A REAL-WORLD PERFORMANCE COMPARISON BETWEEN PARALLEL-ONLY AND SERIES/PARALLEL ARRAY CONFIGURATIONS UNDER NON-UNIFORM CONDITIONS

A. Driesse
Queen's University
Kingston, Canada
anton.driesse@queensu.ca

B. Harris
Sustainable Energy Technologies
Calgary, Canada
brent.harris@sustainableenergy.com

ABSTRACT: Mismatch losses due to non-uniform conditions such as partial shading are the focus of much attention. New products aimed at reducing those losses in long series strings introduce system complexities while promising substantial performance gains. A simpler strategy to combat mismatch losses is to reduce the number of modules in series, and increase the number of modules parallel. This study compares two nearly identical 5kW a-Si arrays to evaluate both the magnitude of mismatch losses and the performance gains that a parallel configuration can provide under various non-uniform conditions. It is also the beginning of a long-term evaluation that will ultimately provide design guidelines and cost-benefit analysis.

Keywords: system design, performance monitoring, mismatch losses, amorphous silicon

1 INTRODUCTION

Guided by the market dominance of feed-in-tariff (FIT) support policies, the PV industry has become increasingly focused on economic performance. With these policies revenue is directly proportional to system performance, which depends not only on the components that make up the system, but also on how they are integrated. Non-uniform conditions at the system level can cause mismatch losses, and the potential loss of revenue justifies investment in system integration solutions to minimize those losses.

2 PROJECT OBJECTIVES

The motivation for this project is the desire to validate the hypothesis that an array consisting of shorter strings suffers lower mismatch losses than one with longer strings [1], and to quantify the difference. However, there are multiple objectives along the way.

First, there is a need to better understand the impact mismatch losses in real systems. The principles are well understood and can be dramatically demonstrated with well-chosen examples, but the long-term impact on the bottom line of an average commercial system is not so well understood. The systems under study represent this type of system, and will be monitored for many years to come.

Second, there is a need for software to model and predict mismatch losses. The study will provide very detailed monitoring to allow different system losses to be distinguished. Experiments are further planned to purposely introduce some non-uniformities (shading in particular) so that cause and effect are clearly linked. This data will be used together with similar data from other projects develop appropriate models.

Third, there is a need for practical design rules and guidelines. Lessons learned from experiments and models must be translated to high-level advice that makes is possible achieve not only good system performance but good economic performance as well.

3 BACKGROUND

3.1 Mismatch Losses

PV arrays are composed of modules connected in series and/or parallel to reach the desired power level, current rating, and operating voltage range. This electrical configuration must fit the capabilities and constraints of the chosen inverter, or alternatively an appropriate inverter must be sought to accommodate the chosen array configuration. Conventional sizing and design methods assume that the electrical output of an array of given capacity will be the same, regardless of how many modules are placed in series or parallel. Nevertheless, it is commonly recognized that there will be losses due to module mismatch, as well as various types of soiling and shading that can be non-uniform. It is difficult to predict the magnitude of these factors, and it is even more difficult to predict the losses they cause. Long strings of cells and modules are particularly vulnerable to non-uniform conditions since the string current is limited by the poorest performers.

3.2 Sources of Mismatch

Mismatch between modules can arise due to a variety of factors. For example:

1. Variations in STC module performance due to manufacturing tolerances. Sorting modules into series strings with similar currents can help to reduce the effect of this mismatch, but is time consuming. With amorphous silicon technology, this may not generate any advantage at all since the flash test data shows only the initial performance. Strings may become 'unsorted' after a few months due to variations in the amount of Stabler-Wronski degradation. [2]

2. Variations in magnitude and phasing of the seasonal annealing effect. When amorphous silicon modules are exposed to high temperatures for extended periods of time, the initial degradation effect is partially reversed. If all modules do not anneal or degrade in the same magnitude or at the same time, mismatch can occur.

3. Soiling. Depending on its location on the roof or within the array, or due to randomly occurring events, a module may collect more or less dirt than its neighbours. Bird droppings, leaves, and other objects settling on the module surface can result in mismatch losses.

