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# A statistical analysis of a 4.5 MW solar energy center

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# A STATISTICAL ANALYSIS OF
# A 4.5 MW SOLAR ENERGY CENTER

By

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# ABSTRACT

This project helps a regional utility evaluate the performance of their 4.5 MW photovoltaic plant. The performance evaluation consists of characterizing the peak and average power and energy output of the plant over varying time periods. A characterization of the output power drops, or dips, is done by performing a statistical analysis of the photovoltaic plant output data. Dips are characterized by dip frequency, depth of dip, energy loss by dip, and dip duration. The results of this study will help the utility to select appropriate voltage regulating equipment on the basis of dip characteristics, and thus, optimize the performance of the solar plant. This study will also provide the utility with information on how to optimize future solar plants.

## ACKNOWLEDGEMENT

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## LIST OF ABBREVIATIONS

1. **max –** maximum
2. **min –** minute
3. **MW –** megawatt
4. **MWh** – megawatt-hour

# 1. INTRODUCTION

The plant described in this thesis is a 4.5 MW photovoltaic plant which provides power to St. Charles County, Missouri. It began operation in the fall of 2014. This photovoltaic plant is one of the largest solar installations in Missouri with more than 19,000 solar panels. The utility provider is interested in evaluating the overall performance of their first photovoltaic plant.

The objective of this project can be divided into two parts. The first objective is to evaluate the performance of the photovoltaic plant. The second objective is to perform statistical analysis of dips/drops in MW output of the plant. The data available to perform analysis is the MW output per minute of the plant. The MW output data provided for one year from November 2014 through October 2015.

The performance evaluation of the plant is done to assist the utility calculate how much energy or power is being generated by the plant over a typical year, especially during summer. The performance evaluation is performed by calculating several performance parameters including the average power and the energy generation during different time periods in a day. The average MW power generation calculation is performed only for the summer months during different time periods of a day and the energy generation is calculated during different time periods in a day for summer months.  The entire day energy generated is calculated for entire year from November 2014 to October 2015.

The dip analysis is performed to help the utility predict any operational problems arising due to the dips occurring in the MW output of the photovoltaic plant. Characterization of dip frequency, dip magnitude, dip duration, and energy loss caused by dips is carried out as part of the analysis. Dip duration plays the most important role in evaluating the impact of dips. The utility is concerned that if dips occurring in the MW output of the photovoltaic plant are large and have long duration, then the voltage drop along the feeder will be significant. The voltage variations due to the dips will be compared to the existing voltage power quality standards. The utility will then be able to develop solutions at locations where the voltage variation may exceed allowable tolerances.

The utility is planning to deploy a larger 13.5 MW photovoltaic plant on a weak feeder. The results that will be obtained from this study will not only help the utility in predicting the operational problems of the current photovoltaic plant but will also give them insight on the performance of the planned solar facility.

# 2. TERMINOLOGY

Throughout the project report, several terms have been used frequently. These terms, such as various time periods and dip characteristics, do not have any specific definitions. These terms are important for this study of dip analysis and performance evaluation of solar power plant, and are therefore defined below. A figure is included to clearly illustrate the terms.

## 2.1. ACTUAL CURVE

The *actual curve* is the measured MW output data of the plant.

## 2.2. IDEAL CURVE

The *ideal curve* of MW output is the maximum amount of power that can be generated at that location for that day under clear skies. The ideal curve is constructed by calculating the MW output values using an online calculator developed by the National Renewable Energy Laboratory (NREL).

The online calculator is the Measurement and Instrumental Data Center (MIDC): Solar Position and Intensity (SOLPOS) Calculator. The values in the online calculator were set as default values except the date and output time interval (set as 1 minute). The latitude and longitude are set as 38.81º N (north) and -90.7º W (west) respectively (same as the plant's latitude and longitude). The tilt angle was set as 35º. Tilt angle is the angle between the horizontal plane and the solar panel.

The ideal curve varies by day due to seasonal variation.  The solar radiation reaching a specific location at earth's surface depends on the position of the Sun with respect to the earth, which varies by day as the earth revolves around the Sun.

## 2.3. SUNRISE-SUNSET TIME PERIOD

The sunrise and sunset time periods are defined by the following points:

- The sunrise time is the time at which the generation of power starts and before this time, there is no power generation by the solar energy plant, i.e. the power generation will be equal to zero MW in magnitude.
- The sunset time is the time at which the generation of power ends and after this time, there is no power generation.
- Due to reflection and refraction, the actual and ideal sunrise and sunset times do not match. Solar rays are refracted by the earth's upper atmosphere and produce twilight, which illuminates earth's lower atmosphere before the sun has risen or set. Twilight conditions may cause the solar panels to produce small amounts of power before and after sunrise and sunset, respectively.

## 2.4. MAXIMUM OUTPUT PERIOD

The maximum output period is described below

- The maximum output period is defined as the period in which maximum generation of power occurs or is expected to occur.
- For this study, the maximum output period is defined as the period in which the power generation is equal to, or above, 4 MW in magnitude.
- While selecting the maximum output period, either the power generation of actual curve or ideal curve can be considered for the selecting the start and end time of this period. Whichever curve starts earlier or ends later than the other one, that curve is considered for selecting the timing of maximum output period.

## 2.5. RAMP-UP AND RAMP-DOWN PERIODS

The ramp-up period is the time period between the sunrise time and the time at which the maximum output period begins. The ramp-down period is the time period between the time at which the maximum output period ends and sunset time.

The actual and ideal curves and the method of selecting sunrise, sunset, and maximum output period are shown in Figure 2.1.

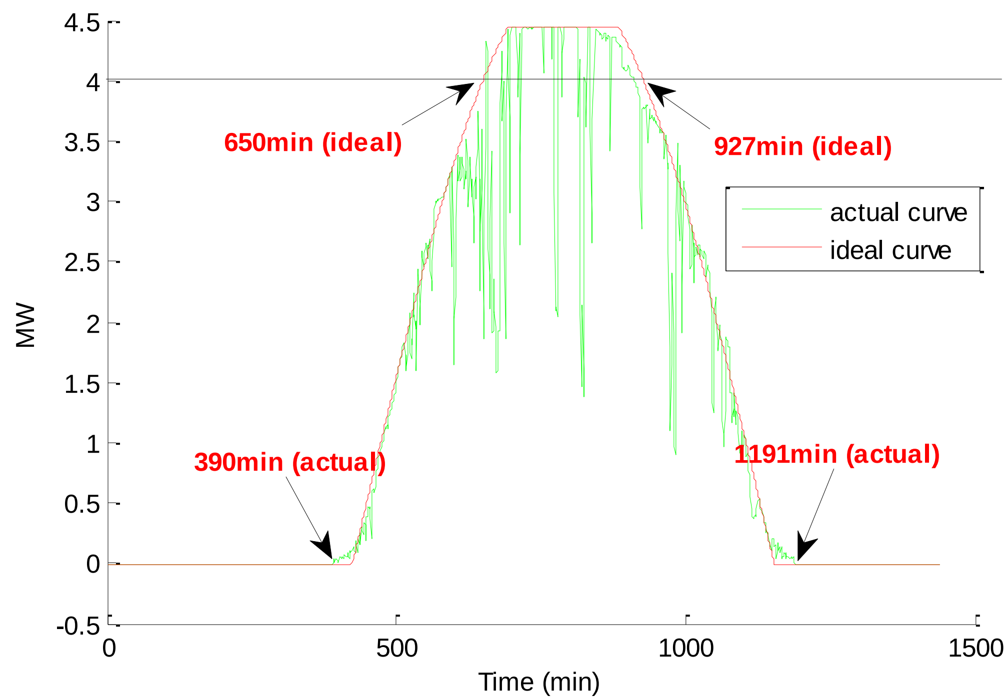


Figure 2.1. Actual and ideal curves for 13th August 2015 showing the sunrise-sunset times and maximum output period

The parameters in Figure 2.1 are described as follows:

- The actual power generation is shown in green and the ideal power generation in red.

- The sunrise and sunset time are calculated on the basis of starting and ending of power generation of actual data, not the ideal data, because actual curve power generation starts earlier and ends later than ideal curve. The sunrise and sunset time are 390 min and 1191 min respectively.
- The maximum output period is the period which lies above 4 MW.
- The maximum output period for this particular day is based on the ideal curve data because the idea curve reaches the 4 MW reference line earlier than actual curve.

## 2.6. ENERGY GENERATION

Two performance evaluation parameters are used for assessing the performance of the power plant. Energy generation is one of the parameters. Energy generation is calculated for two time periods: the entire day and the sunrise-sunset time period.

**2.6.1. Energy Generated During Entire Day.** The energy generated for the entire day is calculated as follows:

- Energy is power multiplied by time. $Energy = Power \times Time$
- The power generated in MW during the entire day is measured as MW per minute. Therefore 1440 values of power generation per minute during entire day is available.
- Energy generated for the entire day, in MW-min is given by

$$Energy, MW - min = (cumulative\ sum\ of\ Power\ generated\ per\ minute) \times Time$$

where $Time = 1440\ minutes\ (for\ a\ day)$

- Energy generated for the entire day, in MWh is given by

$$Energy, MWh = \frac{Energy, MW - min}{60}$$

**2.6.2. Energy Generated During Maximum Output Period.** In this case, the energy generation for the entire day is not calculated, but rather only for a section of the time period in a day is considered.

- The formulas used for the calculation of energy generation during the entire day are used for this time period as well. The only difference is that the time duration during which the power generation has to be considered will be the time period for which the power generation exceeds 4 MW.

## 2.7. POWER GENERATION

Power generation in MW is another important performance evaluation parameter. The power generation is considered for two time periods: the sunrise-sunset period and the maximum output period. The average power generated during the entire day is considered.

**2.7.1. Average MW Power Generated During Sunrise-Sunset Period.** This performance parameter is more useful than the average power generation during the entire day due to:

- The power generation for the entire day is given per minute. That means there are 1440 data set for MW power generation data in a day. The number of data points falling outside sunrise-sunset period may be quite large. These data are equal to zero MW power generation. Therefore, it reduces the average power by a large margin.
- The solar power plant is operational only during the sunrise-sunset time. Before sunrise and after sunset, the photovoltaic plant cannot generate any power.

**2.7.2. Average MW Power Generated During Maximum Output Period.** The average power generation during the maximum output period only is calculated.

## 2.8. CHARACTERISTICS OF DIP

To perform a dip analysis, it is essential to define a dip. In simple terms, dips are the difference between the actual data and ideal data. Various characteristics of dips in MW output are used for dip analysis.

The definitions of dip characteristics given below are:

**2.8.1. Dip Frequency.** Dip frequency is the total number of dips occurring during the maximum output period in a day.

**2.8.2. Depth of Dip.** The depth of dip is the difference in MW from the ideal value to its actual value at a given time instant.

The average and maximum depth of dip are calculated. The *average dip depth* is the average of all the actual MW values in a dip. The *maximum dip depth* is the maximum difference from the actual value to its ideal value in a dip. The *average daily dip depth* in a day is the mean of average depth of all dips occurring in a day. The *maximum daily dip depth* in a day is the maximum value of depth of all dips occurring in a day.

**2.8.3. Energy Loss During Dip.** This is the energy loss occurring during the duration of a dip.

The *average daily energy loss* of all dips in a day is defined as the mean of energy losses of all dips during maximum output period in a day. The *total daily energy loss* of all dips in a day is defined as the sum of energy losses of all dips during maximum output period in a day.

**2.8.4. Dip Duration.** The dip duration is a measure of how long a dip persists.

The average dip duration is the mean duration of all dips occurring during the maximum output period in a day. The total dip duration is the sum of the duration of all dips occurring during the maximum output period in a day.

Only the dips occurring during the maximum output period are considered as the impact of dips during this period on system voltage variation overshadows the impact of dips occurring in the ramp-up and ramp-down regions. Even though the average depth of dips in a day and the total energy loss of all dips in a day are calculated, only the dips during the maximum output period are used in this characterization study.

# 3. CRITERIA FOR SELECTION OF DIPS FOR THE STUDY

A statistical analysis is performed to determine the various characteristics of dips by comparing the actual data, (i.e. solar MW output data of the PV plant) and the ideal data obtained from NREL (National Renewable Energy Laboratory). Due to variances in the data, not all of the dips are suitable for inclusion in the data set. Therefore an inclusion criteria was used to select dips.

## 3.1. MAXIMUM OUTPUT PERIOD CRITERIA

The dips occurring during the maximum output period of day are included in the analysis. Dips during ramp-up and ramp-down periods of the day are neglected. The reason behind this selection criterion is that the dips during the period of maximum output have the greatest impact on the system voltage variation. Dips during the ramp-up and ramp-down periods have limited effect on system voltage.

During the dip analysis, it was found that for some days, the energy loss due to dips during ramp-up and ramp-down periods were more as compared to energy loss by dips during maximum output period. But the utility was concerned only about the dips occurring during maximum output period, not during ramp-up and ramp-down periods. This project was intended to help the utility achieve its objective.

Figures 3.1 and 3.2 illustrate this particular criterion for selection. The dip curve is obtained by subtracting the actual MW data from the ideal MW data. Figure 3.1 shows the dips for the entire day of 1$^{st}$ July 2015 and Figure 3.2 shows the dips only during the maximum output period (i.e. 639 minutes to 928 minutes for the day). As per the criteria, only those dips shown in Figure 3.2 are considered for the dip analysis.

