INCREASING PV SYSTEM PERFORMANCE WITH ACTIVE POWER MANAGEMENT

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ABSTRACT

The issue of PV system underperformance and how to address it is a critical part of the effort to increase PV system efficiency. In this paper, the role of active power management which encompasses monitoring, management, and power optimization will be described. Data that illustrates widespread system underperformance and mismatches in PV systems will be presented, and the results of tests on SolarMagic™ power optimizer performance under mismatched conditions will be described.

1. INTRODUCTION

Despite recent photovoltaic market growth and industry potential, photovoltaic solar energy still only accounts for a mere 0.1% of total global energy production, due in part to inherent flaws in conventional solar system architecture that lead to underperforming solar systems and degradations in performance over the system's lifetime. In the rush to install new PV systems as quickly and economically as possible, system under-performance which often only becomes apparent months after initial installation, is often not recognized or addressed.

The solution to the problem of system underperformance is "active power management," an umbrella term used to describe implementation of:

1. Performance monitoring hardware that provides DC and AC monitoring and weather data
2. Web-based management services that quickly identify underperformance and its causes
3. Power optimization solutions to increase energy harvest under real-world conditions

Until recently, most PV systems were installed with monitoring systems only capable of monitoring AC power. While this might give an indication of gross underperformance, it does little to help diagnose the location within the system or find the root cause without a prohibitive amount of manual inspection and labor. Newer monitoring products, such as those offered by National Semiconductor's SolarMagic monitoring and management portfolio, allow users to analyze performance down to the DC string. By using advanced diagnostic algorithms, the location and root causes of system underperformance can be quickly identified even in very large systems.

Likewise, in the past when performance problems were identified, oftentimes there was not a feasible solution to improve performance. However, now issues such as differential panel aging or damage, shade, or dirt accumulation can be addressed with SolarMagic's power optimization products which offer a viable, cost-effective solution to power losses in many of these underperforming systems.

In this paper, we will show that the issue of system underperformance is widespread, and show how active power management can be used to increase energy harvest.

2. UNDERPERFORMING PV SYSTEMS

The California Solar Initiative (CSI) provides incentive rebates to encourage PV system adoption. As part of the application process for participation in the program, new PV systems are required to submit data on the system design, including results from the PVWatts calculator and the Expected Performance-Based Buydown (EPBB) Calculator. In Fig. 1, the results of these calculations are compared to actual performance, and it can easily be seen that the actual performance of the systems is significantly less than expected from these performance calculators [1].

In looking at the results in Fig. 1, it may be tempting to claim that the real problem is with the PVWatts and EPBB calculators over-predicting performance. However, the general consensus of people familiar with these two calculators is that a well-designed and maintained system will usually exceed the calculated performance. There are some PPAs that take full advantage of this in their business models. This makes the actual underperformance shown in Fig. 1 even more significant because it suggests that the potential for improved performance is even higher than shown. It is also worth noting that the underperformance occurs in both small and large systems – underperformance is not just an issue in residential installations.

2. MISMATCH IN PV SYSTEMS

There are definitely multiple causes of the system underperformance shown in Fig. 1. Many of these causes can be grouped loosely under the term “mismatch,” because they cause the strings or panels in the PV system to have different or mismatched optimum operating points. PV system mismatches occur when voltage and current combinations do not match up, and can be caused by a number of culprits, such as partial shade, moving clouds, reflections from nearby objects, varying tilt angles and orientations, soiling, differential aging, micro cracks and temperature variations across a solar array. These mismatches exist to some degree in all PV systems, but the losses created by these mismatches are often overlooked or underestimated.

One of the major challenges for dealing with mismatches in PV systems is that in a conventional system, performance optimization (also called max power point tracking) is typically carried out by a centralized inverter. As each string of solar panels is wired in series and connected either directly or in parallel with other series strings to the inverter, the inverter can only “see” this module array as a single electrical equivalent. This makes it impossible for the inverter to optimize for every panel in the system and it is forced to compromise.

Seemingly small amounts of mismatches in the array can cause disproportionate energy losses. The results of a shading study shown in Fig. 2 indicate that as little as 2.6% shade on the array can cause the system performance to degrade 7%; shading on 11% of an array can lead to a staggering 30% power loss across the entire system [2].

Although some forms of mismatch such as shade can be easily seen, others such as uneven panel degradation or dirt accumulation can only be measured with monitoring systems. However, in the same way that central inverters cannot compensate for mismatch, AC monitoring systems cannot diagnose mismatches between strings or panels on the DC side. This is one of the reasons why mismatches have been under diagnosed as significant causes of performance degradation in the past.