4. Snow. In addition to a general reduction in system output due to snow cover, mismatch losses may also be produced by uneven snow cover.

5. Partial shading. While it is advisable to avoid shade during system design, this is not always entirely possible. Shade can result from a variety of obstructions, but usually falls into one of the following categories:

    - 'Wires' (nearby power or communication lines, guy wires supporting towers).
    - 'Poles' (chimneys, antennas, flagpoles)
    - 'Boxes' (HVAC RTUs, chimneys, parapets)
    - 'Row-to-row' (like boxes, but in the control of the array designer)

6. Variations in module installation angle. This is usually the result of a choice by the designer to prioritize aesthetics, cost, or some other criteria over performance. It is important to be able to quantify the resulting performance reduction in order to help designers make the right decisions.

3.3 Remedies for Mismatch

It is not possible to change the fundamental nature of PV cells and eliminate mismatch conditions, but there are various remedies available for reducing the associated system losses.

Bypass diodes

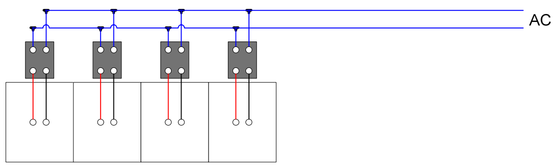
Bypass diodes are included in PV modules in order to meet reliability and safety requirements. When a cell is shaded, it can be forced into reverse voltage by unshaded cells in series with it. This reverse voltage causes heating that can damage the module or potentially cause a fire. The bypass diode protects cells from excessive reverse voltage by taking it and the other cells connected in series across the same diode out of the string. In the process, it also prevents these shaded cells from limiting the output of the remaining cells in the string and so is somewhat effective at mismatch reduction due to occasional partial shading. However, since significant mismatch is required to activate the diode, it is ineffective at addressing the smaller persistent effects.

Multistring inverters

Multistring inverters use several MPP tracking DC/DC converters to feed a single DC/AC inverter. Each converter can control the operating voltage and current of a separate subarray in order to extract the maximum possible power. Multistring inverters are sometimes used in applications such as 'hip roof' residential rooftops where modules are installed in two or three different orientations but are not as effective at addressing any of the other sources of mismatch that may be present within individual strings.

Module scale inverters

Module scale inverters installed on or near the module convert module output to AC before interconnection in parallel on a branch circuit. Each module's maximum power point is tracked by its own inverter, so mismatch losses are effectively avoided.

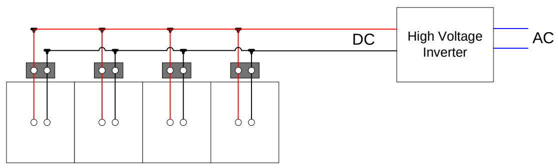


Module Scale Inverters

Module scale MPPT

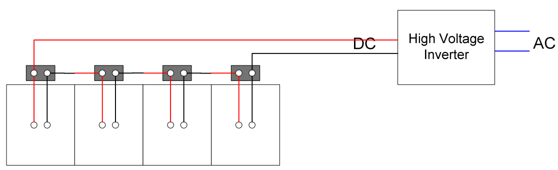
Module scale, or Distributed, MPPT involves placing a simpler DC/DC converter at the module level in order to maximize power output, but still requires a high voltage inverter. There are two ways these are used:

In the first, the output of each module is boosted to match the input voltage of the inverter. All of the boosted module outputs and the inverter input are then connected in parallel.



DMPPT - Boost

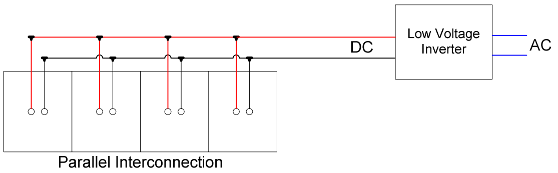
In the second, the DC/DC converter acts as an active bypass that can accurately control the amount of current allowed to bypass a shaded module rather than the simple on/off of the bypass diode.



DMPPT – Active Bypass

All parallel wiring

A simpler approach is to connect all of the modules in parallel without using any electronics.



