Study of a PV – Grid Connected System on its Output Harmonics and Voltage Variation

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Abstract: The effects of solar radiation level and its fluctuations on the voltage levels and power quality at the point of common coupling (PCC) of a 4.5 kWp PV-grid interactive system are reported. Radiation level, PV array output and power quality parameters at the PCC are monitored. The power quality parameters measured are the complex, active and reactive power, the power factor, the voltage and current of each harmonic - up to the 31st harmonic. Analysis is made based on various levels of radiation (300-1000 W/m^2) and its rates of change (4 – 33 W/m^2/s). It is found that at all the radiation levels and fluctuations studied, the voltage fluctuation at the PCC is 1-3 V, well within the prescribed standards. The average increase in the percentage of total harmonic distortion current

(%THDc) is below 6% and is relatively even at all radiation levels and rates of change. There are certain correlations between radiation levels and fluctuations and power harmonics.

Keywords: Solar radiation; PV grid-connected systems; Voltage fluctuations; Harmonics; Power quality.

Introduction

Electrical loads of a household with a roof-top PV-grid connected system can draw power from a PV module, typically 3-5 kW rating, via an inverter in addition to power from a distribution transformer, Figure 1.

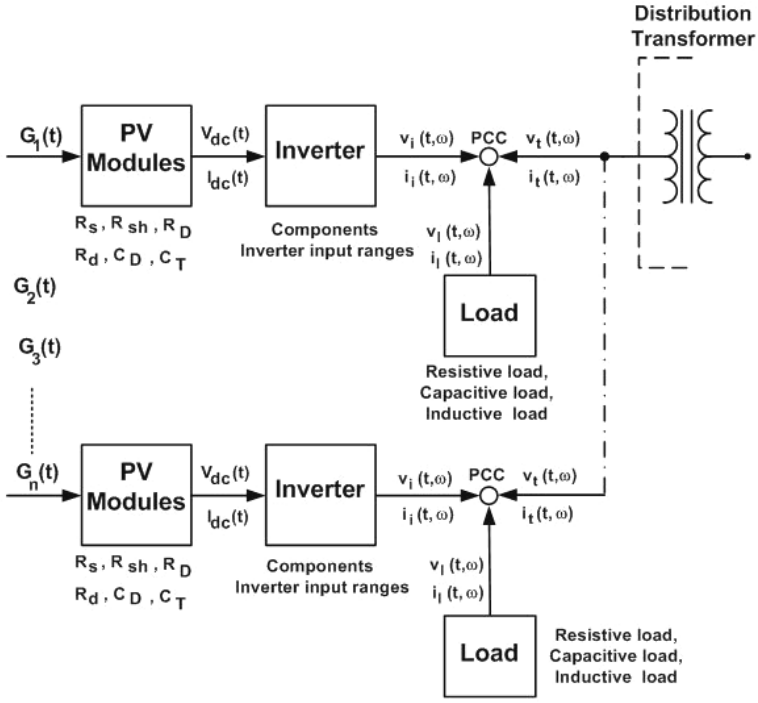

Figure 1. Schematic picture of PV-grid interactive systems connecting a to distribution transformer.

Fluctuation in solar radiation due to moving and amount of clouds and electrical characteristics of PV modules determine dc voltage and current outputs of the PV array. In turn, the PV outputs becoming inverter inputs, in conjunction with the inverter nature (types of circuits and components employed), dictate the inverter ac voltage and current outputs and electrical power quality at the load. The power quality is normally measured at the point of common coupling (PCC) of an inverter, a load and the low voltage end of a distribution transformer. Thus factors influencing the power quality are varied and the interactions between these factors are complex. The more the number of PV-grid interactive systems connected to a transformer, the more the complexity. Apart from power quality of grid-connected or distributed electricity generating systems, whose standards are set by electrical utilities, islanding effects are of concerned. To understand such interactions, study are normally taken on ac or dynamic characteristics of PV modules/arrays, nature of radiation fluctuations and inverter characteristics. The dynamic parameters of interest are series, shunt and dynamic resistance as well as transition and diffusion capacitance [1],[2].

