Even though the mismatch condition prevents a centralized control system from delivering the highest amount of solar energy, significant research has been conducted to minimize the impact. The MPPT algorithm tries to find the optimal operating point, namely the global maximum power point (GMPP). For example, the case study in Section 2.2.1 shows two power peaks, one higher than the other under shading conditions. The highest point is considered the GMPP, giving the highest power output under the mismatch circumstance. Since partial shading is the main cause of such multi-peak phenomena, MPPT research mainly focuses on tracking the global peak instead of any local ones. The approach is commonly referred to as global maximum power point tracking (GMPPT).

Since MPPT algorithms are amenable optimization techniques, the particle swarm optimization (PSO) approach has been proposed for finding the GMPP under partial shading conditions. The method was originally developed in computer science, where it is treated as a multi-variable or multi-agent problem. For GMPPT, the PV array power is defined as the objective function. It is influenced by the voltage of the individual PV modules which are the agents. The agents share information with each other, leading to a unique peak in multidimensional space. Similar to the concept of hill climbing, the PSO can be considered an advanced iterative approach to manage all the agents so that they converge to the position corresponding to the global extremum. Although research has proven the effectiveness of PSO and other optimization techniques for GMPPT, practical implementation is difficult since it sensitive to the initial conditions and other settings. Considering the time-variant nature of PV power generation, practical applications are even more difficult since stability cannot always be proven under various disturbance conditions (Xiao et al. 2011).

8.12 Performance Evaluation of MPPT

The objective of the MPPT has been clearly defined as to extract the highest solar power output from each PV cell at any moment. An number of MPPT algorithms have been recently proposed to give performance superior to previous solutions. It is very important to develop a platform for fair comparison. However, comparisons are difficult since solar irradiance and ambient temperature are not controllable and not repeatable (Xiao et al. 2013).

8.12.1 Review of Indoor Test Environment

In the past, many MPPT algorithms were tested indoors. In general, with the controllable energy sources, the performance comparison of MPPT can be planned and scheduled to give a fair comparison. Based on previous studies (Xiao 2003; Xiao and Dunford 2004a), the indoor testing methods are summarized and described in the following.

1) Computer simulation
   - Always effective to quickly prove the design concept.
   - Low cost and very flexible, allowing variation of environment, loads, and grid.
   - Cannot be used to prove MPPT performance on its own.
   - Should not be confused that the hardware-in-the-loop (HIL) techniques, which are considered a simulation approach, but include some real system components.

- HIL simulation output is sometimes considered an experimental result since the HIL platform can interface with analog signals for instruments such as oscilloscopes. It should be clearly noted that the HIL system is a simulation-based platform, not an experimental one.

2) PV array simulator
   - Defined as a DC power supply which is programmable to simulate PV output characteristics (see Section 1.7).
   - Considered a moderate-cost and flexible solution for repeatable indoor tests of power-conditioning circuits and control algorithms.
   - The simulator can be flexibly programmed to represent different types of PV generators and different environmental variations.
   - The PV array simulator is a power electronic device.
   - It shares the same drawbacks as other switching-mode power supply systems, such as ripple in the current and voltage waveforms.
   - It might show self-resonance when connected to another power converter.
   - The output characteristics of PV arrays can change very quickly in response to variations in operating conditions.
   - The PV array simulator generally shows much slower responses than real PV material.
   - The constraint of dynamic response, which does not match real PV modules, should always be considered when it is used to validate fast MPPT algorithms.
3) Artificial light and temperature test chamber
   - Fully controlled environment using artificial lights can provide variable irradiance levels and regulated ambient temperature for indoor testing and evaluation.
   - Could be one of the most expensive solutions since a solar simulator with accurate solar spectrum is generally expensive and limited to small scale.
   - Difficult to test a system with significant power capacity due to the high cost of artificial light and high power consumption.
   - Furthermore, it is also a high cost to maintain chamber at constant temperature for different tests since self-heating always happens when PV modules are exposed to light.

8.12.2 Review of Outdoor Test Environments

Outdoor evaluations have great advantages since the actual MPPT behavior can be examined using real PV arrays and natural sunlight in order to avoid unrealistic effects of artificial sunlight and power electronic simulators. Furthermore, an effective MPPT algorithm performs well in real-world weather conditions rather than any pre-assumed condition. However, the accurate measurement of solar irradiance and cell temperature is difficult. Some tests intentionally choose sunny days with the assumption that the weather pattern would be repeatable. In the past, many MPPT algorithms were tested outdoors. The methods used are outlined in the following list.