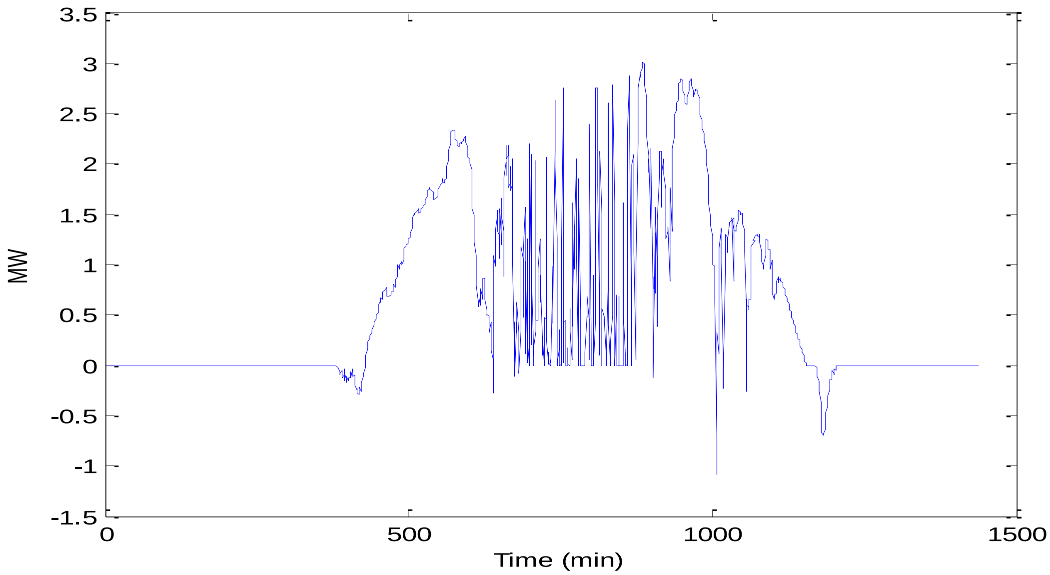


Figure 3.1. The dip curve for 1st July 2015 during the entire day

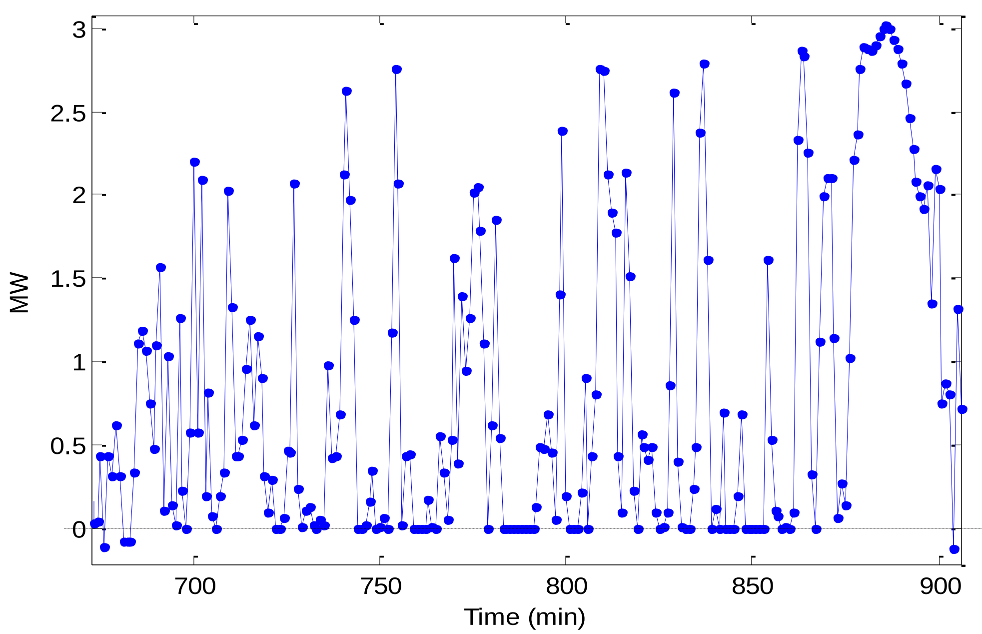


Figure 3.2. The dip curve during the maximum output period from 639 min to 928 min for 1st July 2015

### 3.2. MAXIMUM DEPTH OF DIP CRITERIA

Dips which have a peak magnitude (maximum depth) equal to or greater than 0.5 MW are included in the statistical analysis. This selection criterion can again be attributed to the impact of dip magnitude on system voltage. Smaller dips cause only small system voltage variations whereas larger maximum depths of dip will have a greater impact on system voltage variations.

Figure 3.3 shows the dips that are less than 0.5 MW are not included in the data set for analysis. Any dip that falls below this 0.5 MW line is ignored.

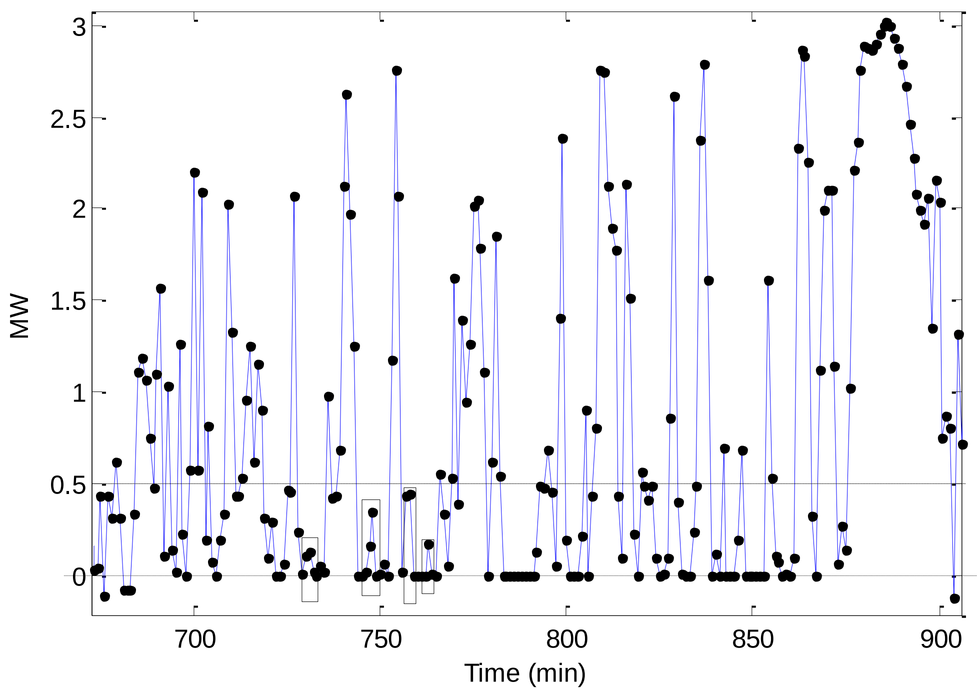


Figure 3.3. Maximum depth of dip criteria shown in the dip curve during the maximum output period of 1st July 2015

## 3.3. DIP DURATION CRITERIA

To be included in the data set, the duration of the dip must be longer than three minutes. Longer durational dips will have a greater impact on system voltage than smaller durational dips. If the duration of dip is large, then the energy loss caused by the dips is more significant since energy is directly proportional to the duration of the dip.

In Figure 3.4, the leftmost dip and the middle dip are ignored as they do not meet the duration criterion.

The dip durations of the three dips shown in Figure 3.4 are

- For leftmost dip, dip duration = 843-841= 2 minutes. This dip is ignored.
- For middle dip, dip duration = 848-845 = 3 minutes. This dip is ignored.
- For rightmost dip, dip duration = 858-853 = 5 minutes. This dip is considered for analysis.

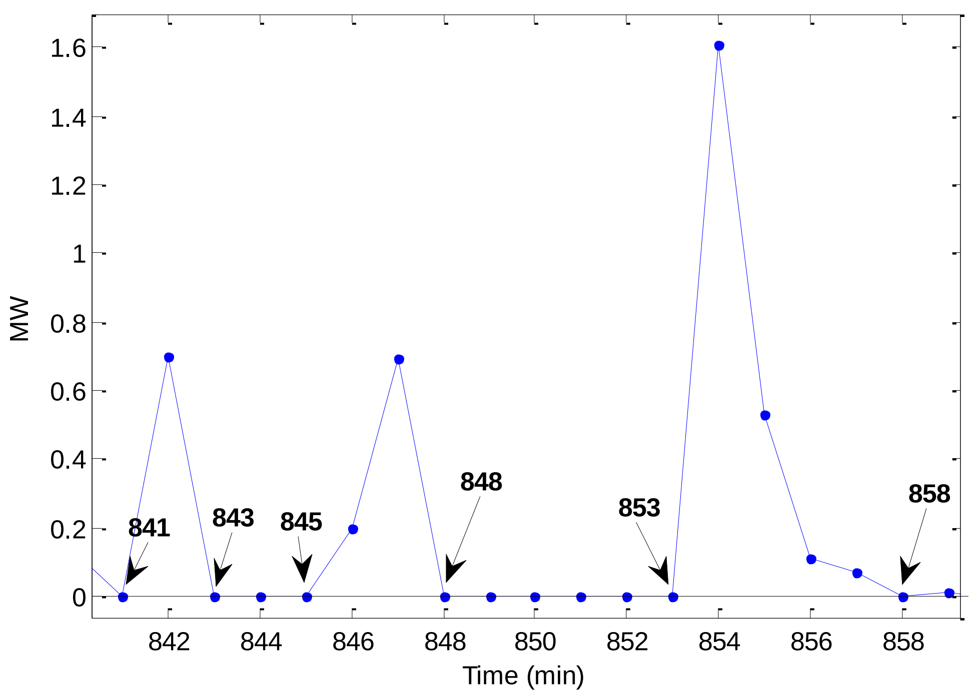


Figure 3.4. Dip duration criterion shown in a zoomed section of dip curve of 1st July 2015

## 3.4. EXCEPTIONS MADE IN SELECTION OF DIPS

Some exceptions were made while selecting the dips. The reasons for these exceptions varied from case to case. Those reasons are listed below.

**3.4.1. On the Basis of Dip Frequency.** If a day has a clear sky and the number of dips during the maximum output period in the day is small, (i.e. only one or two dips), then the maximum depth of dip and dip duration criteria have been ignored.

Figure 3.5 is the dip curve of 24th August 2015 during the maximum output period. The peak magnitude of the dip is 0.22 MW and the duration of the dip is 2 minutes (899 min-897 min). Neither the maximum dip depth criteria nor the dip duration criteria is met in this case. But due to the lack of other dips on this day, the dip was included in the analysis as an exception.

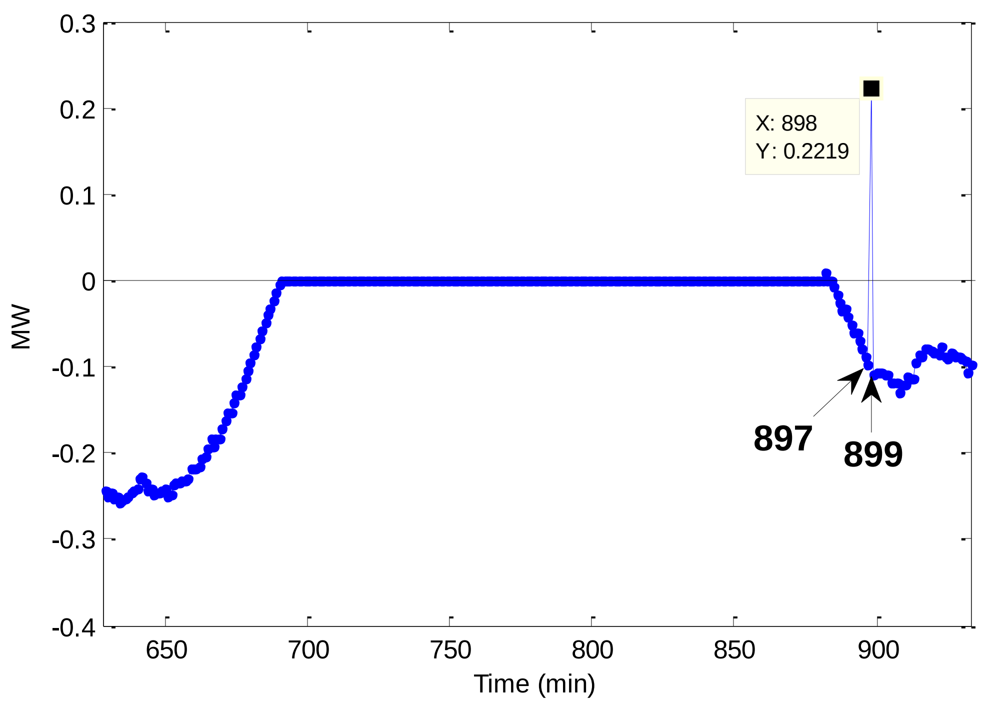


Figure 3.5. Dip curve of 24th August 2015 showing an exception in dip selection

**3.4.2. Highest Maximum Depth of Dip in a Day.** If the peak magnitude (maximum depth) of a dip in a day is significantly higher than average but the duration of that dip did not meet the dip duration criteria (i.e. the dip should have a duration of more than 3 minutes in order to be considered for analysis), then that dip is still taken into account for dip analysis.

For example, Figure 3.6 shows the dips in the loss curve of 12th June 2015. The peak magnitude of the dip is 4.46 MW which is the maximum for that day, but the dip duration for that dip is 3 minutes (879 min-876 min).  This dip was included as an exception.

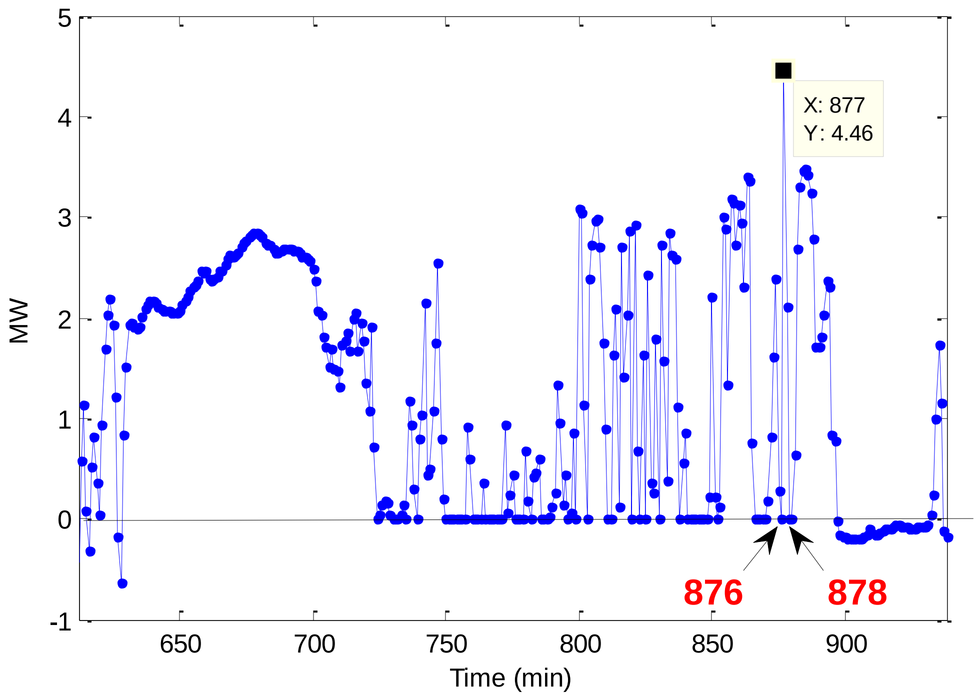


Figure 3.6. Dip curve of 12th June 2015 during the maximum output period showing the exception in selection criterion

# 4. CASE STUDIES

In this section, the performance of a set of specific days is evaluated and the statistical analysis of the output dips is performed. The days were selected being representative of a class of day type, such as clear sky or cloudy sky. One day from each month was selected for the case studies.

## 4.1. 10TH JUNE 2015

The actual and the ideal data for this day are shown in Figure 4.1. The sunrise and sunset times are 366 min and 1198 min. The maximum output period is from 637 min to 923 min.