After nearly two decades of PV stand-alone applications, such as water pumping, centralized battery charging stations at village level, repeaters for telecommunication units and village telephone services and PV- hybrid units in niche applications, grid-connected applications were promoted by the Energy Planning and Policy Office (EPPO) of Thailand in 1998 [3], [4],

[5], [6]. As of 2004, over 30 such systems have been installed in Thailand under the first national demonstration program on PV-grid interactive systems. These systems are funded by EPPO and installed by the Electricity Generating Authority of Thailand (EGAT). Under the national program, there are 10 roof-top grid-connected systems in urban households, whereas the remaining units are at public schools and government buildings. Each of the systems is of 3-4 kWp range. EPPO is now funding the second phase of 50 roof-top grid-connected houses, 70% of the cost is borne by EPPO.

Limited investigations are made on these PV grid-connected systems. As far as the Thai experience is concerned the first preliminary report on power quality of a grid-interactive system was made in 2003[7]. It is reported that the inverter supplies power of low quality at low level of solar radiation. Under such conditions the PV output power and the corresponding inverter input power are low. The inverter when operating under such low input power exhibits large nonlinearity, hence output power with more harmonics. The Clean Energy Systems (CES) Group of the University has monitored four systems installed in Bangkok, Samut prakarn in central Thailand and Chiang Mai in northern Thailand [7], [8], [9], [10]. It is also known from previous studies world- wide in the last few years that the power quality of the output of grid-connected systems depends on radiation, the characteristics of PV arrays and BOS .

In this paper, a more comprehensive study on power quality of a grid-connected system is reported, based on an extensive study of J. Thongpron [11]. Particular attention is paid to effects of solar radiation levels and their fluctuations on harmonics observed, not covered in the earlier reports.

Experiment

The PV grid-connected system under study is at a demonstration site on renewable energy, geothermal, solar thermal and solar cells, of EGAT at Sankampaeng, in the province of Chiang Mai in northern Thailand. The system consists of a 4.5 kWp array (60 panels of 75 Wp Siemens X-Si PV modules connected into 15 panels in series and 4 strings in parallel) and a 3.5 kW locally made, grid-connected inverter. The electrical loads of the system are lighting, computer, heater, office and domestic appliances of the site monitoring office. Figure 2 shows the system configuration and measurement points of the system. The following measurements are taken :

- solar radiation at every 1 second,
- PV voltage and current at every 1 second , and
- real, reactive and apparent power from the fundamental frequency up to the 31^{st} harmonic of inverter output, load voltage and low voltage end of the distribution transformer. Measurements are taken every 12 seconds.

Over 500 data points are taken and analyzed.

For the purpose of analysis of solar radiation levels and their fluctuations, we group

- radiation levels into 7 levels at 100 W/m^2 intervals, starting from the lowest level of under 300 W/m^2 to the highest level of above 900 W/m^2. The changes in radiation level would correspond to different times of day and the type and amount of clouds in the sky, and
- rates of change of radiation into 5 categories, i.e. 4-8 W/m^2/s to above 20 W/m^2/s.

The different rates of change of radiation are due to various speeds of cloud movements.