1) Periodical interrupt method
   - Uses natural sunlight, which is better than artificial light.
   - Divides the testing period into small time pieces for different MPPT algorithms.
   - Usually stops one test and starts another with the assumption that the environmental condition is steady for all tests.

- Errors can be expected due to the time-variant patterns of irradiance and temperature.
- Impossible to test fast MPPT dynamics in response to conditions such as moving clouds.

2) Day-by-day test based on single PV system
   - Aims for a long-term test to evaluate the MPPT performance in response to different weather conditions.
   - A comprehensive statistical analysis is required to identify the MPPT performance, since the day-to-day weather conditions are not repeatable when the variation of both irradiance and temperature are considered.
   - The drawback lies in the long test period and the complication of statistics to prove that one MPPT algorithm is more effective than another.
3) Day-by-day testing on multiple parallel PV systems
   - Based on at least two PV systems that are identical and installed in the same condition.
   - One can be used as the benchmark for the power output comparison.
   - The two systems should be calibrated under identical conditions in order to identify any mismatches between them due to non-ideal factors in the system components.
   - The test requires multi-day evaluation and statistical analysis to identify the performance of the MPPT since no two systems are exactly identical when component tolerances are considered.
   - The approach is considered the most comprehensive evaluation method since both systems are under the same operating conditions for a long-term test.
   - Both the MPPT dynamics and steady state can be revealed for the highest power generation.

By comparing the three testing methods in natural sunlight, it has been observed that the parallel PV system is the most effective testing platform for MPPT evaluation (Xiao et al. 2013).

8.12.3 Recommended Test Benches for MPPT Evaluation

Results for two different weather patterns have been reported by Xiao et al. (2013), as shown in Figures 8.8 and 8.9. A fair comparison of one day's performance of a PV system against another is impossible since the weather pattern is not repeatable day by day. The results will be inaccurate when one PV system is used to test MPPT performance on different days. Therefore, the following introduction is based on a parallel testing configuration, with two independent PV systems tested and evaluated simultaneously under the same operation conditions and in the same natural environment.

The first test bench system we will consider is recommended for evaluating the MPPT algorithms that are usually used in DC microgrids or two-stage conversion systems. The system diagram is shown in Figure 8.29. The system is formed by a programmable DC electronic load and parallel PV power systems. The MPPT algorithms are implemented to control the two DC/DC conversion units. One can be used as the benchmark; the other can be implemented with an advanced MPPT algorithm in order to prove its effectiveness. The voltage and current at the PV and DC links should be continuously measured and recorded by a data acquisition system to assess the long-term operation.

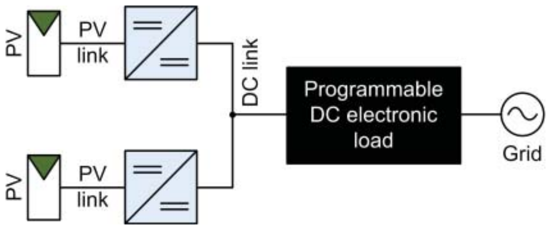

Figure 8.29 Test bench system for evaluating MPPT in DC microgrids and two-stage conversion systems.

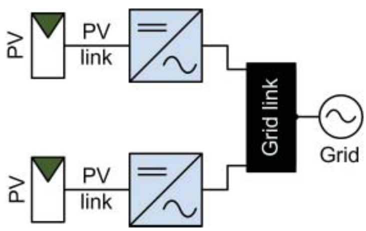

Figure 8.30 Test bench system for evaluating MPPT in single-stage DC/AC conversion systems.

The programmable DC electronic load can create a DC link with constant voltage, which is shared by the two PV systems. It is flexible and can be programmed to have other functions, such as voltage disturbance. It should be noted that the majority of programmable DC electronic loads do not inject power into an AC grid. The grid connection is mainly for the ancillary power supply to control the load system. Depending on the application, the PV and DC/DC units can be as small as a single PV module or as large as a PV array. The PV string and array levels are important in testing the MPPT performance in response to partial shading or other mismatch conditions.