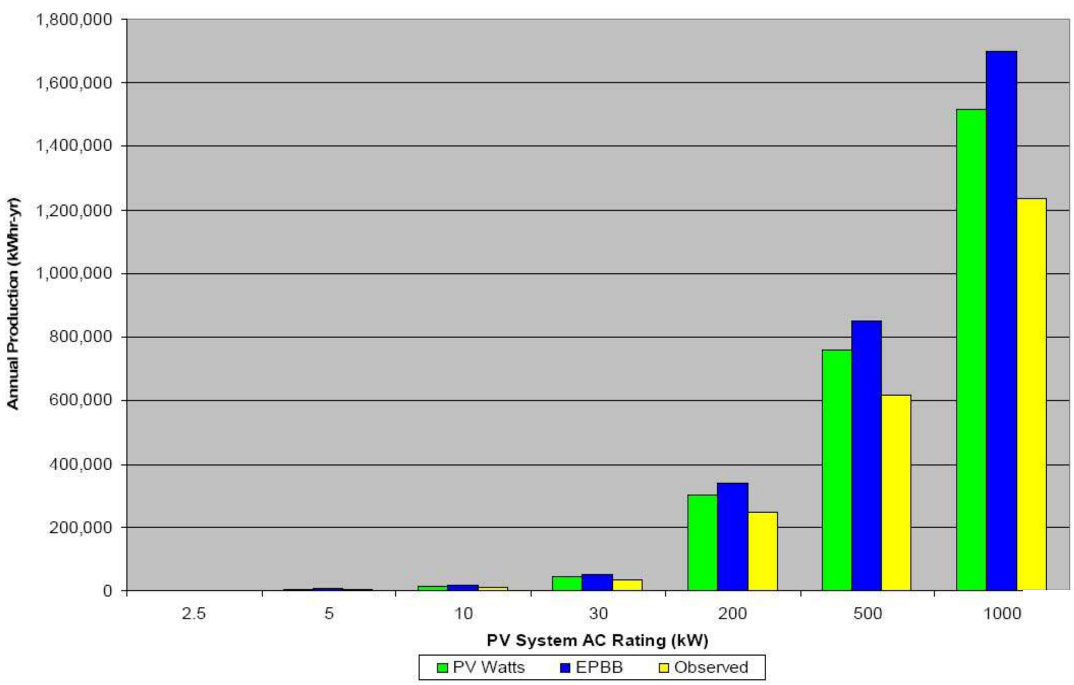


Fig 1. Comparison of predicted and actual (observed) performance of systems in CSI program [1].

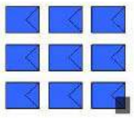
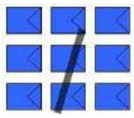
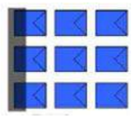
Shade pattern	% Area Shaded	Power Loss
	**0.15%**	**1.7%**
	**2.6%**	**7%**
	**11.1%**	**30.5%**

Fig. 2. Results from shade impact study [2].

Today, with SolarMagic's DC monitoring and management solutions, it is possible to quickly identify these mismatches and measure their impact on performance. One way to quantify how much power is lost to mismatch is to compare performance between seemingly identical strings in a PV system.

To illustrate how common mismatches are in today's PV systems, an analysis was conducted on sites using SolarMagic's DC string monitoring systems. The population consisted of several hundred sites with strings numbering in the 10's of thousands. Virtually all of the strings analyzed are from commercial and utility scale installations, sites for which common wisdom would suggest should have fewer mismatch issues than residential sites.

The annual energy output for each string was compared to the performance of strings connected to the same combiner box. By restricting the comparison to strings in the same combiner box, we are assured that the strings compared will be connected to the same inverter, have the same string length, and same type of panels. Combiner boxes in this study had between 4 and 12 strings. The ratio of each string's performance relative to the best performing string in its combiner box is calculated as an indicator of the power losses that occurred due to mismatched conditions. The results are plotted in Fig. 3.

The results indicate that 57% of the strings are performing at least 5% below the max possible performance, and 23% of the strings are 10% lower than optimal. Clearly, performance mismatch between strings is widespread, and this provides a conservative estimate of the potential energy improvements that can be gained when power optimization or other solutions are applied.