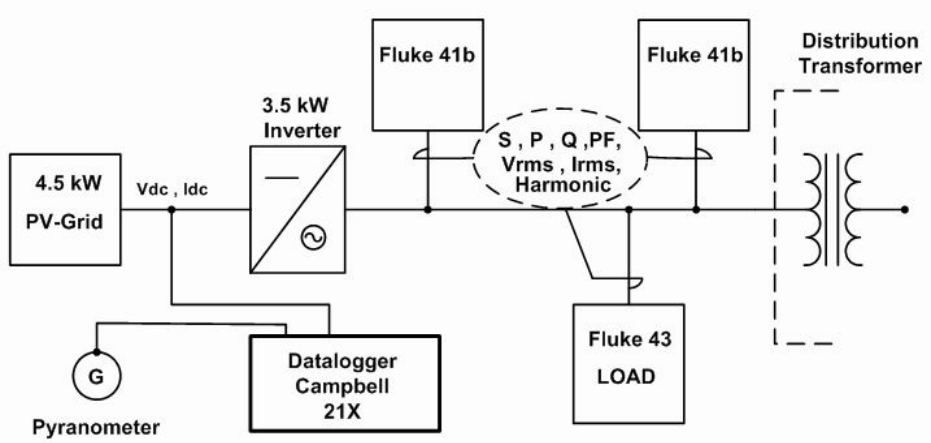

Figure 2. System configuration and measurement points of a PV grid connected system.

Results and discussion

When the inverter input power is compared with solar radiation (not show here), the inverter input power varies linearly with the radiation, as can be expected. On the inverter output side, the power factor becomes smaller and the phase angle gets larger at low radiation levels. As it has been mentioned above, this is because at low radiation levels, hence low PV output power and low inverter input voltage, the inverter operates nonlinearly.

By plotting the inverter output current and its %THDc at the PCC with the solar radiation, we can see from Figure 3 that

- the output current varies linearly with radiation, and
- nonlinearity of the inverter becomes large at low radiation, as manifested by large %THDc. Under such conditions, electrical power of low quality will be ejected into the distribution system. The magnitude of the harmonic currents at low radiation is small, even though the % THDc is large. However, if a large number of PV grid-interactive units are connected to a distribution system, methods must be found to lessen this detrimental effect, otherwise the electrical power system quality will deteriorate.

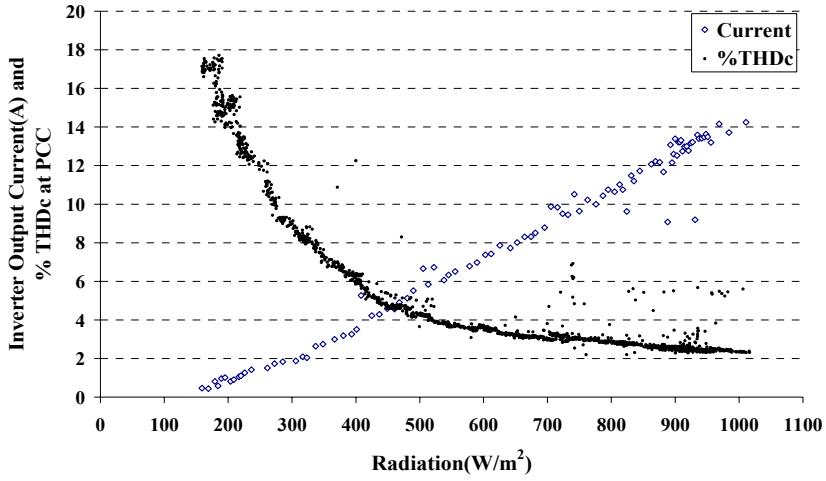

Figure 3. Relationship between inverter output current and % THDc at PCC.

Next the effects of the radiation level and radiation fluctuation rates on inverter output were examined. It is previously reported, based on a separate site measurement near Bangkok in central Thailand, that inverter output harmonics are influenced by inverter input, hence, radiation level [7]. This is also observed in the present study, Figure 3. Previous studies did not look into detailed effects of radiation levels and their fluctuations. It is further suspected that not only the radiation level determines the power quality, but the rate of change of radiation level could also affect inverter output harmonics. Hence, quality of power supplied by grid-connected inverters to the distribution network could depend on fluctuations in radiation level or cloud movement.

Figure 4 illustrates the relationship between the voltage variation at PCC with different radiation levels and rates of radiation change. It is evident that at all the radiation levels and fluctuations studied, the maximum voltage fluctuation at the PCC is 1-3 V. This is well within the prescribed standards. While the majority of the average voltage variation is below 1.5 V, the two over 1.5 V cases are due to the fact that only one measurement point was taken. There is no discernable difference in the magnitude of the voltage variation at PCC due to different radiation levels and fluctuations. This could be explained in terms of damping of voltage fluctuations by capacitors in the inverter. It is concluded, from the study at this site, that rates of radiation change are of no significance to the voltage fluctuation at the PCC.