The second test bench system is used to evaluate MPPT algorithms for single-stage DC/AC conversion systems. The system diagram is shown in Figure 8.30. The system is connected to the grid directly. The test bench is especially important in testing MPPT performance for single-phase grid interconnections. The single-phase connection introduces significant double-line frequency ripples at the PV link, which limit the MPPT performance. The MPPT algorithms should be independently implemented in the two DC/AC conversion units. One can be used as the benchmark, and the other can implement an advanced MPPT algorithm for improved performance. The voltage and current at the PV link and grid link should also be recorded to enable day-by-day operation to be assessed.

8.12.4 Statistical Paired Differential Evaluation

The test systems in Figures 8.29 and 8.30 are flexible enough to test MPPT performance over any time period, from several days to several years. The comparison assumes that the parallel systems are identical. However, all PV panel manufacturers state power output tolerances ranging from ±1% to ±5%. One example was discussed in Section 2.2.1 and illustrated in Figure 2.8. Even though the PV modules are the same model and were manufactured on the same date, the output characteristics are slightly different under identical test conditions. Furthermore, the components that form the DC/DC and DC/AC power converters are often non-ideal. The uncertainty in the parallel systems might therefore dominate the system output, defeating the attempt to make a meaningful performance comparison and leading to a wrong conclusion.

A calibration test should be always conducted using the same MPPT algorithm. The long-term output result reveals any differences between the two independent systems. In addition, the hardware systems can be alternated, swapping the control algorithms in order to minimize any initial mismatch effect. When a significant quantity of data has been collected, paired difference tests can be used to assess the significance of the difference between the two sets of data that are produced by the system power output (Xiao et al. 2013). The paired t-test is used to distinguish the performance of the MPPT algorithms. The t-statistic is expressed as

$$t = \frac{\overline{P_1} - \overline{P_2}}{s_{\overline{P_1}-\overline{P_2}}} \tag{8.32}$$

where $\overline{P_1}$ and $\overline{P_2}$ are the mean values of the two system power outputs. The $s_{\overline{P_1}-\overline{P_2}}$ is the standard error of the difference between the two datasets. The t-statistic has a zero-mean-normalized probability distribution function that is dependent on the number of points in the datasets.

Values of t that lie outside approximately two standard deviations of the mean (zero) are termed 95% confidence intervals, and are usually used in statistical inference as a measure of testing whether a certain parameter is significantly different from a certain hypothesized value. The correctness of the hypothesized value is called the null hypothesis. If the value of t obtained is significantly far from that value (formally outside 95% on the probability distribution), then the null hypothesis can be rejected, and it is safe to conclude that the experimentally obtained quantity is not equal to the hypothesized value with 95% confidence. The null hypothesis indicates that there is no difference between the power outputs obtained by the experimental test. It can be statistically stated as the difference between the two means being equal to zero. If the t-value obtained from (8.32) is significantly different from zero, then it can be inferred that the difference between the power outputs of the two methods is statistically significant.

The statistics toolbox of Matlab provides a function for the paired t-test. It is provided as the function $t - test(x, y)$, where x and y represent the random samples following a normal distribution. x and y must be vectors of the same length. The function can be used to conduct the t-test and assess the null hypothesis. If the result of the test returns 1, the $t - test$ indicates a rejection of the null hypothesis at the 95% confidence level. A returned value of 0 indicates a failure to reject the null hypothesis at the 95% confidence level.

8.13 Summary

For MPPT, hill climbing (HC) methods are widely used. An alternative name for this approach is perturbation and observation (P&O). The standard algorithm generally involves a tradeoff between the tracking speed and the magnitude of steady-state oscillations. The selection of the perturbation size is considered a dilemma in balancing these requirements.

The incremental conductance method (IncCond) was developed to solve the problems of the HC-based MPPT approaches. It is based on the extremum value theorem (EVT), seeking to locate the local extremum value, either maximum or minimum.

The mathematical operation of differentiation is required. However, the function of the PV output power output is not exactly known to the controller since the parameters significantly change with environmental conditions. Instead, the IncCond operation relies on a numerical approximation of the differentiation, which introduces a truncated error. Therefore, experiments show that the oscillations in the steady state cannot be removed by the IncCond method. The truncated errors of the numerical approximation mean that the IncCond operation is not a significant advance on HC-based algorithms.

It is important to choose carefully the sampling frequency and perturbation size in HC-based or EVT-based MPPT algorithms. These parameters drive the response speed and steady-state performance. The sampling frequency can be determined by system dynamic analysis, ideas introduced in Sections 6.3 and 7.8 respectively. With a dedicated voltage-regulation loop for the PV link, the system dynamics can be improved, benefiting MPPT performance. The perturbation size should be determined through consideration of the ripple that is caused by the switching-mode power interface. For practical applications, the SNR should always be investigated to decide the size. Additionally, weather variation patterns must be considered on a case-by-case basis.