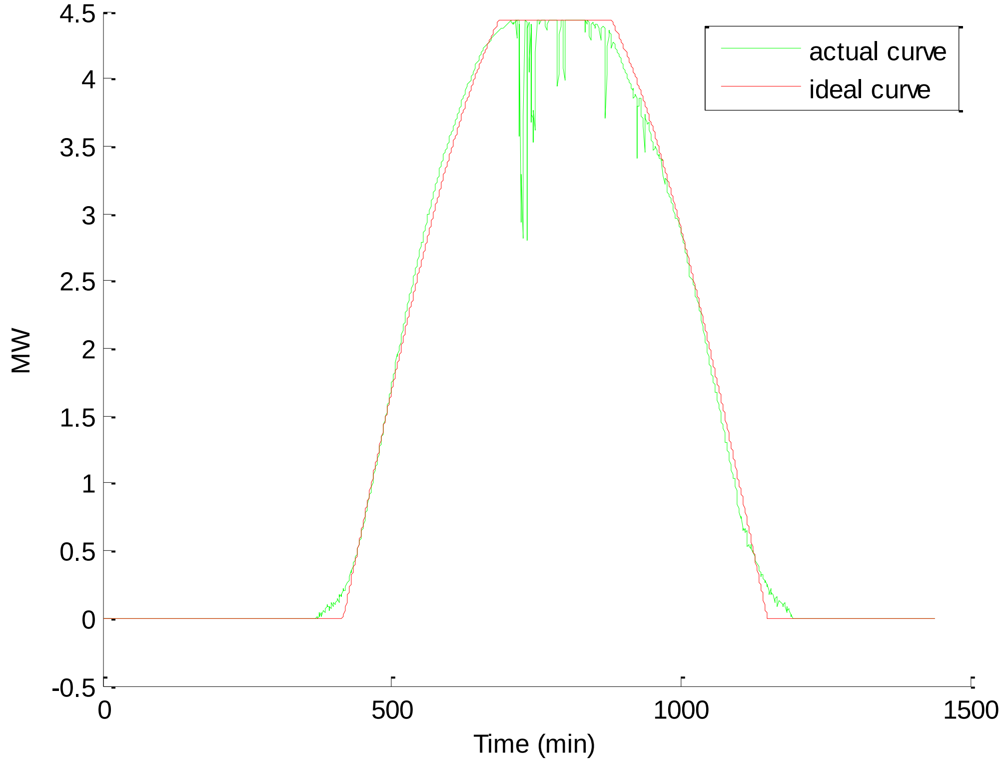


Figure 4.1. Actual and ideal MW output curves for 10th June 2015

From Figure 4.1 it is apparent this day is nearly an ideal clear sky day with only a few dips. The various performance parameters of this day are summarized:

- The energy generated during the entire day and during the maximum output period are 35.26 MWh and 20.31 MWh respectively.
- The average MW output from sunrise to sunset and the average MW output during the maximum output period are 2.62 MW and 4.25 MW respectively.

The above performance parameter values are calculated from the actual data and are compared with their corresponding values of ideal data. The performance is evaluated by this comparison and by calculating the performance parameters values of actual data as percentage of their corresponding values in ideal data. The performance comparison is given in Table 4.1.

Table 4.1. Performance evaluation for 10th June 2015

| **Performance Parameters** | **Actual values** | **Ideal values** | **Actual as % of Ideal** |
|---|---|---|---|
| Energy generated during the entire day (MWh) | 36.26 | 36.67 | 99% |
| Average MW output from sunrise to sunset (MW) | 2.62 | 2.65 | 99% |
| Energy generated during maximum output period (MWh) | 20.31 | 20.88 | 97% |
| Average MW during maximum output period (MW) | 4.25 | 4.36 | 97% |

All of the actual values of the performance parameters are 97% or above of their corresponding ideal values. Hence the power produced is nearly ideal.

Figure 4.2 shows the dip curve for 10th June 2015 during the maximum output period of the day. As it has been mentioned earlier, the output dips only during the maximum output period are considered for the analysis as during this period, the impact of dips in output on system voltage is greater as compared to dips that occur during the ramp-up and ramp-down periods.

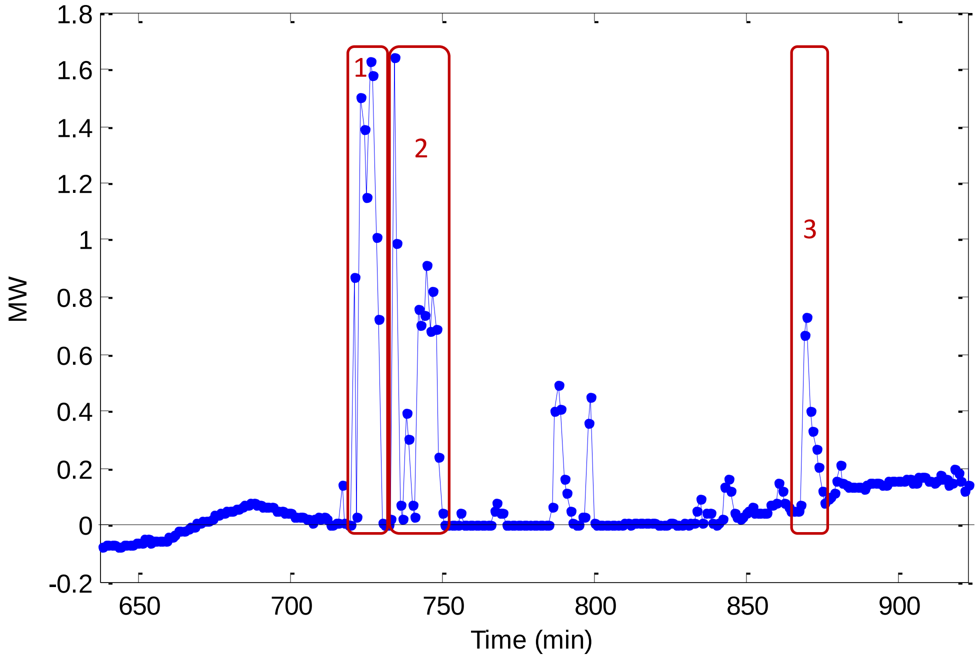


Figure 4.2. Dip curve for 10th June 2015 during maximum output period

The analysis of dips is carried out using MATLAB software. Only those dips that meet the dip selection criteria are selected for analysis. The dips that do not meet the maximum output period, maximum dip depth and dip duration criteria are ignored.

The results of statistical analysis of these dips obtained from the previous figure are summarized in Table 4.2.

Table 4.2. Dip analysis results for 10th June 2015

| Dip Frequency | Maximum Depth of Dip | Energy loss during Dip | Mean of Dip | Duration of Dip | Time period of Dip | |
|---|---|---|---|---|---|---|
| # of dip | (MW) | (MWh) | (MW) | (min) | From (min) | To (min) |
| 1 | 1.63 | 0.16 | 0.82 | 11 | 720 | 731 |
| 2 | 1.64 | 0.15 | 0.45 | 19 | 732 | 751 |
| 3 | 0.73 | 0.05 | 0.29 | 9 | 867 | 876 |

On 10th June 2015, there were only three dips that met the selection criteria. In Table 4.2, the first column gives the dip number. The second, third, and fourth column shows the maximum depth, energy loss caused by each dip, mean, and duration of each dip respectively. The fifth column shows the time period during which the dip occurred. The time period column is included in the table to indicate which dips are considered from the curve. There are two dips which are ignored during the analysis. One has a time period from 785 min to 794 min and another has time of occurrence from 795 min to 801 min. These dips do not meet the maximum dip depth criteria (i.e. these dips have maximum depth less than 0.5 MW and hence are neglected during the study). The purpose of collecting this information for each day is to combine all these data obtained for each day and then perform a complete analysis of dips at the end with the data from all days of the summer.

Table 4.2 highlights the following information:

- There are three dips on 10th June 2015.
- The maximum dip depth is 1.64 MW and maximum dip duration is 19 minutes.
- The total energy loss is 0.36 MWh, which is obtained by summing up the energy loss of individual dips during maximum output period.

## 4.2. 14TH JULY, 2015

The actual and the ideal data for this day are shown in Figure 4.3. The dip curve is given in Figure 4.4. The performance parameters are calculated using actual and ideal data, but the dip analysis uses Figure 4.4.

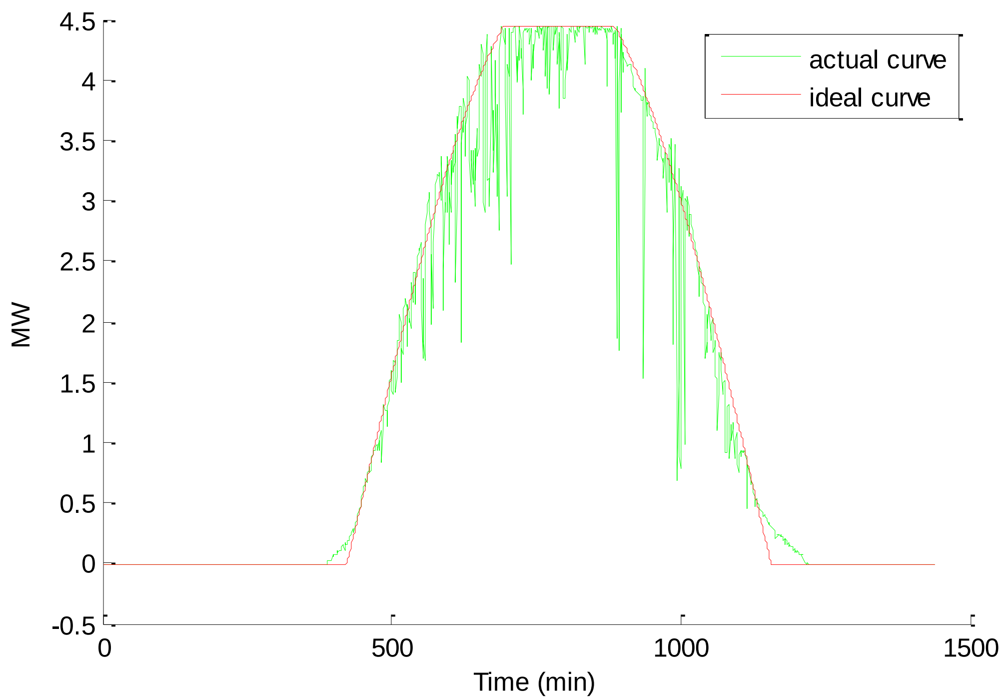


Figure 4.3. Actual and ideal MW output curves for 14th July 2015

It can be seen from Figure 4.3 that this day has many dips. The dips mainly occur in the ramp-up and ramp-down periods. Fewer dips occur during the maximum output period. The sunrise and sunset time are 389 min and 1221 min. The maximum output period is from 632 min to 939 min.

The performance metrics for this day are evaluated by comparing various parameters of actual data with their corresponding values of ideal data. The performance metrics for the day are given in the Table 4.3.

Table 4.3. Performance evaluation for 14th July 2015

| **Performance Parameters** | **Actual values** | **Ideal values** | **Actual as % of Ideal** |
|---|---|---|---|
| Energy generated during the entire day (MWh) | 34.81 | 36.63 | 95% |
| Average MW output from sunrise to sunset (MW) | 2.51 | 2.65 | 95% |
| Energy generated during maximum output period (MWh) | 21.03 | 22.24 | 95% |
| Average MW during maximum output period (MW) | 4.10 | 4.33 | 95% |

From Table 4.3, it is observed that all of the actual values of the performance parameters are 95% or above of their corresponding ideal values. Hence the power produced is quite high regardless of the non-ideal power produced.

The performance evaluation for this day is over. Next part is the analysis of dips. The analysis is carried out by characterizing the dips into various characteristics. As it has been pointed earlier, the dips occurring only during maximum output period will be considered for analysis as those dips will have greatest impact on voltage variations. The dips occurring during ramp-up and ramp-down period will have limited impact on voltage variations. The statistical analysis of dips is performed using MATLAB software.

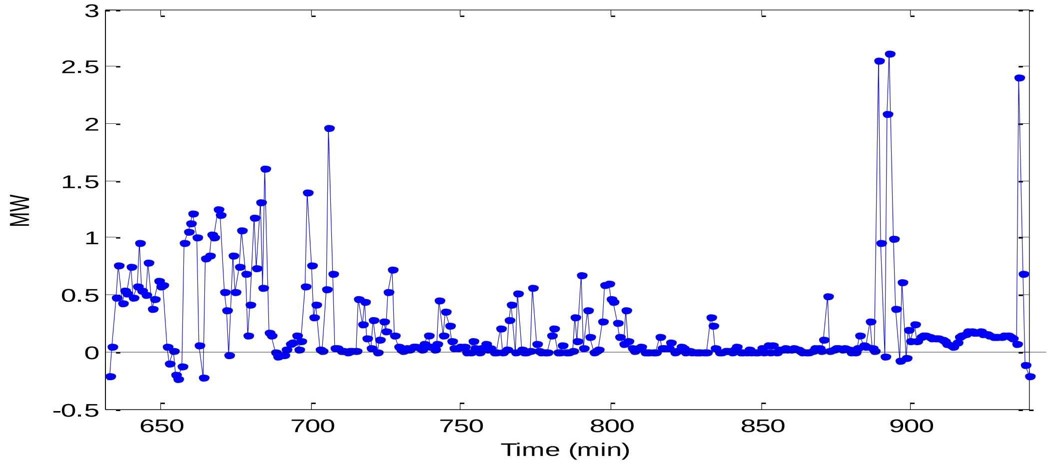


Figure 4.4. Dip curve of 14th July 2015 during the maximum output period

Figure 4.4 will be used to carry out the dip analysis. The results obtained from analyzing dips from the loss curve for 14th July 2015 are given in Table 4.4.

Table 4.4. Dip analysis results for 14th July 2015

| Dip Frequency | Maximum Depth of Dip | Energy loss during Dip | Mean of Dip | Duration of Dip | Time period of Dip | |
|---|---|---|---|---|---|---|
| # of dip | (MW) | (MWh) | (MW) | (min) | From (min) | To (min) |
| 1 | 0.95 | 0.16 | 0.46 | 20 | 633 | 653 |
| 2 | 1.21 | 0.08 | 0.63 | 7 | 657 | 664 |
| 3 | 1.25 | 0.11 | 0.68 | 9 | 664 | 673 |
| 4 | 1.60 | 0.17 | 0.59 | 16 | 673 | 689 |
| 5 | 1.40 | 0.06 | 0.28 | 13 | 691 | 704 |
| 6 | 1.96 | 0.05 | 0.47 | 6 | 704 | 710 |
| 7 | 0.72 | 0.03 | 0.20 | 9 | 722 | 731 |
| 8 | 0.67 | 0.03 | 0.20 | 7 | 787 | 794 |
| 9 | 0.60 | 0.06 | 0.24 | 13 | 795 | 808 |
| 10 | 2.55 | 0.07 | 0.37 | 10 | 881 | 891 |
| 11 | 2.62 | 0.10 | 0.99 | 5 | 891 | 896 |

From Table 4.4, the following observations are made:

- There are 11 dips.
- The maximum dip depth and maximum dip duration are 2.62 MW and 20 minutes respectively.
- The total energy loss is 0.93 MWh.