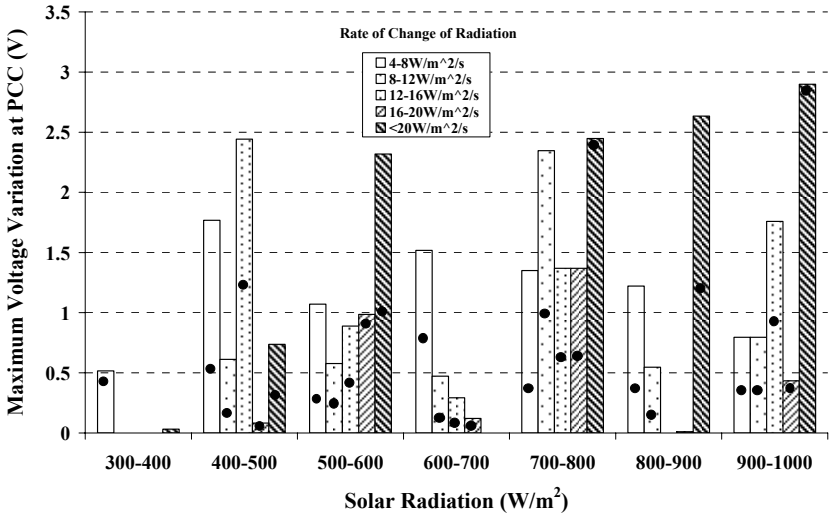

Figure 4. Relationship between voltage variation at PCC, solar radiation and rates of change of solar radiation. The black points are the average values.

In Figure 5, the %THDc of inverter output is compared with different radiation levels and rates of radiation change. It can be seen that the maximum %THDc is somewhat larger than the maximum voltage variation (in percentage terms) at the PCC under the same conditions. It is also observed that the average increase in %THDc is below 6% and is relatively even at all radiation levels and rates of change. However, it must be borne in mind that the actual values of harmonics current increase with radiation, the larger the radiation the bigger the harmonics current.

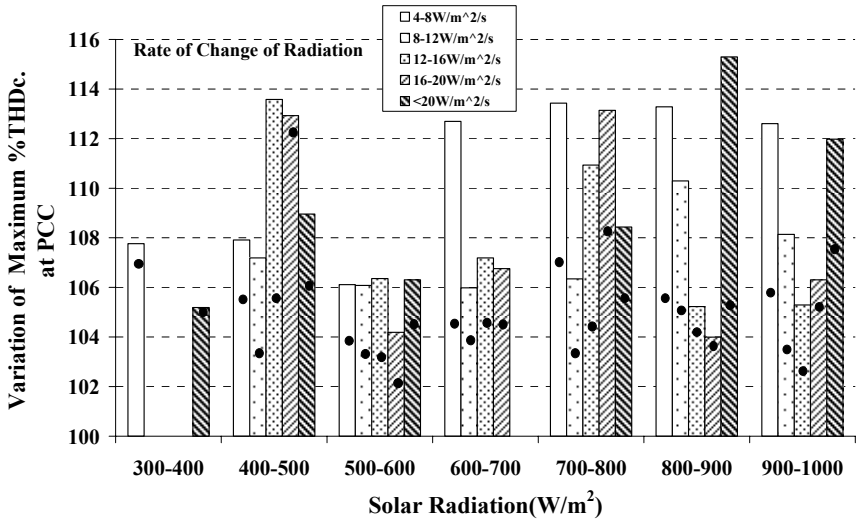

Figure 5. Relationship between % THDc at PCC, solar radiation and rates of change of solar radiation. The black dots are the average values.