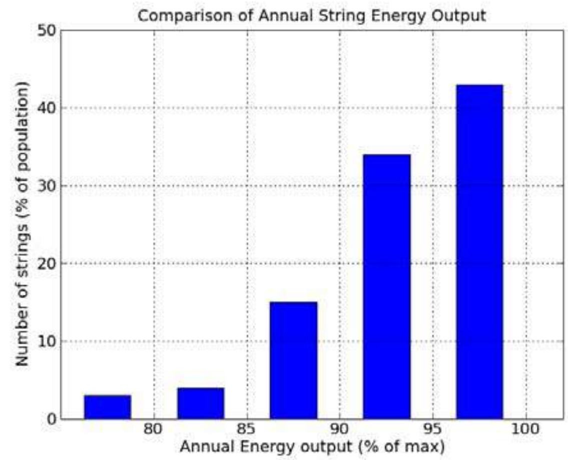


Figure 3. Symmetry analysis of annual string energy output. Energy outputs compared to strings within same combiner box.

The "symmetry analysis" that was conducted here to compare annual energy output can also be used in real-time to determine which strings are having performance issues. Depending on the severity of the performance impact, personnel can then be dispatched immediately or at the next scheduled service call. Further diagnosis can then be made on-site to determine the root cause and if power optimization or a simple repair can recover the lost power.

3. ADDRESSING MISMATCH WITH POWER OPTIMIZATION

Historically, research and development efforts aimed at increasing energy output have been directed towards increasing solar cell efficiency, or in developing streamlined manufacturing processes for higher energy yields. However, these are almost always expensive avenues and consequently inefficient routes to grid parity. Providing a cost-effective solution to increase solar system power output means developing a technology capable of boosting both energy efficiency and economic feasibility, thus accelerating the mass-market adoption of solar energy technology. With this in mind, the industry is now embracing electronic solutions at the string and module levels to both increase energy harvest and reduce balance of systems costs.

Researchers and engineers at National Semiconductor have developed power optimizer technology, which utilizes distributed electronics to extract the maximum energy available from each module and adjust until a string optimum is achieved, thereby mitigating all forms of panel mismatch.

To illustrate the effectiveness of power optimization technology in mitigating mismatch, an experiment was conducted in conjunction with the California Energy