### 4.3. 25TH AUGUST 2015

The actual and ideal data are plotted in Figure 4.5.

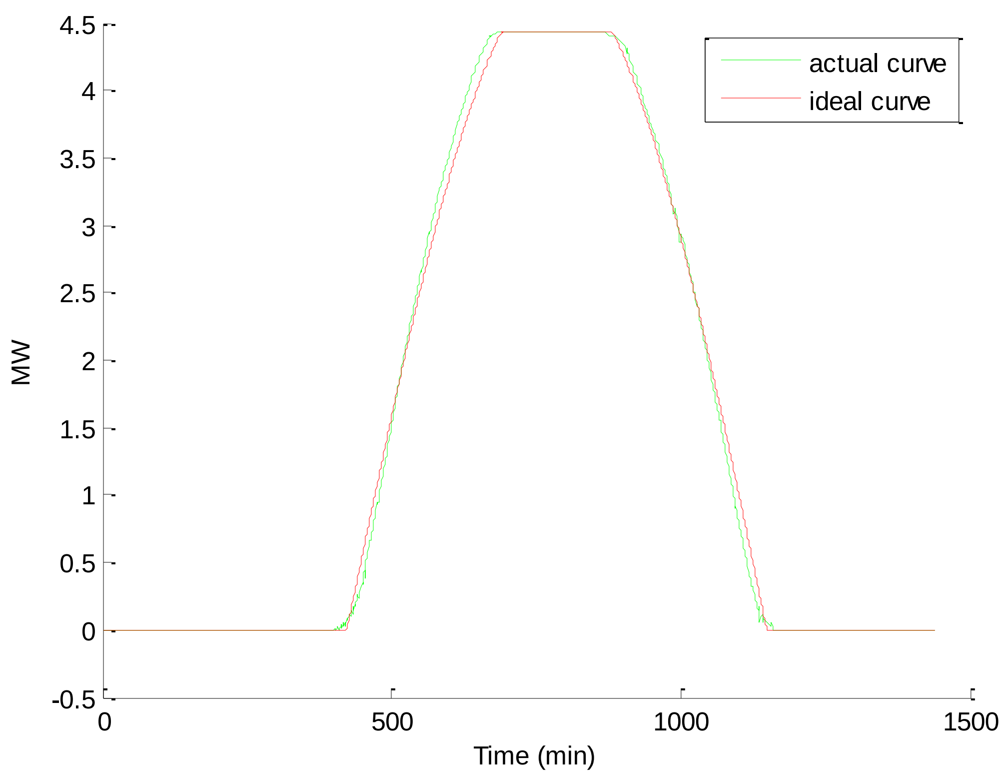


Figure 4.5. Actual and ideal MW output curves for 25th August, 2015

From Figure 4.5, it can be said that this day has no dips. The actual and ideal curves nearly coincide. The performance analysis for the day is given in Table 4.5.

Table 4.5. Performance evaluation for 25th August 2015

| **Performance Parameters** | **Actual values** | **Ideal values** | **Actual as % of Ideal** |
|---|---|---|---|
| Energy generated during the entire day (MWh) | 36.43 | 36.34 | 100% |
| Average MW output from sunrise to sunset (MW) | 2.82 | 2.81 | 100% |
| Energy generated during maximum output period (MWh) | 21.89 | 21.71 | 100% |
| Average MW during maximum output period (MW) | 4.38 | 4.34 | 100% |

The dip curve given in Figure 4.6 is used for the statistical analysis of dips. This dip curve is used to produce the various dip characteristics given in Table 4.6.

The dip curve is generated by subtracting the actual curve from the ideal curve. Sometimes, the values of dip curve fall below zero. It can be said for these points, the actual curve exceeds the ideal curve. As it has been pointed out earlier, because of reflection and refraction, the actual and ideal curves sometimes do not coincide completely. There are other factors as well that might affect the actual curve for that day. Factors like temperature and humidity on a particular day might cause the actual curve to deviate from its ideal curve.

The analysis of dips is carried out using MATLAB software. The dips occurring during maximum output period are only considered for the study. The dips during ramp-up and ramp-down periods are ignored.

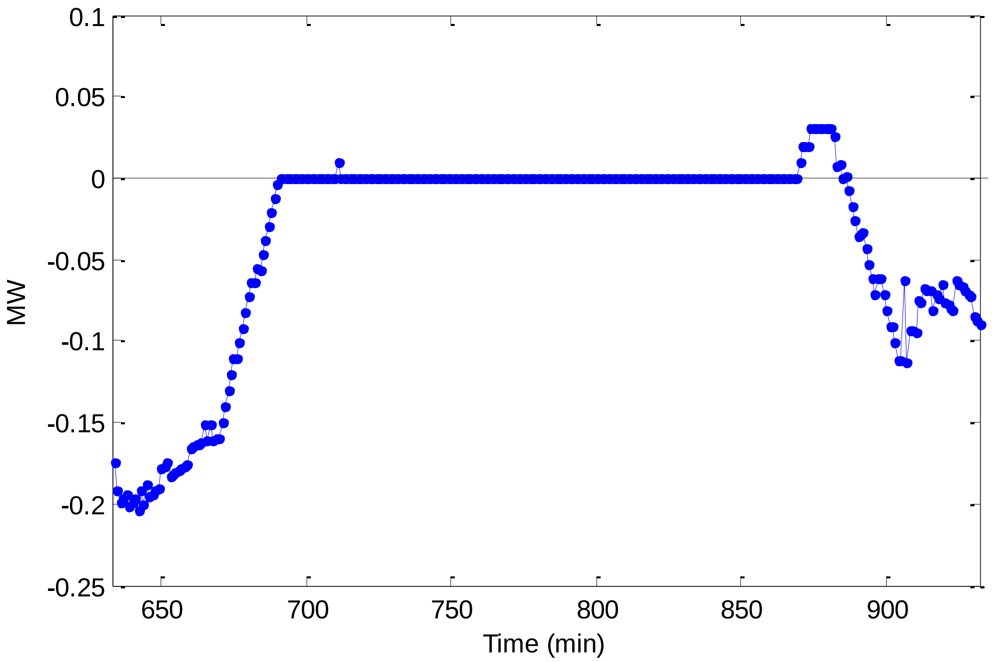


Figure 4.6. Dip curve for 25th August 2015 during the maximum output period

The following points are made by observing the dip curve in Figure 4.6

- The dips are very small in terms of its maximum depth and frequency.
- Although the dips do not meet the maximum dip depth criteria for selecting dips, these dips are considered for the analysis as exceptions.
- The loss curve falls below the zero reference line because at some points in time, the real curve exceeds the ideal curve due to measurement imprecision.

The dips analysis results obtained by statistically analyzing the loss curve of 25th August 2015 during the maximum output period are given in Table 4.6.

Table 4.6. Dip analysis results for 25th August 2015

| Dip Frequency | Maximum Depth of Dip | Energy loss during Dip | Mean of Dip | Duration of Dip | Time period of Dip | |
|---|---|---|---|---|---|---|
| # of dip | (MW) | (MWh) | (MW) | (min) | From (min) | To (min) |
| 1 | 0.01 | 0.00 | 0.00 | 2 | 710 | 712 |
| 2 | 0.03 | 0.01 | 0.02 | 16 | 869 | 885 |

The information obtained from the above Table 4.6 can be summarized as follows

- There are two dips.
- The maximum depth of dip and maximum duration of dip are 0.03 MW and 16 minutes respectively.
- The total energy loss caused by the dips is 0.01 MWh.

### 4.4. 28th SEPTEMBER 2015

The actual and ideal curves are given in Figure 4.7 and are used to find the performance metrics. The dip curve is given in Figure 4.8.

The actual curve is generated using the measure MW output data provided by the utility. The Ideal curve is the maximum amount of power that can be generated at the location where the photovoltaic plant is situation for that day under clear sky. The performance evaluation and dip analysis are carried out by comparing the actual with its ideal curve.

The performance evaluation is performed by comparing the actual values of performance evaluation parameters with their corresponding ideal values. The dip analysis is performed by using the dip curve. The dip curve is generated by subtracting the actual curve from its ideal curve.

The actual curve, ideal curve and the dip curve are generated in MATLAB.

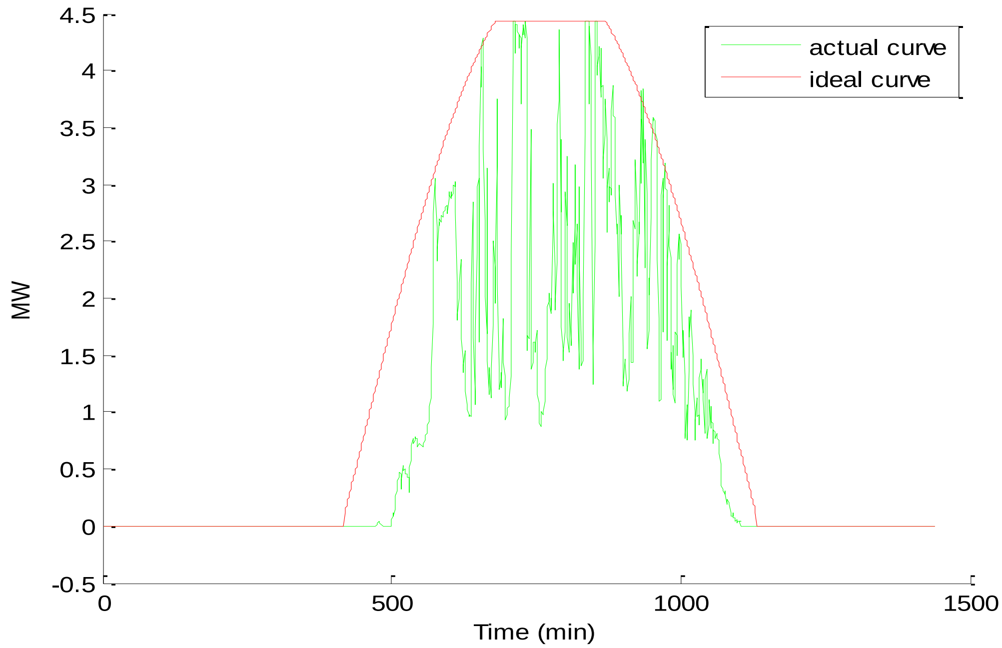


Figure 4.7. Actual and ideal MW output curves for 28th September 2015

Figure 4.7 shows that this day is replete with dips that are significant in terms of both maximum dip depth (magnitude) and dip duration. The day appears to be a cloudy one and not much power was produced for this day. The performance evaluation is given in Table 4.7.

Table 4.7. Performance evaluation for 28th September 2015

| **Performance Parameters** | **Actual values** | **Ideal values** | **Actual as % of Ideal** |
|---|---|---|---|
| Energy generated during the entire day (MWh) | 19.56 | 36.04 | 54% |
| Average MW output from sunrise to sunset (MW) | 1.65 | 3.04 | 54% |
| Energy generated during maximum output period (MWh) | 11.48 | 20.12 | 57% |
| Average MW during maximum output period (MW) | 2.50 | 4.37 | 57% |

From Table 4.7, it is observed that the performance of the day is poor, with the generated power and energy around 54% of what it could have generated if the day had a clear sky.

The dip curve given below is obtained by subtracting the actual data from the ideal values of MW power generation for the day. Some values of dip curve falls below the zero reference line because of measurement noise.

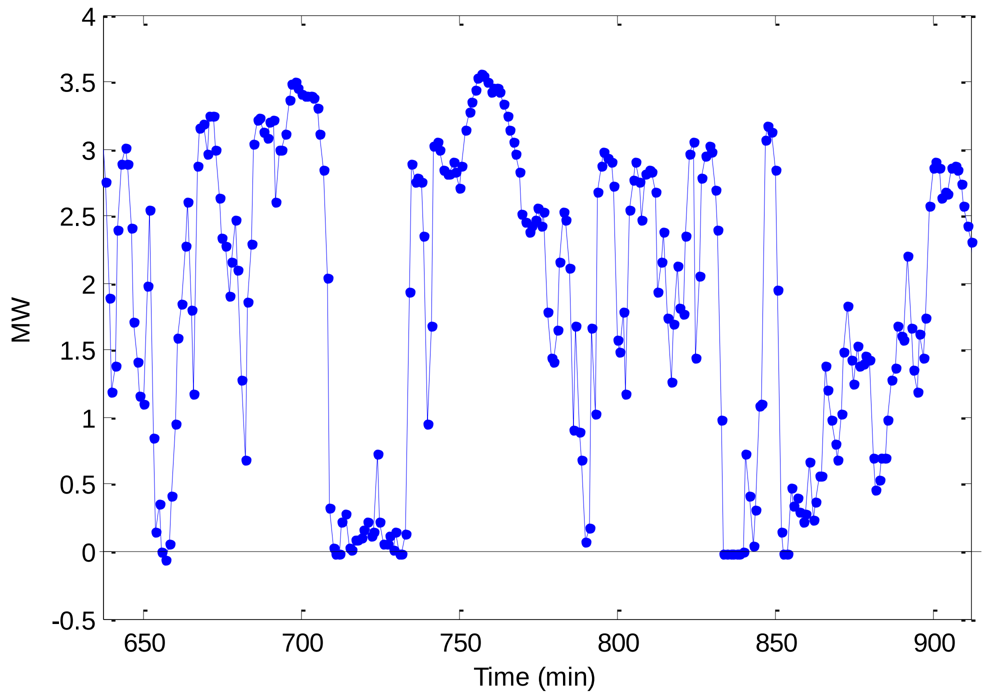


Figure 4.8. Dip curve for 28th September 2015 during the maximum output period

The results generated by statistically analyzing the dips present in Figure 4.8 are given in Table 4.8.

Table 4.8. Dip analysis results for 28th September 2015

| Dip Frequency | Maximum Depth of dip | Energy loss during dip | Mean of Dip | Duration of dip | Time period of dip | |
|---|---|---|---|---|---|---|
| # of dip | (MW) | (MWh) | (MW) | (min) | From (min) | To (min) |
| 1 | 3.51 | 2.22 | 2.42 | 54 | 657 | 711 |
| 2 | 0.74 | 0.05 | 0.15 | 19 | 712 | 731 |
| 3 | 3.57 | 4.08 | 2.38 | 102 | 732 | 834 |
| 4 | 3.19 | 0.30 | 1.30 | 13 | 840 | 853 |

Summarizing the results given in Table 4.8:

- There are 4 dips on this day.
- The maximum dip depth and dip duration are 3.57 MW and 102 minutes respectively.
- The total energy loss caused by all the dips is 6.65 MWh.

Even though there are only four dips during the maximum output period, the dips occurring in the ramp-up and ramp-down periods also reduce the power generation capacity drastically, making the overall performance for that day poor.