Lastly, the correlation coefficients between harmonic distortion power- THDp of each harmonic of the inverter output (up to the 31st harmonic) and four rates of changes of radiation

at the three levels of radiation are calculated. A number of observations can be made, namely,

(i) At the three levels of radiation studied, the magnitude of correlation coefficients are significant, over 0.6. At the lowest level, 0-400 W/m^2, correlation is slightly higher than those at higher radiation and correlation is more positive, and

(ii) Odd harmonics are dominant at low levels of radiation.

It is believed that what has been observed is primarily determined by the nature of the inverters used, in addition to effects of radiation levels and rates of change. At this stage, the relative importance of the effects due to radiation and those due to inverters cannot be separated. Greater understanding of these would be important in designing power conditioning equipment for PV-grid interactive systems to reduce the harmonics whose effects would become more important as more grid interactive units are connected to distribution lines. It is intended to undertake more measurements of other systems installed throughout the country, particularly those with different inverter types.

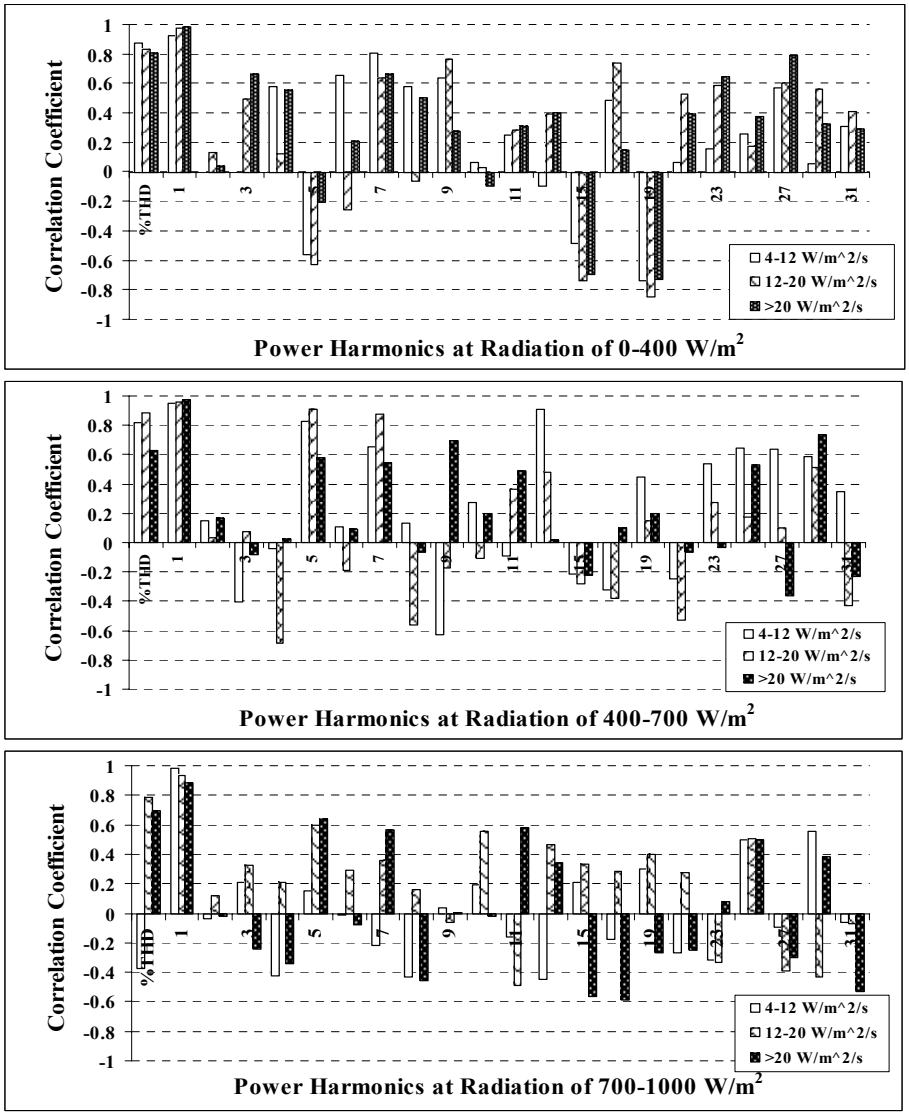

Figure 6. Relationship between correlation power harmonics of inverter output up to the 31st at PCC and rates of change of solar radiation.