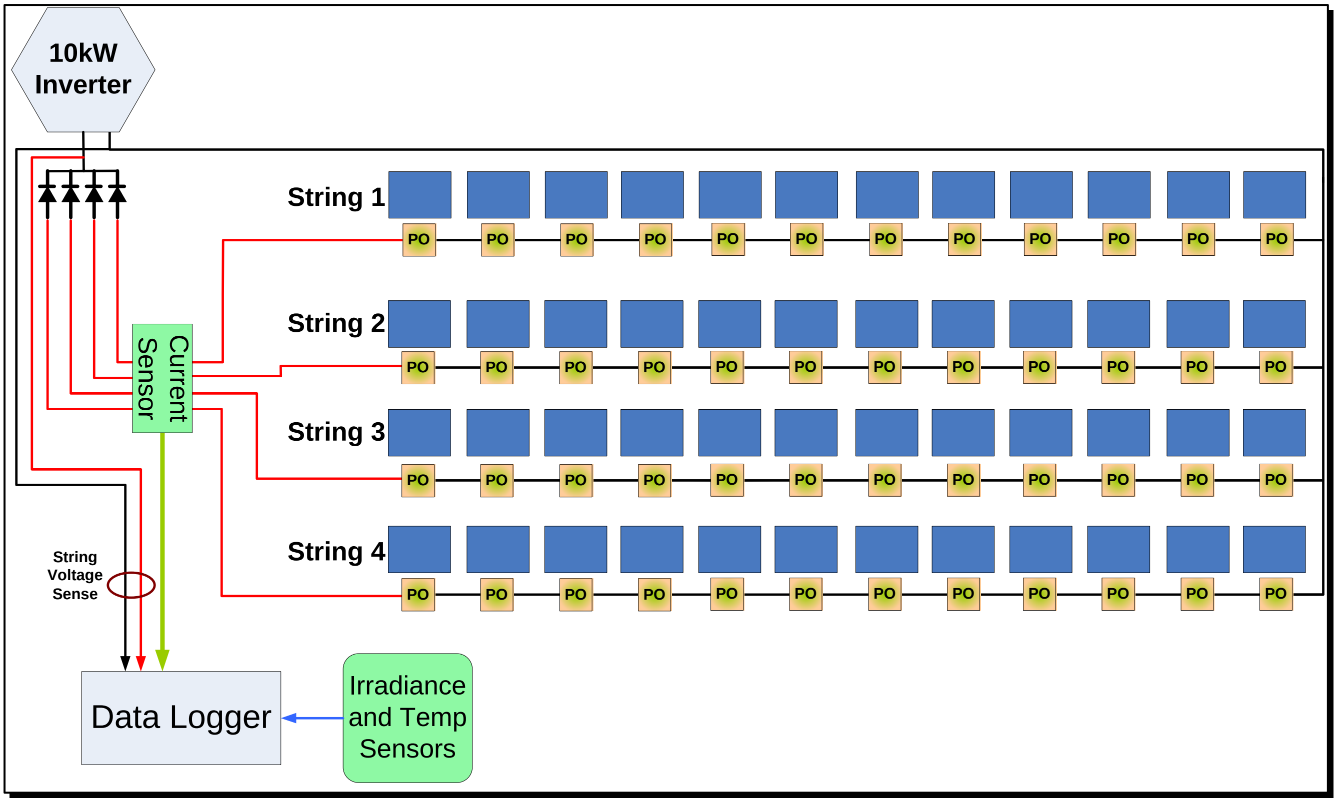


Figure 4. Schematic of test setup. PO indicates a power optimizer.

Commission. The tests were designed to measure performance under a variety of realistic shading conditions. A schematic of the test setup and description of the equipment is shown in Fig. 4, and Table. 1 describes the equipment used.

TABLE 1: TEST SYSTEM CONFIGURATION

System Configuration
4 strings of 12 panels
Kyocera KD205GX Panels
Voc = 33.2V, Vmp = 26.6V (STC)
Isc = 8.36A, Imp = 7.71A (STC)
Fronius IG Plus 10
10kW, 240V output, single-phase inverter
MPPT input range of 230V – 500V

For this test, 24 different shade conditions were applied to the array. These shade conditions are enumerated as described in Fig. 8. Shade was applied by placing a frame with translucent window film over each shaded panel as shown in Fig. 6. The window film had a translucency of 40% transmission, which emulated the effect of diffuse irradiation under normal shade conditions.

Each shade condition was applied for 5 minutes. Measurements of irradiance and temperature were taken continuously during the test and were used to normalize the power to constant irradiance conditions. For each test condition, the power was measured and compared to the unshaded condition. A shade impact factor (SIF) was then calculated using the equations shown in Fig. 8. A SIF = 1 would indicate that the reduction in power was completely proportional to the reduction in photons hitting the solar panels. A SIF greater than 1 (which occurs in all practical cases) indicates that there is additional power loss due to mismatch. The power used to calculate the SIF was only taken after the inverter's MPPT had enough time to settle.

An overlay of the test results of the baseline system and the system with power optimizers is shown in Fig. 5, and a summary of the equations and results from the test are provided in Fig. 8. It can be seen that the performance of the power optimized system is higher under all shading conditions.

This test clearly demonstrates the effectiveness of power optimization in increasing energy output under mismatched conditions. Further testing conducted worldwide has shown that the distributed electronics solution creates smart panels capable of recapturing up to 71% of energy that would otherwise be lost to mismatches, maximizing both the array's energy output and the owner's return on investment.