# 5. PERFORMANCE EVALUATION

## 5.1. AVERAGE POWER GENERATION

As has been mentioned previously, the performance evaluation is done by comparing the various performance metrics comparing the actual data with their corresponding values of ideal data**.** The average MW power generation is calculated for various time periods for a particular day in summer and is shown in figure 5.1. Those time periods are sunrise-sunset period and maximum output period. The average MW power generation is calculated only for the summer. The months that are being taken into account for the study are June, July, August, and September. Some days are excluded as anomalies due to unexplained performance behavior, mostly likely due to measurement or operating disruptions. Except for those days, all of the other days have been used for performance evaluation and dip analysis. The total number of days in the summer evaluation is 75.

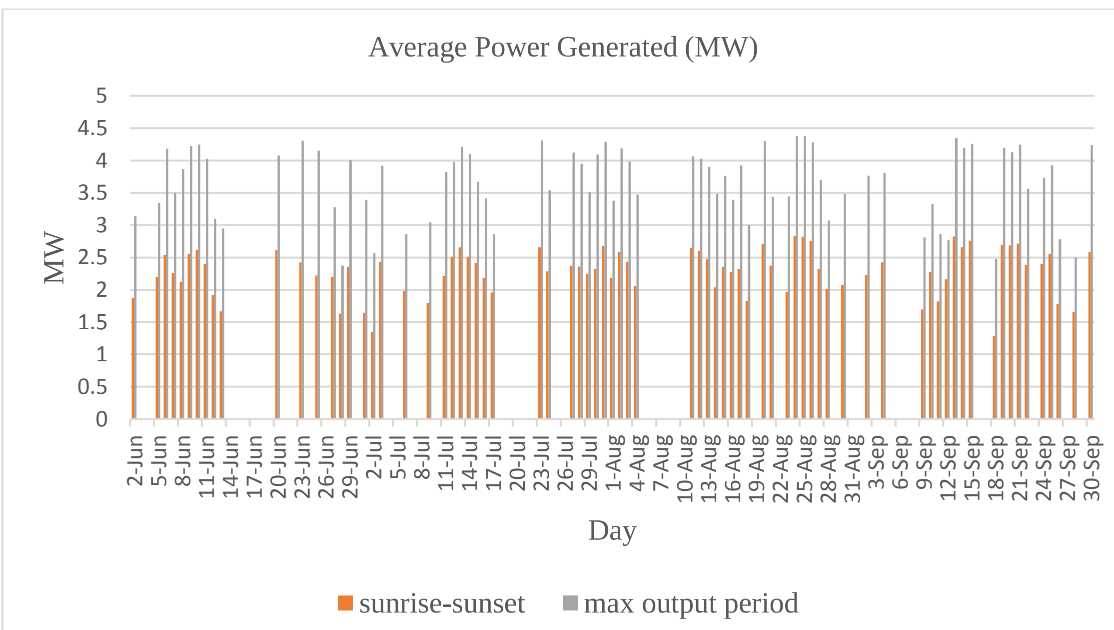


Figure 5.1. Average power (MW) generated for the 2015 summer

Interpretation of Figure 5.1 indicates that the average MW power varies is considerably different between the sunrise-sunset and maximum output periods. The important distinction is that for some days there is a difference between the actual average MW power as a percentage of its ideal value for maximum output period and for sunrise-sunset period. This provides information about during which time period (ramp-up and ramp-down period or maximum output period) the majority of the energy was lost due to dips took place. For example, on 23rd August 2015, the percentages for sunrise-sunset period and maximum output period are 68% and 80% respectively. This indicates that although the actual average MW power generation during maximum output period generates 80% of it ideal value but due to excessive dips during ramp-up or ramp-down periods, the average MW power generation from sunrise-sunset was reduced drastically to 68% of its ideal value.

A histogram is constructed in Figure 5.2 to assess the performance of the plant by using the average MW power generated for two different time periods. In Figure 5.2, the y-axis represents the frequency of occurrence of the number of days. The x-axis shows the actual average MW power as a percentage of ideal average MW power generated. It should be noted that for every histogram shown in this report, the x-axis does not represent single values but is actually a range of values. For example in Figure 5.2, only four days out of the summer produced power in the range of 50-60% of ideal. Only two days produced less than 50% of ideal throughout the whole period, whereas there were no days that produced less than 50% during the maximum output period.

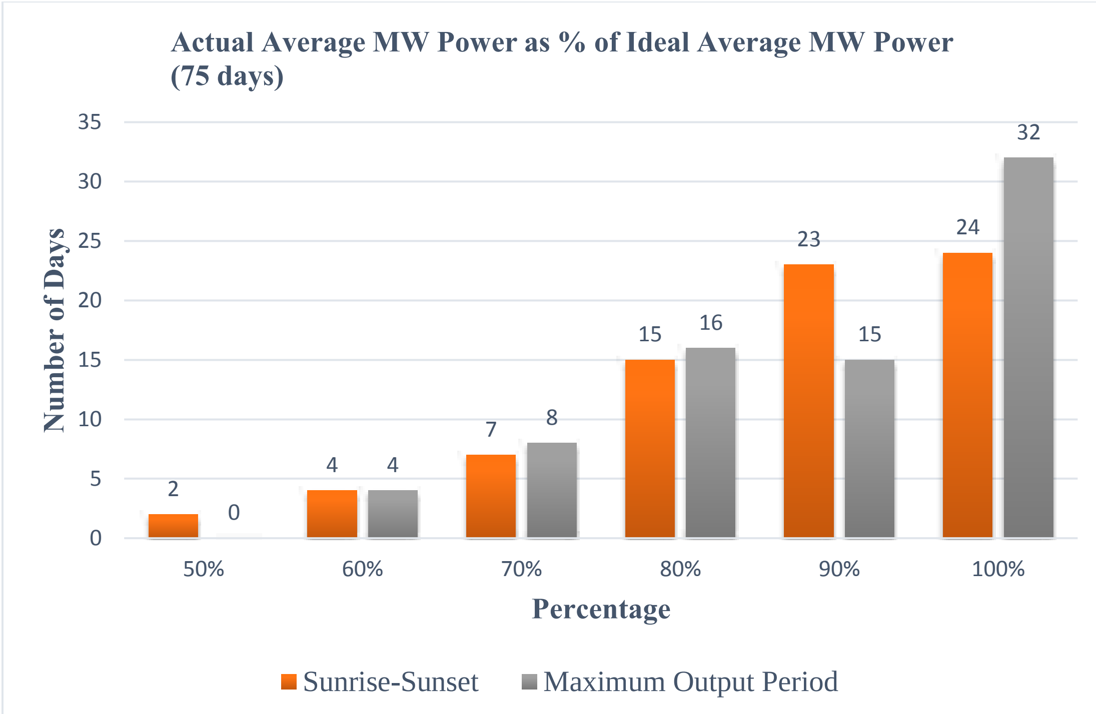


Figure 5.2. Histogram of actual average MW power generated as percentage of ideal for summer

The following observations can be made from the histogram in Figure 5.2:

- For 24 of the 75 days of summer, the photovoltaic plant performed well by generating an average MW power of more than 90% of the ideal average power during the sunrise-sunset period.
- Note that during maximum output period, nearly 32 days have produced an actual average power of more than 90% of ideal average power, whereas only 24 days produced same result during sunrise-sunset period. This is because more dips occurred in the ramp-up and ramp-down regions than in the maximum output region. Therefore the average power output for sunrise-sunset period was reduced for those 8 days (32-24) in the 90 -100% range.
- The mean of the average MW power generated during the sunrise-sunset period and the maximum output period are 2.29 MW and 3.67 MW, respectively, and the mean of the ideal

average MW power generated during the sunrise-sunset period and the maximum output period are 2.79 MW and 4.34 MW, respectively.

### 5.2. ENERGY GENERATION

The energy generation for the entire day is calculated for the entire year starting from 1st November 2014 to 31st October 2015. The energy generation during the maximum output period is calculated only for the 75 days of summer and shown in figure 5.3. Out of 365 days, a few days were anomalous and the energy MWh generation for those days is zero.

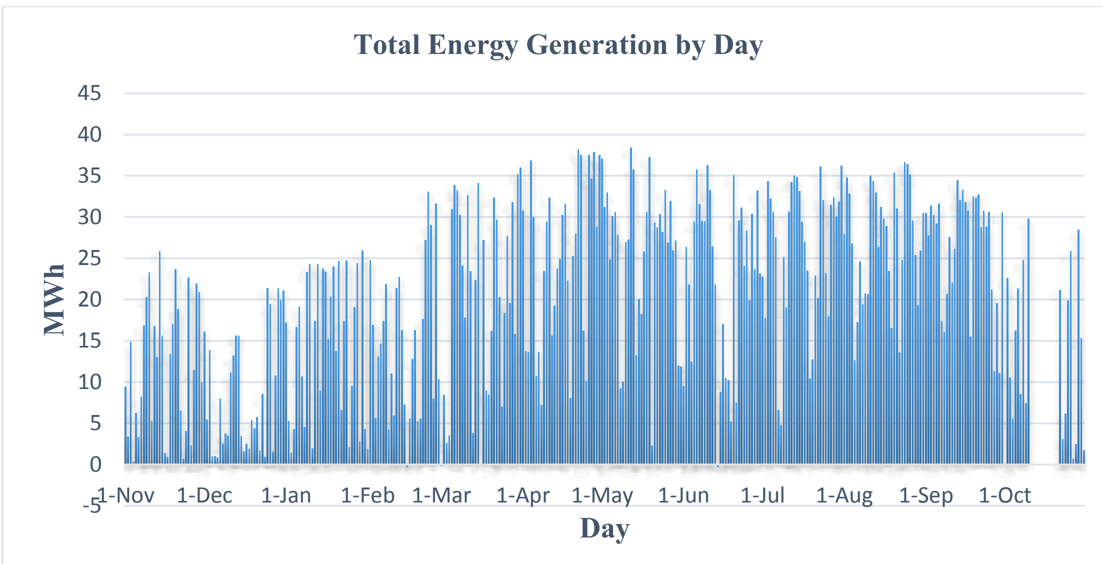


Figure 5.3. Total energy MWh generated per day

In Figure 5.3, the mean of the energy generation during the entire day for all the 365 days is 19.35 MWh. The maximum MWh generation is 38.43 MWh and is on 12th May 2015. It can be seen that the energy generation from the photovoltaic plant is typically lowest during the winter and increases towards the summer. In order to clearly estimate the performance of the plant in each month and season, the total energy generation by month is calculated.

The total energy generation by month is calculated by summing the total energy MWh of each day of the month. The total energy generated per month by the photovoltaic plant is shown in Figure 5.4.

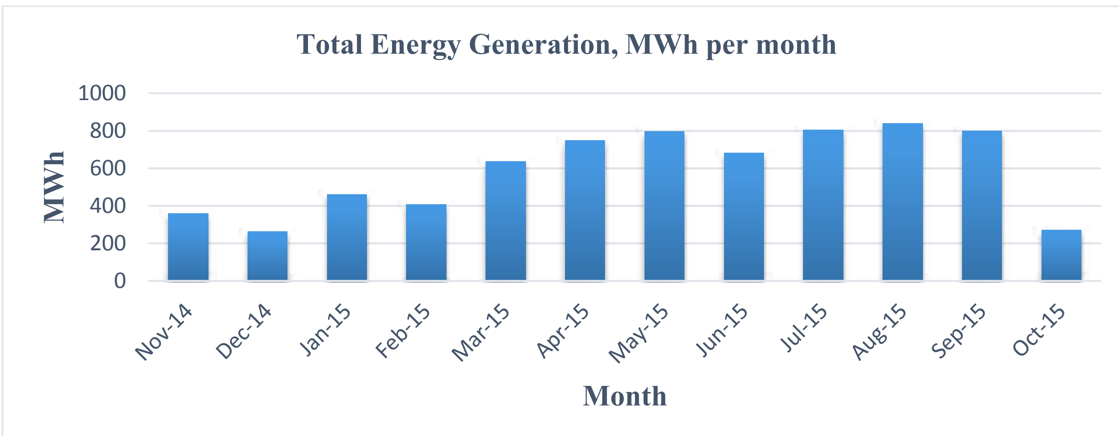


Figure 5.4. Total energy generation in MWh by month

From Figure 5.4, the total energy generation during the winter (Nov, Dec, Jan) is 1081.64 MWh, during spring (Feb, March, April, May) it is 2586.41 MWh, and the total energy generated during summer (June, July, August, September) is 3124.18 MWh. The total energy generation by the plant in summer exceeds the spring generation by nearly 17% and the winter generation by 65%. It is observed that the energy MWh generation is lowest during winter and then starts to increase from spring onwards and attains the highest generation during summer. There is a reduction in the total energy generation in June 2015 as compared to May 2015. Poor weather conditions may have been a factor. August 2015 has highest energy generation of 839.39 MWh.

A histogram is constructed in Figure 5.5 using the energy generation data for each day for 365 days.

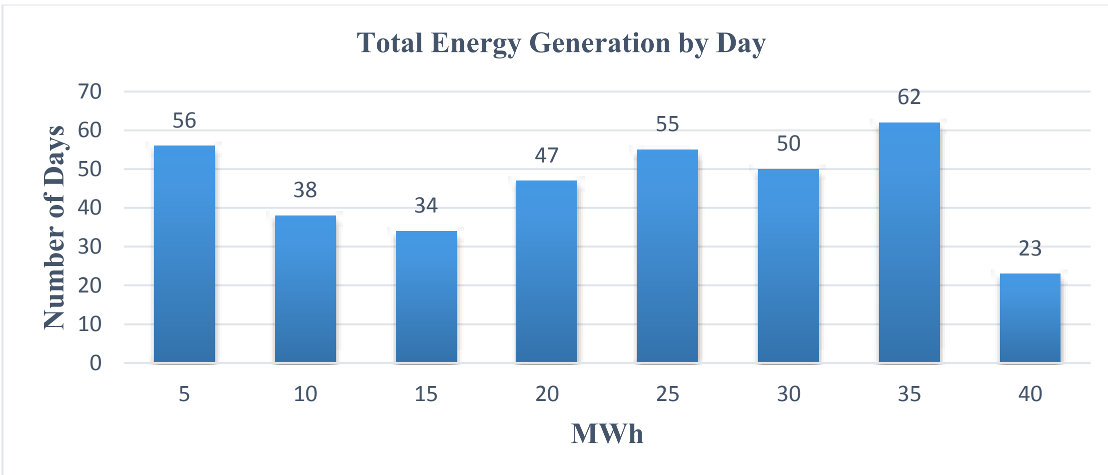


Figure 5.5. Histogram of total energy generation for 365 days

The following observations can be made from Figure 5.5:

- Only 23 days of the year have a maximum energy generation between 35 MWh – 40 MWh.
- For 56 days, the energy generation is less than 5 MWh.
- 192 days have an energy generation of more than 20 MWh. It means out of 365 days, over half of them have an energy generation of more than 20 MWh.