This way, although the modules all share the same voltage, their currents are independent. Since module voltage does not vary significantly in response to real-world conditions, parallel wiring is an effective method to minimize mismatch losses.

4 PROJECT DESCRIPTION

The system that serves as object of the study is the result of a close collaboration between several partners. The utility company Enmax, owned by the City of Calgary, provided the financing and is the owner of the system. The building on which the system is mounted is part of the Strathcona-Tweedsmuir School, which has also agreed to purchase the power produced by the system. Sustainable Energy Corporation, which manufactures the low-voltage inverter, was the instigator of the study and funded the scientific equipment. All parties share an interest better understanding the real-world performance of this type of system.

4.1 System Description

The experimental system has two PV arrays consisting of identical modules, but of different electrical configurations. In one case, all modules are connected in parallel; in the second case they are connected in strings of 5 modules. The modules used for this system comparison are amorphous silicon (NexPower NH-100UX-4A).

Amorphous silicon modules are more likely to give rise to mismatch conditions because the rate and degree of the initial degradation are difficult to predict, as are the seasonal variations caused by partial annealing in summer. At the same time amorphous modules offer higher output voltages than crystalline modules of similar power ratings, which makes the parallel-only approach easier to implement.

Structural concerns dominated the physical configuration. The array is mounted at a slope of about 6° to minimize wind loading. The spacing of the rows is wider than needed to avoid row-to-row shading, but this distributes the static load more broadly. And finally, the orientation of the array is about 40° east of south so that the static load could be kept in line with the supporting walls. (See Figure 1.)

Aside from the structural concerns, a major influence on the layout was the presence of a large roof-top air-conditioning unit. (See Figure 2.) Although it is a perfect example of the type of real-world constraint we wish to consider, its shadow would not have the same effect on the two arrays, and would therefore hinder the comparison. Therefore, both arrays were kept further away from it than might otherwise be done.

Figure 1 Close-up of the arrays and mounting structure

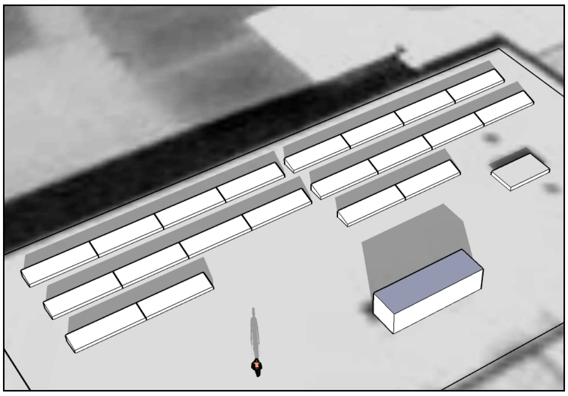


Figure 2 View from South with shadows for Dec. 21

Each array is coupled to an inverter that is suitable for the resulting DC voltage. The parallel-only array uses a Sunergy ELV 208 inverter from Sustainable Energy Technologies nominally operating at 75Vdc, whereas the series-parallel array uses a Sunny Boy 5000U inverter from SMA nominally operating at 375Vdc.

4.2 Sensors and Data Acquisition

The quality of the measurements is a key factor for the success of the project. It is very important to identify where in the system various losses are incurred and what external factors influence those losses.

To begin, both DC and AC power are measured separately to ensure that differences in inverter efficiency can be evaluated separately from the differences attributable to the array configuration. Both the AC and DC transducers continuously integrate the power signal so that energy production is accurately recorded as well.

To ensure that variations module output within each array are observed, 60 current shunts are installed: one per module in the parallel-only array; one per string on the series-parallel array. The DC voltage on each system is also measured for completeness.

To identify at least one potential cause of mismatch, non-uniform cell temperature, 10 thermocouples are distributed throughout each of the two arrays, fastened to the rear of selected modules. Although large temperature differences are not expected, this is the only way to be sure. Other factors such as soiling can only be examined through periodic visual inspection, while a webcam is installed to monitor snow conditions.