Conclusion

The effects of solar radiation levels and their fluctuation on the voltage levels and power quality at the PCC of a 4.5 kWp PV-grid interactive system were studied. It was found that at all the radiation levels and fluctuations studied, the voltage fluctuation at the PCC is 1-3 V, well within the prescribed guidelines. The maximum %THDc is larger than the maximum voltage variation (in percentage terms) at the PCC under the same conditions. The average increase in %THDc is below 6% and is relatively even at all radiation levels and rates of change. However, the actual values of harmonics current increase with radiation, the larger the radiation the bigger the harmonics current. Even though the magnitude of the voltage fluctuations and % THDc of the system under study fall within prescribed guidelines, as more units of grid-interactive systems are connected more harmonics will be injected into the distribution system. Lastly, there are certain correlations between radiation levels and fluctuations and power harmonics.

Acknowledgements

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References

[1] Chenvidhya, D., Kirtikara, K., and Jivacate, C. (2003) A new characterization method for solar cell dynamic impedance, *Solar Energy Materials and Solar Cells* , Vol. **80**, pp. 459-464.

[2] Chenvidhya, D., Kirtikara K., and Jivacate, C. (2004) PV module dynamic impedance and its voltage and frequency dependencies, *Solar Energy Materials & Solar Cells*, [in print].

[3] Kirtikara, K. (2004) Lessons learnt from using PV stand-alone systems to provide a better quality of life for rural people, *Technical Digest of the 14th PVSEC*, Bangkok, Thailand.

[4] Kwanmuang, P., Kirtikara, K., Songprakorp, R, Thepa, S., and Suwannnakum, T. (2001) Assessment of photovoltaic pumping systems in Thailand – one decade experience, *Solar Energy Materials and Solar Cells* , 2001, Vol. **67,** 2, pp. 529-534.

[5] Songprakorp, R., Somsak, T., Thepa, S. and Kirtikara, K. (2001) Assessment of centralized rural-based photovoltaic battery charging station in Thailand, *Technical Digest of the 12th PVSEC*, June 11-15, Korea.

[6] Boonbamroong, U. (2004) Techno-Economic Assessment of PV/Wind/Diesel Hybrid System Installation at Two National Parks in Thailand, *Technical Digest of the 14th PVSEC*, Bangkok, Thailand.

[7] Chenvidhya, D., Thongpron, J., Sangpanich, U., Wongyao, N., Kirtikara, K. and Jivacate, C. (2003) A Thai national demonstration project on PV grid – interactive systems: Power quality observation, *Proceedings of the 3rd WCPEC*, Osaka, Japan.

[8] Thongpron, J., Sangpanich, U., Limsakul, C., Kirtikara, K. and Jivacate, C. (2004) Effects of radiation level and fluctuations on voltage variation and harmonics at the point of common coupling (PCC) of a PV-grid interactive system, *Technical Digest of the 14th PVSEC14*, Bangkok, Thailand.

[9] Sangpanich, U., Thongpron, J., Kirtikara, K. and Jivacate, C. (2004) Study of moving cloud effects on the power quality of grid-connected photovoltaic system compared with simulation of PV power using a DC generator, *Technical Digest of the 14th PVSEC14*, Bangkok, Thailand.

[10] Sangpanich, U., Thongpron, J., Kirtikara, K. and Jivacate, C. (2004) Power quality of four rooftop grid-connected photovoltaic systems, *Technical Digest of the 14th PVSEC14*, pp 139, Bangkok, Thailand.

[11] Thongpron, J. (2004) Study of parameters affecting power quality of PV-Grid connected systems, Doctor of Engineering Thesis in Energy Technology, School of Energy and Materials, King Mongkut's University of Technology Thonburi, Bangkok, Thailand.