For comparing actual energy generation during two different time periods and for comparing it with ideal energy generation, the 75 days summer, starting from 1st June 2015 to 30th September 2015 are analyzed. These same days will be used for the dip analysis which will be discussed later. Figure 5.6 compares the energy generated during the entire day and the maximum output period. The days with no data presented are due to anomalies in the data.

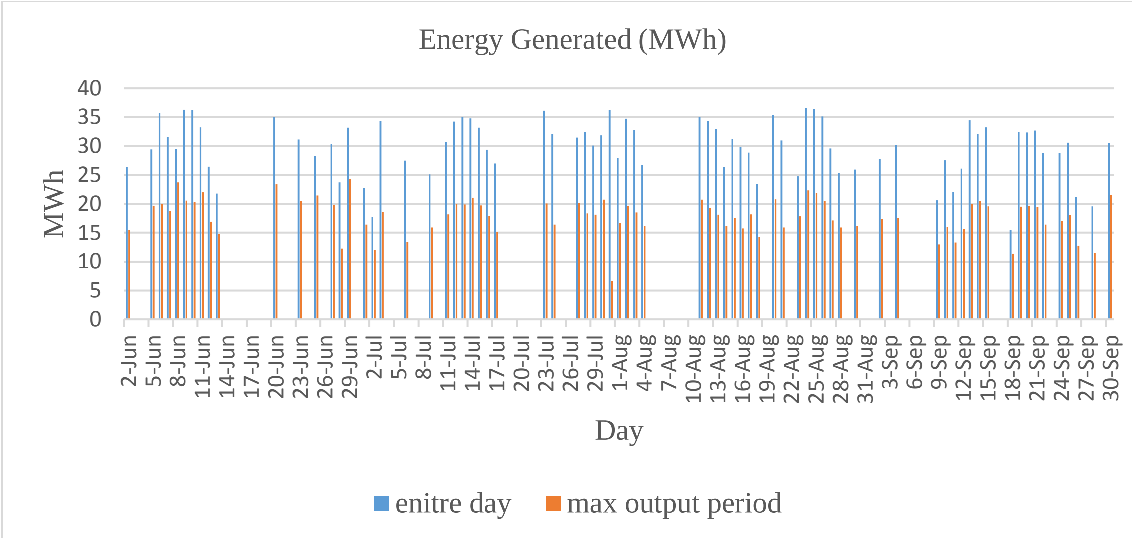


Figure 5.6. Energy MWh generated during two time periods for summer

The data from Figure 5.6 can be summarized as follows

- The energy generation for entire day is more than the energy generated during maximum output period.
- For some days, the gap between the energy generation during entire day and the energy generation during maximum output period is small. This is because the energy generation during ramp-up and ramp-down period is minimal.
- For some days, the gap is large. For example, on 31st July 2015, the energy generation during the entire day and during the maximum output period are 36.21 MWh and 6.65 MWh, respectively. The reason behind this large gap is that the energy loss due to dips occurring during maximum output periods is more than ramp-up and ramp-down regions.
- The maximum energy generation during the entire day (36.65 MWh) and maximum output period (24.27 MWh) occurred on both 29th June 2015 and 24th August 2015 and respectively.

A histogram is constructed in figure 5.7 to check the performance of 75 days in summer.

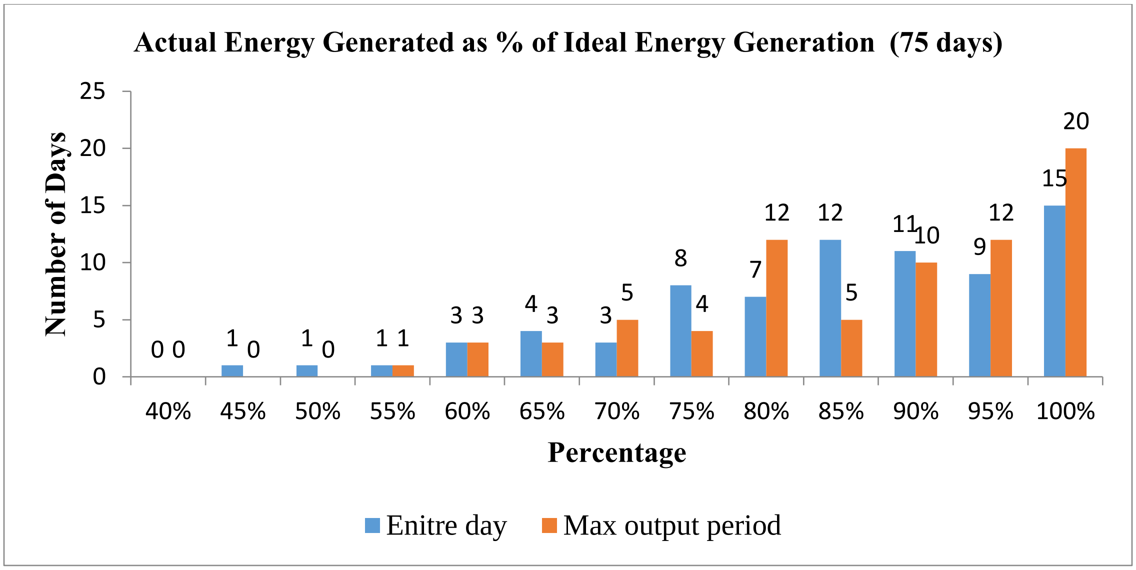


Figure 5.7. Histogram of actual energy generation as % of ideal energy generation for summer

The following observations are made from Figure 5.7

- The number of days for entire day and maximum output period having actual energy generation more than 95% of ideal energy generation are 15 days and 20 days respectively.
- The mean of actual energy generation during the entire day and the maximum output period are 29.88 MWh and 17.89 MWh respectively.
- The mean ideal energy generation during the entire day and the maximum output period are 36.44 MWh and 21.19 MWh respectively. These ideal MWh values are calculated as the average of ideal energy generation in summer days during their respective time periods.
- 47 days (63% of the 75 days) have actual energy generation during both entire day and maximum output period more than 80% of their respective ideal values.

# 6. DIP ANALYSIS

Various characteristics of the dips in the MW output are used for dip analysis. The characteristics are dip frequency, dip duration, depth of dip, and energy loss during dip. It is important to note that only dips occurring during the maximum output period are used for analysis. Dips occurring during the ramp-up and ramp-down periods of the day are not included in the dip frequency or in any of the dip characteristics.

## 6.1. DIP FREQUENCY

Dip frequency is the number of dips that occurred in a day. Dips are primarily responsible for energy loss. The larger the number of dips, the greater the chance of energy loss due to dips. But it is important to note that a higher dip frequency does not necessarily result in a higher energy loss. Energy loss of dips mainly depends on dip duration and depth (magnitude) of dip.

The number of dips occurring in each day for summer are given in Figure 6.1.

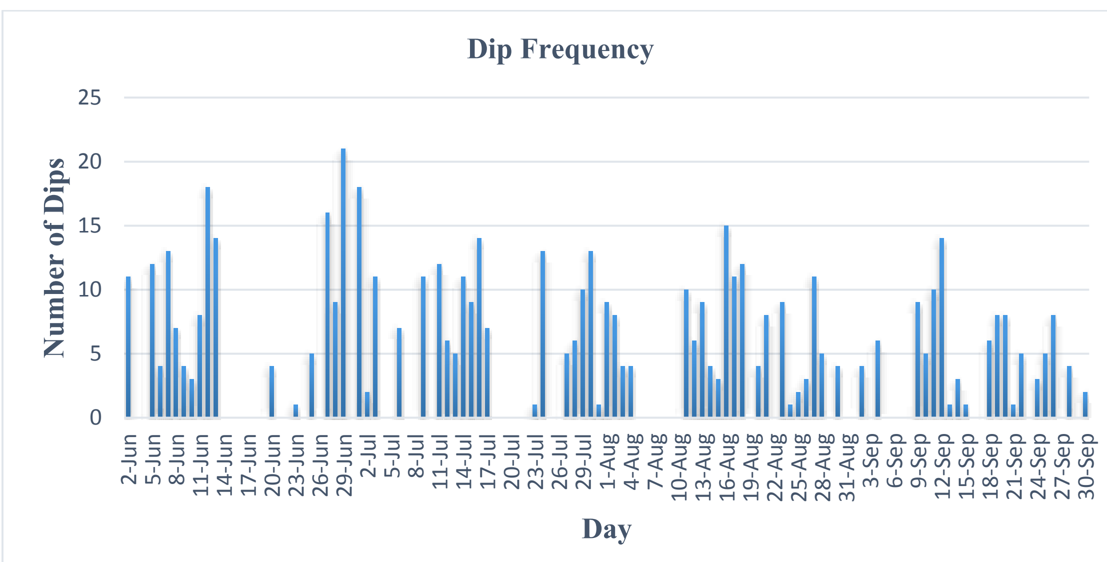


Figure 6.1. Dip frequency per day for summer

In Figure 6.1, several days that have been ignored during the study due to data anomalies, but in reality there are dips in those days as well. The followings observations are made from Figure 6.1:

- The total number of dips in the summer period is 557.
- The mean of the dip frequency for summer is 7.43 which can be rounded off to 7. Therefore, it can be said that average number of dips per day in summer is 7.
- The maximum number of dips occurred on $29^{th}$ June 2015 with a value of 21 dips.
- The minimum number of dips is 1 which occurred on a few days.

Note that although a few of the dips do not meet the dip selection criteria, those days are considered for analysis. When the number of dips in a day is 1, it is highly probable that it may not be a dip but may actually be noise in the output.

## 6.2. DEPTH OF DIP

The magnitude of the dip is defined by the depth of dip. The depth of dip can be described by two properties. One property is maximum or peak depth of dip. The other one is average depth of dip.

**6.2.1. Maximum Depth of Dip.** The maximum depth of dip is the peak magnitude of the dip, and indicates how low the actual MW power has decreased from its ideal value.

If the maximum depth of a dip is high and that dip persists for a long period of time at that maximum depth, it can cause a large energy loss. But in most cases, dips do not stay at their maximum depth for a long time period. Thus, the average depth of dip can give more information about the depth as opposed to the peak depth of dip.

There were 557 dips in the summer period during maximum output period of the day. In Figure 6.2, the 557 dips of summer are shown in a range of maximum depth of dip.

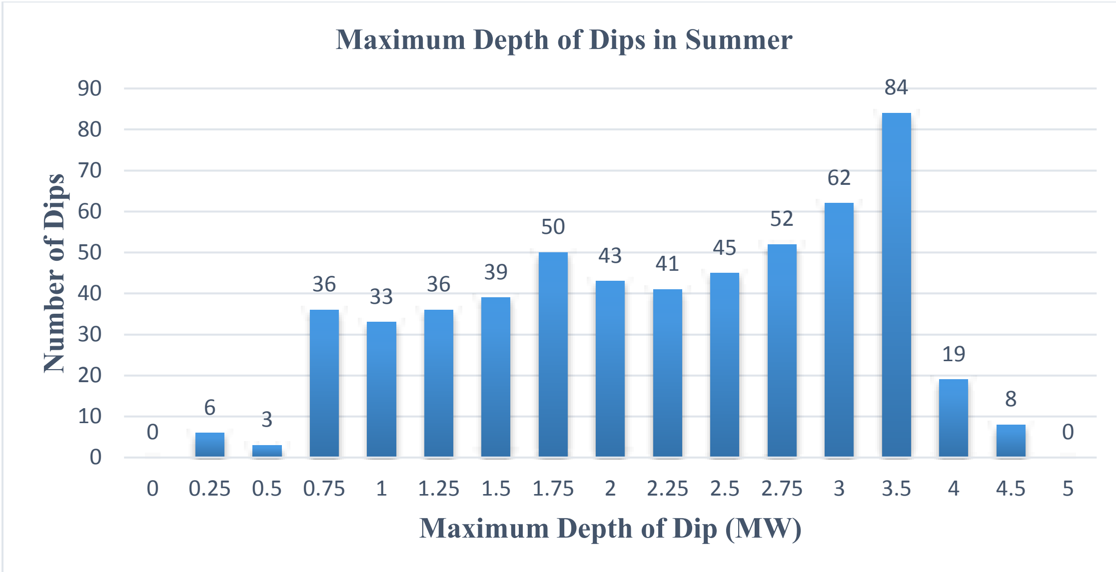


Figure 6.2. Histogram of maximum/peak depth of dip for 557 dips in summer

The following observations are made from Figure 6.2:

- The greatest number of dips (84 dips) have a maximum depth of 3 MW-3.5 MW. These dips are large and hence may cause voltage variations which are undesirable, although the impact on system voltage variations is not purely dependent on the depth or magnitude of dip. The dip duration plays an important role.
- 270 dips have a maximum depth of more than 2.25 MW. This means that 48.4 % (nearly 50%) of the dips that occurred in summer have maximum depth of more than 2.25 MW. In a photovoltaic system of 4.5 MW output, a peak depth of 2.25 MW translates to a 50% loss in MW output at that instant.
- The average maximum depth of dip for 557 dips is 2.15 MW. This is the mean value of maximum depth of all dips occurred in the summer period.

- 8 dips have a maximum depth of 4 MW - 4.5 MW. This implies that the time at which these 8 dips peaked, the output of the photovoltaic system reduced drastically. These are very sharp drops or dips in the output.

In Figure 6.3, the average maximum depth of dip per day is shown. It is calculated by taking the average of the maximum depth of all dips occurring in a day during maximum output period.

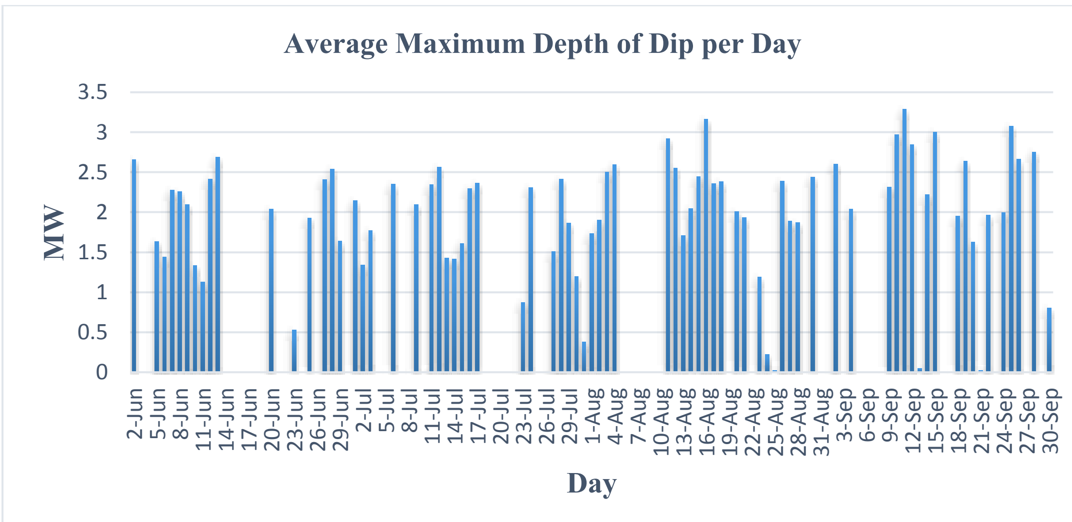


Figure 6.3. Average maximum depth of dip per day for summer

The following observations are made from Figure 6.3:

- The highest average maximum depth of dip is 3.29 MW and it occurs on 11$^{th}$ September 2015, followed by a 3.16 MW of average maximum depth of dip on 16$^{th}$ August 2015.
- 34 days have average maximum depth of dip of more than 2.25 MW. This implies that 34 days out of 75 days have incurred a minimum loss of 50% in the MW output from the plant for a certain duration.