A start-stop mechanism can be integrated with a conventional HC-based MPPT algorithm, bringing the advantages of simplicity and effectiveness. It can give oscillation-free operation in the steady state since unnecessary perturbations can be avoided. When the MPP changes, active perturbations can be restarted to locate the new MPP. The implementation is relatively easy and straightforward and is an ideal complement to conventional HC-based MPPT algorithms.

The step size in active tracking can be adaptively adjusted to give fast tracking in transient conditions, and low steady-state errors. In theory, this is an ideal solution since many mathematical methods can be used to drive the adaptations. The common algorithms used are the steepest decent method and the Newton–Raphson method. However, practical implementations can be difficult because the mathematical model to represent the real-time PV output characteristics is missing. When making numerical approximations of the differentiation, truncated errors have been reported when using Euler methods. It turns out that the MPP cannot be fully represented when using a numerical assumption of $\Delta P/\Delta V \approx 0$.

Centered differentiation has been introduced to minimize truncated errors and improve the approximation accuracy of the condition $dp/dv = 0$. One additional measurement is required to perform centered differentiation. Improved performance has been reported when centered differentiation is integrated with the steepest descent algorithm and the dedicated start-stop mechanism. Overall, the implementation is more complicated than using only the HC algorithm and the simple start-stop mechanism.

The real-time identification method is another MPPT approach, which utilizes a mathematical model that is constructed using polynomial equations. The parameters are identified by recursive least squares (RLS) estimation in real time, so as to follow variations in operation conditions. The Newton–Raphson method is used as the numerical solver to find the PV-link voltage, which represents the MPP. The approach is model-based and does not require a numerical differentiation used in EVT-based algorithms or the perturbation in HC-based algorithms. However, practical implementation can be difficult due to the significant computation demand required for system identification. Furthermore, the stability of the RLS solution is another concern.

Extremum seeking (ES) control is another optimization approach for MPPT, which does not require prior knowledge of the system model. The standard method injects an sinusoidal excitation signal into the control loop in order to identify the extremum point. Its effectiveness was demonstrated by simulation in this chapter. Since switching-mode power converters are commonly used for PV systems, the ES algorithm can also utilize the switching ripple as the excitation signal. However, the implementation is not as straightforward as the HC and simple start-stop mechanisms. The tracking performance has not been shown to be significantly better than others.

In general, the MPPT algorithm is not as effective in dealing with PV mismatch conditions in CMPPT systems as in DMPPT systems, even though there has been significant research and many publications in the area. The complication of mismatch conditions in PV arrays creates a problem that is difficult to solve quickly for practical applications. Up to now, a DMPPT configuration has been the most effective way to minimize power degradation when there are mismatch conditions among PV cells.

Even though significant research has been published, many of the studies involved did not provide a fair comparison to demonstrate MPPT effectiveness. An outdoor test with natural sunlight is considered the ideal condition for evaluating MPPT effectiveness. However, a fair comparison of different MPPT methods is not easy outdoors. First, the true MPP is unknown when a PV system is in uninterrupted operation. The weather conditions – irradiance and temperature – are not repeatable. It is important to create a practical bench test system to evaluate MPPT performance under identical operating conditions.

A parallel testing system using two independent PV systems is highly recommended in this chapter. However, it is impossible to construct two truly identical systems when the difference between solar modules and other non-ideal factors in the power-conditioning circuits are considered. A pairwise difference comparison is introduced in order to statistically distinguish energy harvesting efficiency of two MPPT algorithms regardless of non-ideal factors. The pairwise t-test formula can be applied to filter out the effect of the difference in PV panel outputs, to enable accurate quantification of the statistical significance between two MPPT methods. The proposed method is considered as a systematic approach for both short-term and long-term side-by-side comparisons of MPPT performance using natural sunlight.

Problems

8.1 Readers are encouraged to research other MPPT algorithms that have not been covered in this chapter. Compare them with the solutions presented in this book and provide comment about their pros and cons.

8.2 Use any available simulation tool, construct an MPPT block based on the HC algorithm.

8.3 Based on the developed MPPT model, implement the start-stop mechanism.

8.4 Based on an example, compare the performance with and without the start-stop mechanism. The comparison can be based on the produced energy within a predefined time period.