently under progress.

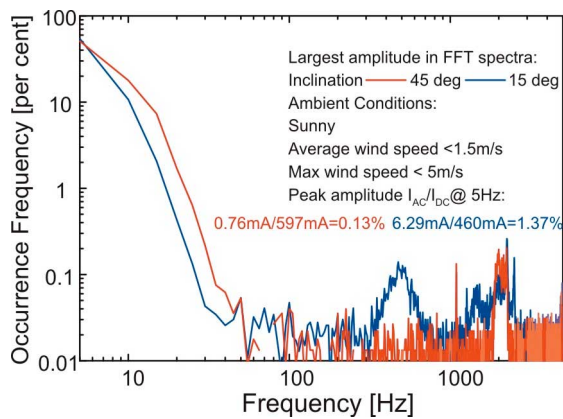


Fig. 3: Example of statistical evaluation showing the relative number of occurrences that the largest amplitude was observed at a certain frequency.

4 CONCLUSIONS

Although the presented exemplary results were obtained on an individual small photovoltaic system we believe that vibration induced current oscillations caused by wind forces are a widespread and often the dominant source of low frequency distortion. Once several conditions are met at the same time the magnitude of current oscillations easily can exceed one per cent of its d.c. value. Obviously the magnitude of mechanical oscillations depend on the mounting construction and will increase with increasing wind forces. Due to thermal management of photovoltaic collectors construction design favours good ventilation conditions which in return eases wind attacks. Thus vibration induced distortion appears to be unavoidable.

Low incident angles of direct sun radiation with respect to the module's orientation can reduce the magnitude of the distortion. Therefore tracked concentrating systems potentially will experience less distortion than building integrated photovoltaic facades. Although in the first case the mounting system permits large displacements caused by external forces it is permanently facing the sun. Due to their large inclination angles facades however are considerably misoriented towards the sun most of their operation time.

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