- The average maximum depth of dip per day for summer is 1.98 MW. This is the mean value of average maximum depth of dips per day for all 75 days in summer.

**6.2.2. Average Depth of Dip.** The average depth of dip is another important characteristic of depth of dip that defines dip magnitude. In the histogram in Figure 6.4, 557 dips are shown in various range of average depth of dip (MW).

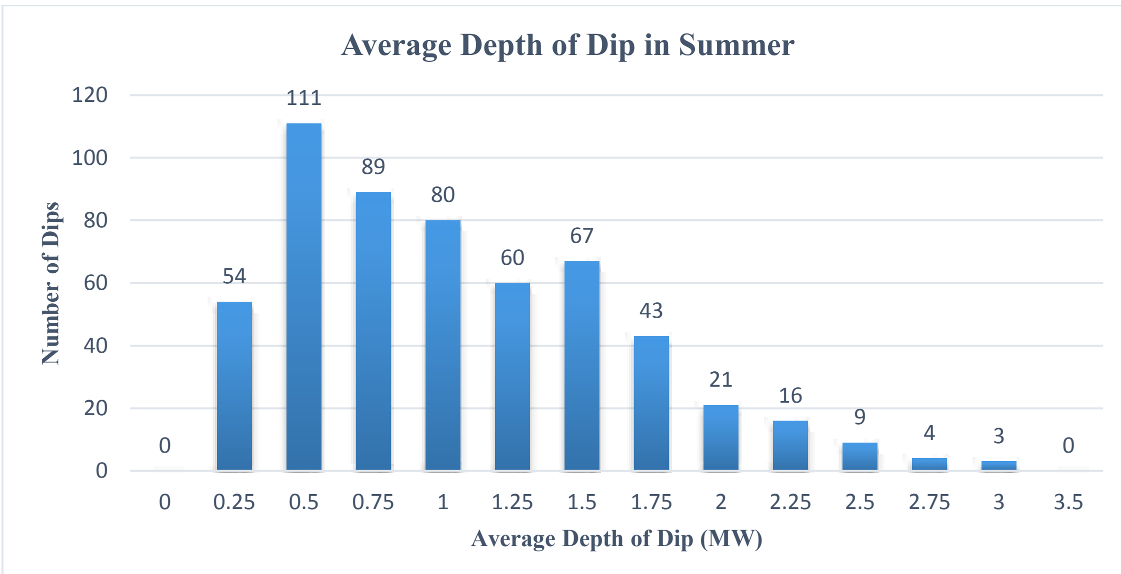


Figure 6.4. Histogram of average depth of dip for summer

Observations from Figure 6.4 are:

- 16 dips have average depth of more than 2.25 MW. That implies that 541 dips have an average depth of dip of less than 2.25 MW.
- The maximum number of dips (i.e. 111 dips) have an average depth of dip of 0.25 MW - 0.5 MW. The smaller the magnitude of the dip, the smaller the system voltage variations

resulting from it. As the magnitude of dip is defined by depth of dip, a lower average depth of dip is desirable.

- The mean of the average depth of all 557 dips in summer is 0.93 MW.

An important point that should be made here is that the maximum depth of dip is different from the average depth of dip. The maximum depth of dip is the maximum value a dip reaches during its duration whereas the average depth of dip is the mean of all actual MW values in a dip.

Figure 6.5 shows the average depth of all dips in a day. The average depth of dip per day is calculated by taking the mean of average depth of all dips occurring in a day.

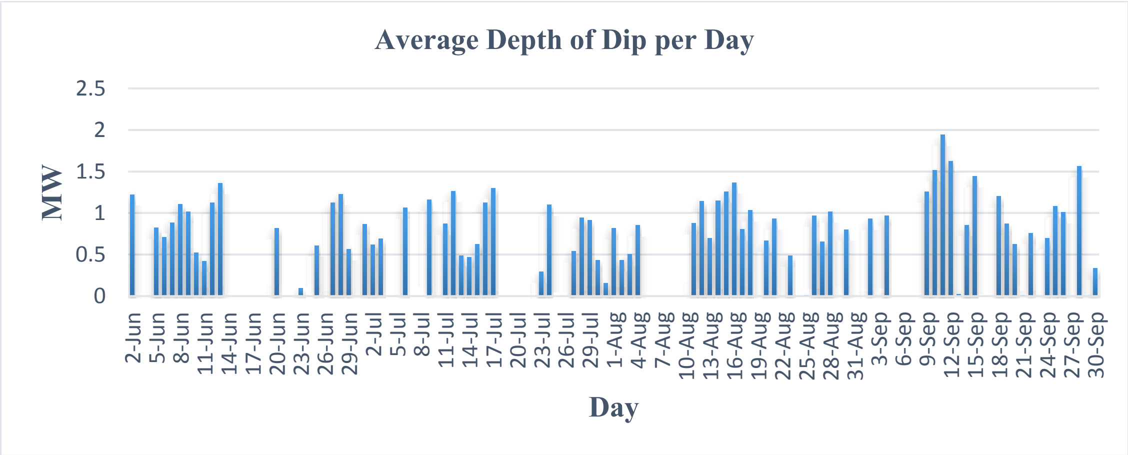


Figure 6.5. Average depth of dip per day for summer

The following information can be extracted from Figure 6.5

- The maximum average depth of dip in a day is 1.94 MW and it occurred on 11th September 2015.

- The average depth of dip per day for summer is 0.85 MW. It is the mean value of the average depth of dip per day for the summer period.

### 6.3. ENERGY LOSS DURING DIP

A total of 75 days have been considered for dip analysis from the months of summer. The energy loss during a dip is one of the most important characteristic for analyzing the dips as it directly indicates the performance of the photovoltaic plant. The higher the energy loss due to dips, the smaller the energy output from the plant.

The previous dip characteristics analyzed (dip frequency and depth (magnitude)) do not take the impact of the duration of dip into account. The energy lost by dips primarily depends on the dip duration. If any dip produces a high energy loss, it is highly probable that the duration of dip is long. The energy loss by dip also depends on the magnitude of dip.

The histogram shown in Figure 6.6 gives the number of dips incurring a range of energy losses (MWh). This histogram indicates how many dips are causing how much energy loss.

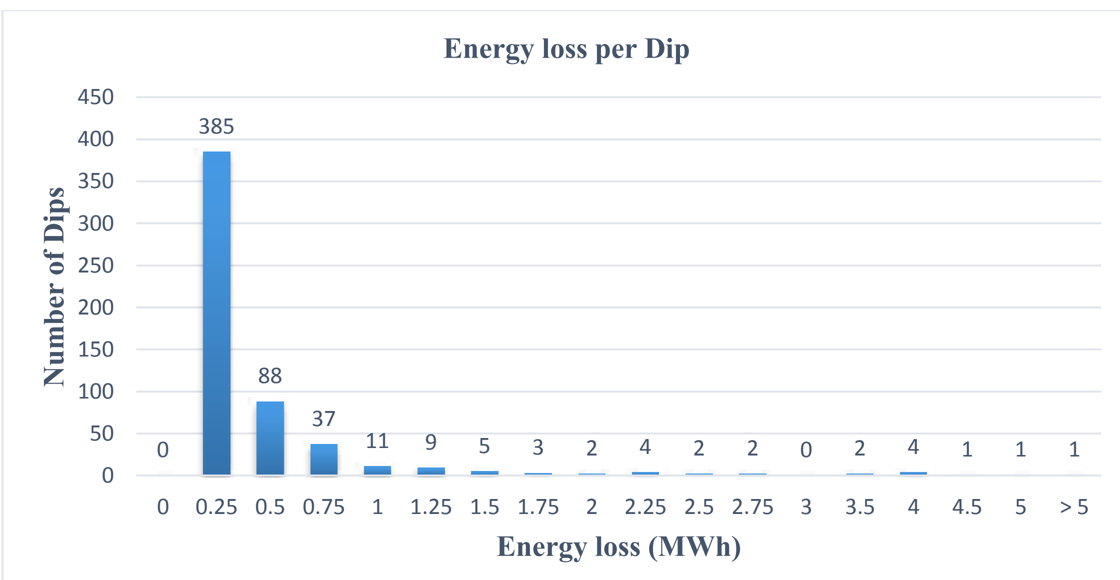


Figure 6.6. Energy loss per dip for 557 dips for summer

From Figure 6.6:

- The maximum number of dips (i.e. 385 dips) have an energy loss of less than 0.25 MWh. This indicates that most of the dips occurred during the maximum output period have resulted in an energy loss of 0.25 MW or less on the system.
- 521 dips have an energy loss of less than 1 MWh. This indicates that 93.5% of the total dips have an energy loss of less than 1 MWh.
- There is one value of energy loss during dip which is greater than 5 MWh. That value is 8.25 MWh. Such a large energy loss can be attributed to either a long dip duration or a large depth of dip, or both.
- The average energy loss during a dip is 0.33 MWh. It is calculated by taking the mean of energy loss of all 557 dips during the summer.

In order to assess the energy loss caused by dips per day on the photovoltaic system, the average energy loss of the dips and the total energy loss of the dips are calculated on a daily basis. The average energy loss of the dips per day is the mean of the energy losses of all dips occurring in a day. The total energy loss of the dips is the sum of the energy losses of all dips occurring in a day.

The objective of the project is to provide as much information as possible to the utility. Various figures are constructed to look at the data from different angle. Every figure gives some amount of unique information. Energy loss by dips is the important characteristic of dip as it directly shows the impact of dips on the system. The average energy loss of the dips per day and the total energy loss of the dips per day are calculated to provide some information on the impact of dips for individual day.

Total energy lost by dips per day in summer is shown in figure 6.7.

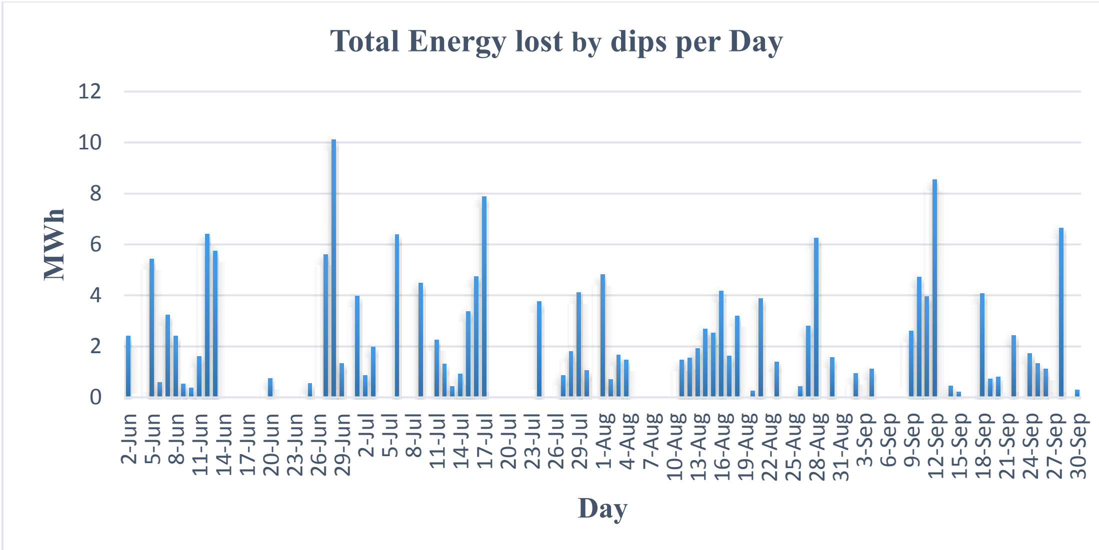


Figure 6.7. Total energy lost by dips during the maximum output period per day for summer

The following observations are made from Figure 6.7:

- The total energy lost during the maximum output period is the highest on 28th June 2015 with a value of 10.11 MWh. The ideal energy generation on 28th June 2015 during the maximum output period is 22.3 MWh. The actual energy generation of as percentage of ideal energy generation during maximum output period on that day is 55%. Because of the prolonged dips on that day, the photovoltaic system incurred a loss of 45% during that time period.
- The average total energy lost per day due to dips is 2.45 MWh. It is calculated as the mean of total energy lost by dips per day for 75 days in summer.

Figure 6.8 shows a histogram of the total energy lost by dips per day. Histogram will provide information on the performance of the days by showing how many days incurred how much energy loss per due to dips.

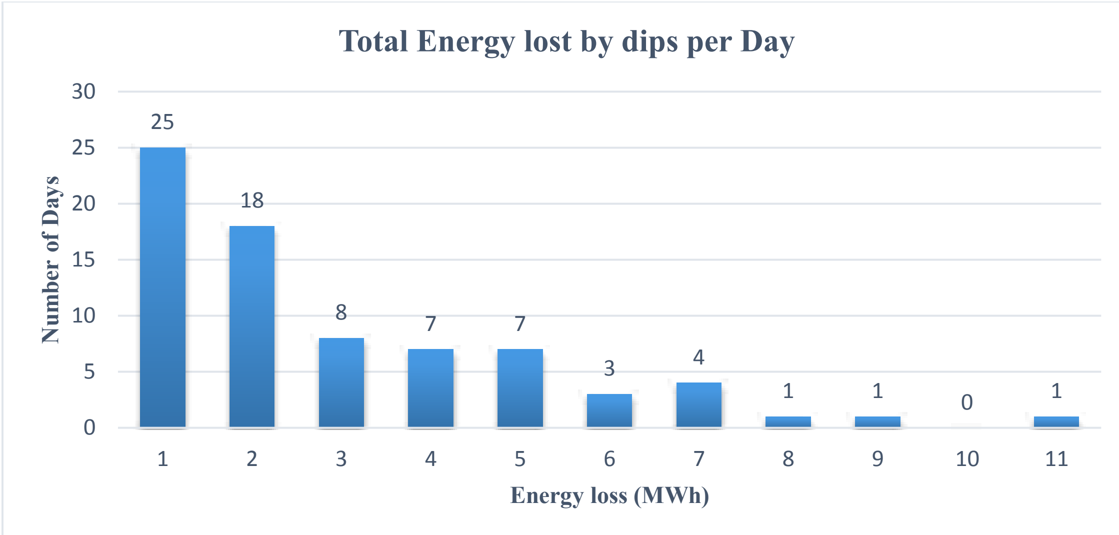


Figure 6.8. Total energy lost during dips per day for summer

The following observations can be made from Figure 6.8

- The highest number of days (i.e. 25 days) have a total energy loss caused by dips of less than 1 MWh. This implies that 33.33% of total number of days analyzed have incurred an energy loss less than 1 MWh.
- 65 days have a total energy loss caused by dips of less than 5 MWh. The average ideal energy generation during the maximum output period in summer is 21.19 MWh. It can be said that 65 days have energy generation of 16.19 MWh (21.19 MWh -5 MWh) i.e. 65 days have actual energy generation of 76.4%. It can be concluded from this point, that 65 days have actual energy generation more than 75 % of ideal MWh generation.
- On the other hand, 59 days have actual energy generation more than 75% of ideal energy generation during maximum output period.