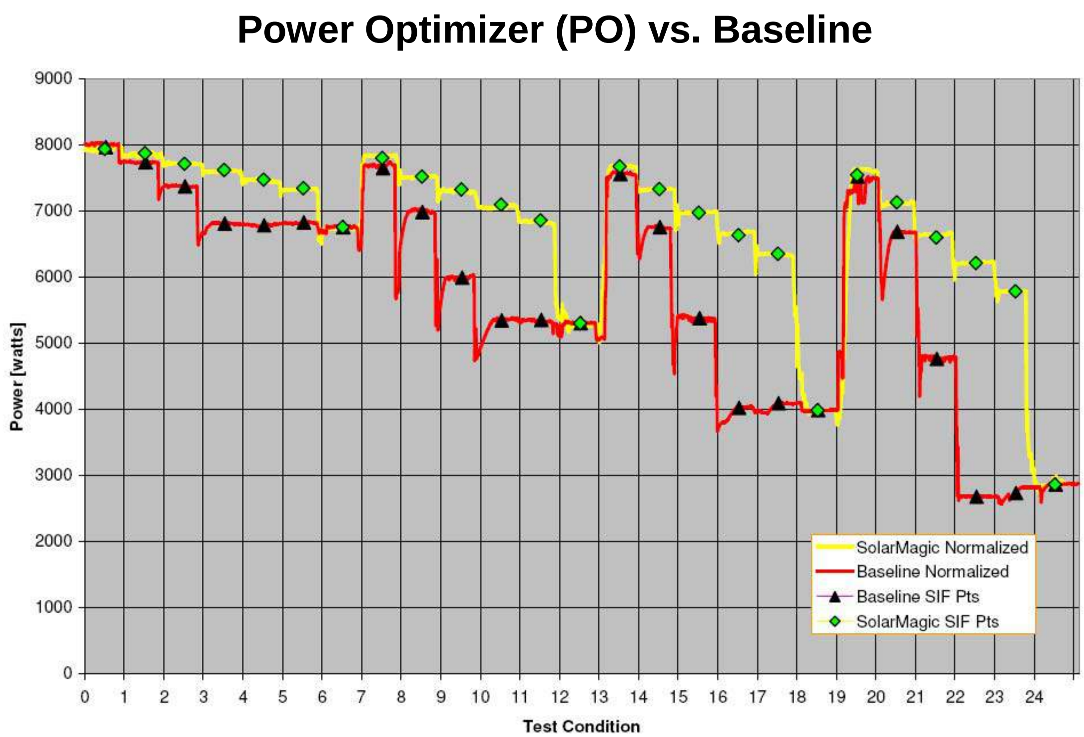


Fig. 5. Comparison of power output under 24 tested shade conditions for baseline and power optimized system. The SIF pts markers indicate the data points used for the summary table in Fig. 8.

4. CONCLUSION

In this paper we have illustrated the widespread nature of PV system underperformance. Active power management in the form of performance monitoring, web-based management services, and power optimization provide a powerful new set of tools to help PV systems achieve their optimal performance.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge Pat Saxton of the California Energy Commission, and Jeff Newmiller of BEW Engineering for their help in designing the experiment described in this paper.

Fig. 6. Photo of panel with shade applied using framed window film.

6. REFERENCES

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2. Chaintreuil, N. et al. “Effects of Shadow on Grid Connected PV System” INES R.D.I. Laboratory for Solar Systems (L2S), Le Bourget-du-Lac, France. Proceedings of the 23rd EU PVSEC, 2008.

Figure 7. Photo of test setup under test condition 11 (5,2).

Test Condition	n	m	Baseline SIF	Power Opt SIF
1	1	1	**2.89**	**1.27**
2	2	1	**3.32**	**1.48**
3	3	1	**4.16**	**1.32**
4	4	1	**3.20**	**1.37**
5	5	1	**2.47**	**1.37**
6	12	1	**1.09**	**1.09**
7	1	2	**1.91**	**1.02**
8	2	2	**2.67**	**1.26**
9	3	2	**3.52**	**1.18**
10	4	2	**3.48**	**1.19**
11	5	2	**2.79**	**1.21**
12	12	2	**1.18**	**1.19**
13	1	3	**1.60**	**1.13**
14	2	3	**2.21**	**1.18**
15	3	3	**3.09**	**1.21**
16	4	3	**3.51**	**1.21**
17	5	3	**2.76**	**1.16**
18	12	3	**1.18**	**1.18**
19	1	4	**1.30**	**1.20**
20	2	4	**1.76**	**1.15**
21	3	4	**2.86**	**1.23**
22	4	4	**3.51**	**1.18**
23	5	4	**2.77**	**1.17**
24	12	4	**1.13**	**1.13**

Baseline SIF Average = 2.51

Power Optimizer SIF Average = 1.21

$$G_{s,nm} = \frac{G_d \cdot n \cdot m + G_u \cdot (N \cdot M - n \cdot m)}{N \cdot M}$$

$$SIF_{b,nm} = \frac{\left(1 - {P_{s,nm}}/{P_u}\right)}{\left(1 - {G_{s,nm}}/{G_u}\right)}$$

- **N = # of modules in a string (12)**
- **M = # of Strings (4)**
- **n = # of shaded modules in a string (1 - 12)**
- **m = # of shaded strings (1 - 4)**
- **P_u = Normalized unshaded power**
- **$P_{s,nm}$ = Normalized shaded power**
- **G_u = Unshaded irradiance normalized**
- **G_d = Irradiance measured in the shade normalized**
- **$G_{s,nm}$ = Effective irradiance incident on entire shaded array**

Figure 8. Summary of test results and equations used in calculating shade impact factor (SIF).