While many causes of mismatch may be hard to measure directly, some may be identified through the way in which the performance varies with time. Changes may be gradual or sudden; and they may occur periodically, seemingly randomly or only once. To detect such changes requires a stable reference, which in our system is provided by a combination of a reference cell with KG5 filter, a spare module recording short circuit current, and two Licor pyranometers.

Finally, the basic weather parameters such as wind and precipitation, ambient temperature and humidity are all recorded.

4.3 Experimental Procedures

In addition to long-term monitoring and analysis, short-term experiments will be carried out to observe the response of both systems to various forms of partial shading. Obstructions chosen will be those typically found on commercial roof tops, such as overhead wires, poles and pipes, and changes in elevation. Such obstructions will be identical for each array, and typically left in place for an entire day. The same experiment may be repeated under different weather conditions or in different seasons.

We also expect to work together with other teams pursuing these goals, such as [3], so that our experiments complement each other and lead to a broader and deeper understanding.

5 RESULTS AND CONCLUSIONS

The installation was delayed by approximately 6 months and is about 90% complete as of mid-September 2009. Nevertheless, some relevant observations can be made already before the system starts:

1. The building was not chosen for its inherent suitability for this study, and hence it presented us with several typical constraints: structure, orientation, shadows. The analysis done to keep the array out of the shadows (Figure 2) demonstrated just how difficult it is to avoid this particular source of mismatch.

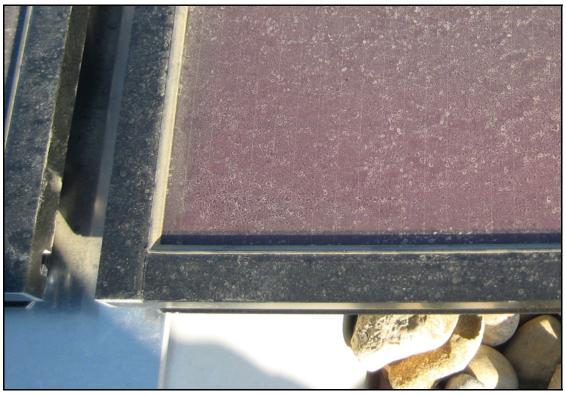


Figure 3 Soiling became apparent soon after installation

2. Building on the previous point, the design process usually involves trade-offs and compromises. If the trade-off involves a mismatch of some sort, and the configuration can tolerate mismatch, then no compromise is necessary.
3. Flash test data from the factory confirmed that all of the modules fell within the manufacturer's tolerance specifications, with a nearly linear distribution in that range. The variations in Impp were smaller than the variations in Pmpp.
4. Based on visual inspection a short time after the installation began (Figure 3) soiling may become a significant loss factor. A longer time will be needed to see whether the dirt accumulates in certain areas but it seems certain that the elevated frame will hamper the shedding of water and snow.

As we put the finishing touches on the system and instrumentation one thing that seems certain is that we will learn even more that we set out to do.

6 REFERENCES

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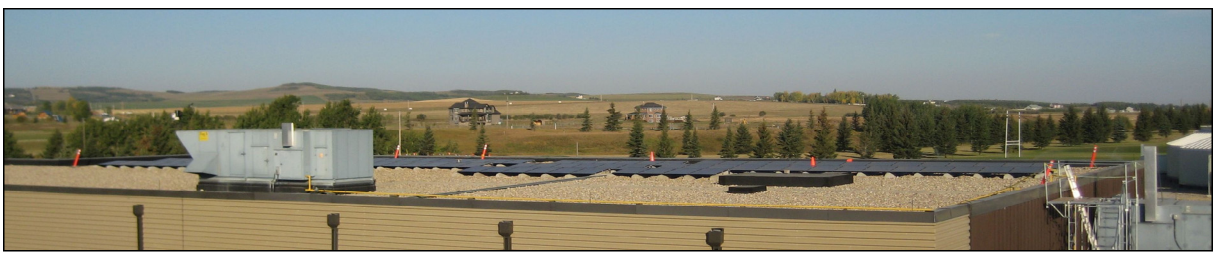

Figure 4 View of the complete installation looking from the East