Average energy loss caused by dips per day in summer is shown in figure 6.9.

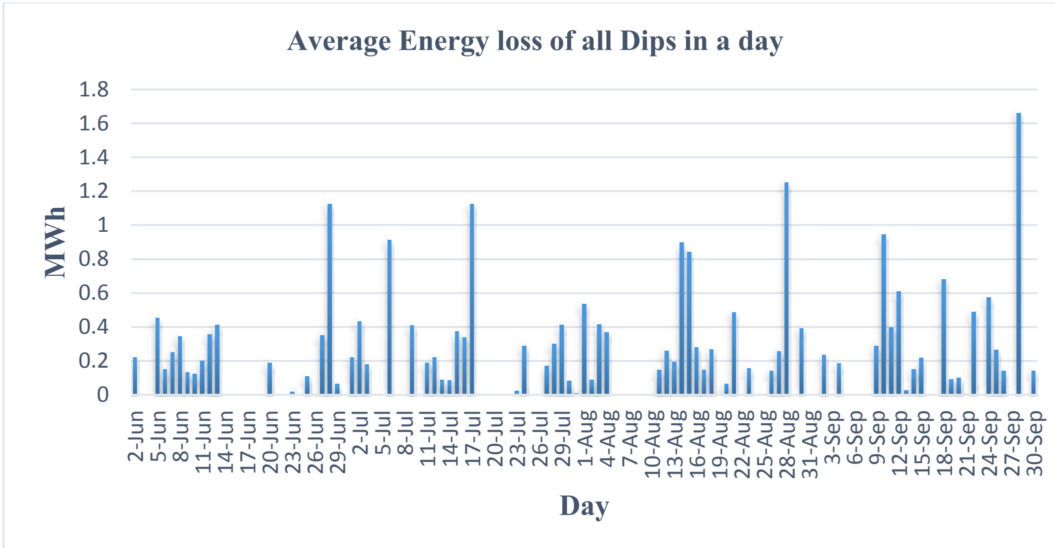


Figure 6.9. Average energy loss caused by dips per day for summer

Figure 6.9 shows the average energy lost due to dips per day. The summary of the results obtained after analyzing Figure 6.9 is given below:

- The average energy loss in a day caused by dips is highest on 28$^{th}$ September 2015 with a value of 1.67 MWh. However, the total energy lost per day is highest on 28$^{th}$ June 2015, not on 28$^{th}$ September 2015. This is due to the dip frequency and range of energy loss values on that day.
- 63 days have average energy loss due to dips less than 0.5 MWh.
- The average of average energy loss by dips per day is 0.33 MWh.

### 6.4. DIP DURATION

The dip duration is one of the most important characteristic of dip that can have an impact on the energy loss caused by dips. The energy loss of a dip is directly proportional to the duration of the dip. The longer the dip duration, the more the energy loss caused by the dip.

Figure 6.10 is a histogram showing the range of dip duration for each dip occurring in summer.

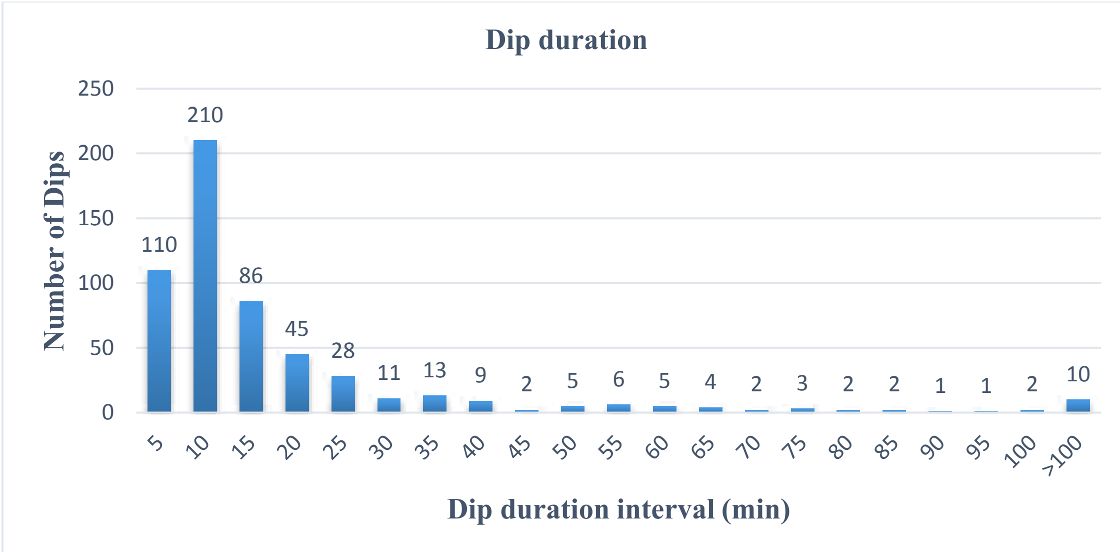


Figure 6.10. Histogram of dip duration for 557 dips in summer

The following observations are made:

- The maximum number of dips (i.e. 210 dips) have a dip duration between 5-10 minutes.
- 27 dips have a dip duration of more than 60 minutes (1 hour). The implies that out of 557 dips, 4.8% of the dips have a long dip duration. The reasons for this might be sustained cloud covering or a foggy climate.
- In the lowest range 0 - 5 minutes, the number of dips is 110. This also includes few dips that have duration 3 minutes or less than that.
- The average dip duration for all 557 dips is 16.49 minutes.

The histogram in Figure 6.11 shows the average dip duration in a day for a number of days. The average dip duration is calculated by taking the mean of duration of all dips occurring in a day (maximum output period).

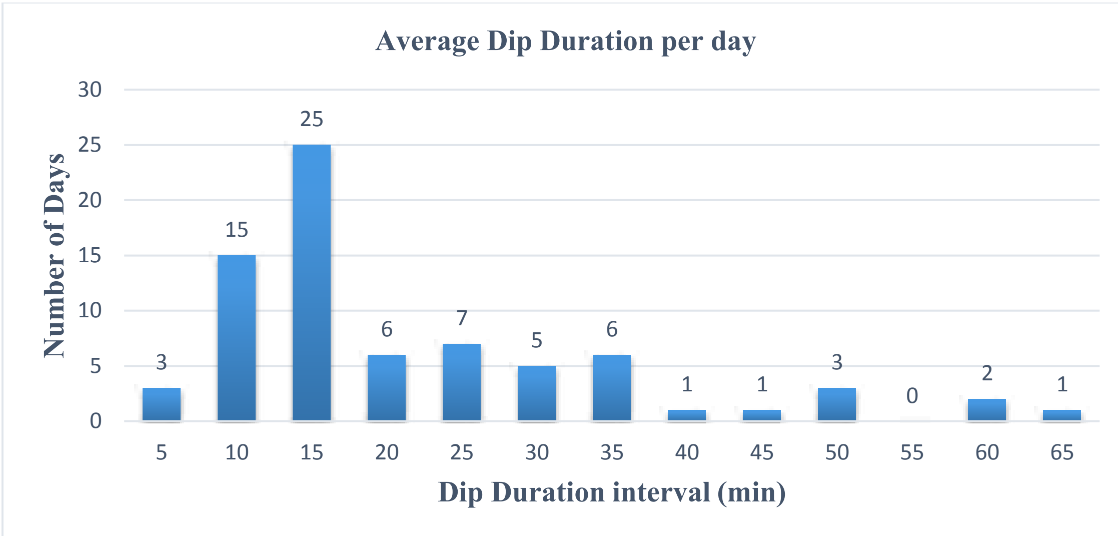


Figure 6.11. Histogram of average dip duration per day for summer

The results from Figure 6.11 imply:

- The highest number of days (25 days) have an average dip duration per day between 10-15 minutes.
- The mean of the average dip durations per day is 19.06 minutes. This implies that the average dip duration per day is 19.06 minutes.
- 8 days have an average dip duration per day of more than 35 minutes. This indicates that particularly for these days very long sustained dips occurred, which increased their average values considerably as compared to average dip durations of other days.

Figure 6.12 shows the total duration of all dips in a day for the summer period. The total dip duration is calculated by summing up the duration of all dips occurring in a day (maximum output period).

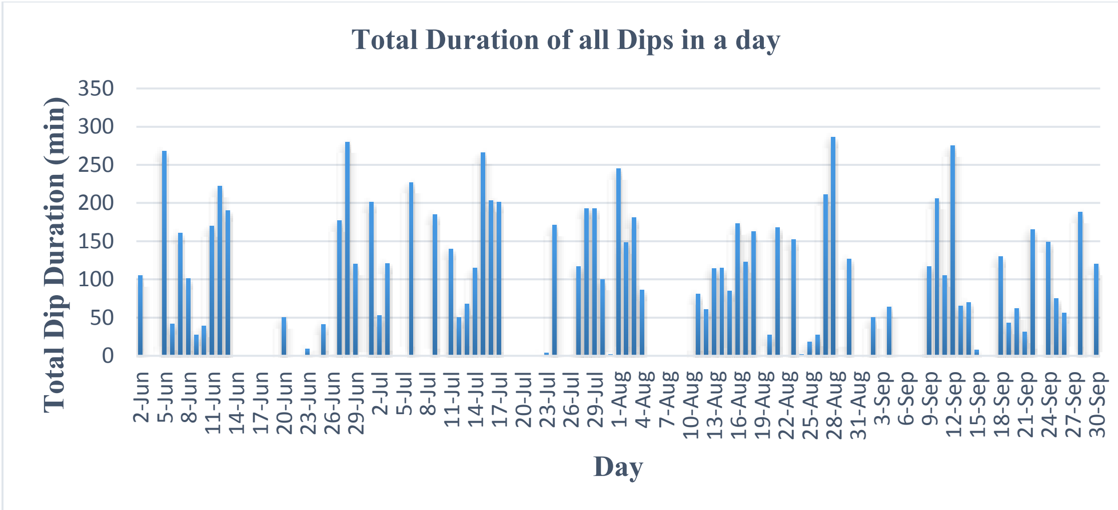


Figure 6.12. Total duration of all dips in a day during maximum output period for summer

The observations from Figure 6.12 are summarized as follows

- The highest total dip duration occurred on 28th August, 2015 with a value of 286 minutes (1 hour 46 minutes). The total energy lost during those dips is 6.26 MWh and the dip frequency for the day is 5.
- The second highest total dip duration took place on 28th June 2015 with a total dip duration of 280 minutes (1 hour 40 minutes). The total energy lost during those dips is 10.11 MWh and the dip frequency for the day is 9.
- It is observed that even though on 28th June 2015 the total dip duration is less than the total dip duration on 28th August 2015, but the energy loss is greater on 28th June 2015 during the maximum output period by 3.85 MWh (10.11-6.26 MWh). This might be because of the fact that energy loss during dip depends on both the magnitude (depth) and duration of dip, not only on dip duration. The average depth of dip per day for 28th June 2015 and 28th August 2015 are 1.23 MW and 1.02 MW respectively.

- By comparing the total energy lost per day in Figure 6.7 with the Figure 6.12, it can be seen clearly that for $28^{th}$ June 2015, the total energy lost per day due to dips is highest among all the days in the summer. This major reason behind this is the total duration of all dips in that day. Similarly for $28^{th}$ August 2015, the total energy lost per day may not be the highest but definitely very high as compared to most of the days.
- 21 days have a total dip duration per day of more than 1 hour (60 minutes) and 35 days have a total dip duration of more than 2 hours (120 minutes). This implies that out of 75 days, 74.6% of days have total dip duration per day of more than an hour.

# 7. CONCLUSION

The solar plant in this study generated a total energy of 1081.64 MWh during the winter (Nov 14, Dec 14, Jan 15), 2586.41 MWh during the spring (Feb 15, March 15, April 15, May 15) and 3124.18 MWh during the summer (June 15, July 15, August 15, September 15). In the summer, the plant generated 17% and 65% more than the spring and winter respectively. Hence as expected, the performance of the solar facility is better in summer than spring and winter.

The mean ideal energy generation in summer is 36.44 MWh during entire day. For 122 days in summer, total ideal energy generation is 4445.68 MWh, but the actual energy generated is 3124.8 MWh. Hence, the solar facility produced 70.27% of the ideal energy generation/maximum possible energy generation in summer. There is a loss of nearly 30% in energy output of the plant in summer.

The mean of actual average MW power generated during the sunrise-sunset period and the maximum output period in the summer (75 days) are 2.29 MW and 3.67 MW respectively and their corresponding mean ideal values (75 days) are 2.79 MW and 4.34 MW respectively.

The average number of dips per day in summer is 7. The average maximum depth of dip for is 2.15 MW. The mean of average depth of all 557 dips in summer is 0.93 MW. The average energy loss during a dip is 0.33 MWh. The average total energy lost per day due to dips is 2.45 MWh. The average dip duration for all 557 dips is 16.49 minutes. The voltage regulating equipment and any batteries connected to the plant should be sized to accommodate a minimum of 7 dips, a maximum dip depth of 2.15 MW, an average dip depth of 0.93 MW, and a dip duration of 16.5 minutes.

The regulating equipment should also be adjusted accommodate a maximum number of 21 dips, maximum dip depth of 4.5 MW, an average dip depth of 3 MW, and a dip duration of 2 hours in the worst case.

**BIBLIOGRAPHY**

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# VITA

Archit Patnaik was born in Dhenkanal, Orissa, India on 11th November, 1992. In May 2014, he received his Bachelor in Technology (B.Tech) degree in Electrical Engineering from Kalinga Institute of Industrial Technology (KIIT) University, Bhubaneswar, India. He received his M.S. degree in Electrical Engineering with a specialization in Power Systems from Missouri University of Science and Technology, Missouri, USA in July 2016.

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He was a student member of the Institute of Electrical and Electronics Engineers (IEEE). He was also a member of other IEEE societies including the Industrial Application Society (IAS) and the Power Energy Society (PES).