Performance evaluation of a 200 kWp grid tied solar power plant

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Abstract. Grid tied solar power plants are found to be very adaptable for academic institutions as the load profile almost matches with the generation profile. For the academic institution under consideration, optimum capacity of the solar power plant is arrived at as 250 kWp, based on studies carried out. Since the institution was already having a plant of 50 kWp, it is decided to augment it with another solar plant of 200 kW capacity. The normal power supply available from the utility was not very reliable, which leads to frequent power failures. Hence a 200 kVA capacity Diesel Generator (DG) was provided for standby power requirement. An automatic power factor control (APFC) unit is also provided to improve the power factor of the system. During commissioning, the performance of the 200 kWp solar power plant was assessed based on the measurement of various parameters at site and were compared with the standard specifications. Integrated operation of the system was carried out and few operating difficulties were faced. In this paper, performance evaluation test results of 200 kWp solar plant, experience in integrated operation, the difficulties faced and the measures adopted to rectify them are discussed.

1. Introduction

In India, solar power generation is growing at an accelerated pace. Solar power is green and clean power. Use of grid tied solar power plants are gaining acceptance and are widely used in domestic and industrial applications[1]. Grid tied solar power plants are found to be very suitable for academic institutions as the load profile is generally in coherence with the generation profile. Studies have been carried out on the basis of the load profile of the academic institution under consideration and an optimum capacity of the solar power plant for the institution is arrived at as 250 kWp. Since the institution was already having a plant of 50 kW it was decided to augment it with another plant of 200 kW capacity. As per the rules and regulation of the utility providing power supply to institution, the maximum capacity of solar plant permitted is based on the feeder capacity and the contract demand. The contract demand of the Institution was 280 kW and feeder capacity was much higher. The Institution is fed with single circuit, three phase feeder by the utility without any redundant power supply provision. Hence, the power supply was not very reliable, leading to frequent power failure. Therefore, a 200 kVA capacity Diesel Generator (DG) was installed for standby power. The operation of the solar plant along with Diesel Generator set was considered in the design. Automatic power factor control (APFC) unit, using capacitor banks have been connected in order to improve the power factor of the system and are automatically switched on/off based on variation in power factor. During
commissioning, the performance of the 200 kWp solar power plant was assessed based on measurements of various parameters at site and were compared with specifications. Integrated operation of the system was carried out and few operating difficulties were faced. The difficulties were overcome by adopting appropriate measures. This paper describes the methodology adopted for plant capacity selection, configuration details of the plant, specifications of the plant components, commissioning experience, performance evaluation, experience in integrated operation, the difficulties faced and the measures adopted to tackle them.

2. Plant capacity selection

The power demand of the institution varies with respect to time on each day and also with respect to season in each year. The power demand on a working day and a holiday will be entirely different. To determine the optimum capacity of the solar plant, the power demand on a working day in the peak summer season is taken as the reference. Figure 1 shows power demand curve of the institution. Area under the power demand curve is 3705 kWh, which gives the energy demand of the day. The power generation curve of a PV solar power plant for a day will be parabolic in nature and area under the curve would be the total energy generated. To make the Institution self-sufficient in electrical energy, the area under power demand curve should be made equal to the power generation curve assumed. To achieve that, plant capacity should be very much higher than the peak demand of 310 kW, which is not economical. A plant capacity equal to peak demand is also found to be uneconomical. Average demand of the entire day is only 154 kW. The average demand during day time (6 AM to 6 PM), when solar plant generation is taking place is 213 kW. The optimum capacity needed for solar power plant is taken as the mean of day time demand and peak demand which is 261.5 kW. A 50 kW plant was already installed and functioning in the institution. Hence it was decided to go for a 200 kWp capacity solar plant (211.5 kWp approximated to 200 kWp). Considering economic factors and as the load profile is generally matches with the generation profile, grid tied system is selected.

![Figure 1. Power demand curve of the institution](image)

3. Solar plant configuration

The location for the 200 kWp solar plant was selected at the roof top of the D block of the institution which was shadow free and the highest elevation in the campus. The distance from the plant to the substation is around 250 m. In order to ensure availability of the plant and reduce the DC cabling it was decided to go for two independent 100 kWp units. It was also decided to go for inverters of 100 kW capacity and solar panels of the same rating. Based on market survey, the state-of-art poly
crystalline solar modules of 350Wp capacity was selected. Sixteen modules are connected in series to form a string. Three strings are connected in parallel to a Maximum Power Point Tracker (MPPT) of the inverter [2]. So there are 48 modules connected to an MPPT. An inverter has 6 MPPTs and total number of modules connected to the inverter is 288. There are two inverters and the total number of modules are 576. Modules are wired in series using 4 sq.mm copper cable and it forms strings. Inverters have DC and AC wiring box. Two numbers 250 A DC isolator and 48 numbers of 15 A DC fuse is provided in the DC input side of inverter. The inverters are connected to the LT main switch board (MSB) in the substation using two UG cables in parallel. Output from both the plant is joined at the substation and connected to MSB bus through switch gears and energy meter. The capacitor banks for power factor improvement are connected to the MSB through SFU and switching contactors. The panel receives AC power from the utility at 415 V, 50 Hz. In addition, a 200 kVA capacity DG is linked to MSB through auto main failure panel. Figure 2 shows the schematic layout of the integrated power distribution system of the institution.

![Figure 2](image)

**Figure 2.** Layout of the integrated power distribution system of the institution

### 4. Specifications of plant components

The PV modules, Inverters and the interconnecting cables are the main components in the power generation and transmission chain.

#### 4.1 PV modules

Polycrystalline cell is used to form the modules. 72 cells are used in a module. PV cells have generic characteristics of diminishing efficiency with increasing temperature. Specifications of the module are given below. The nominal cell temperature and the temperature coefficient at rated power are as specified below.

- Maximum power \( P_{\text{max}} \) : 350 W
- Maximum power Voltage \( V_{\text{mp}} \) : 38.1 V
- Open circuit voltage \( V_{\text{oc}} \) : 46.39 V
- Short circuit current \( I_{\text{sc}} \) : 9.79 A
- Module efficiency : 18.00
Nominal operating temperature : 47 ± 2°C
Temperature coefficient of $V_{oc}$ : -0.35 %/°C
Temperature coefficient of $I_{sc}$ : +0.05 %/°C
Temperature coefficient of Power : - 0.45 %/°C
Module surface area : 19404 cm$^2$
Est. shunt resistance : 69.2447 ohm
Est. series resistance : 0.1971 ohm

4.2 Inverters
Two inverters of 100 kW capacity delivering power at unity power factor was used for converting DC to 3 phase AC at 415 V and 50 Hz [3,4]. The specifications of inverter is given below.

4.2.1 Input side.
Absolute maximum DC input voltage ($V_{max,abs}$) : 1000 V
Start-up DC input voltage ($V_{start}$) : 420 V (400…500 V)
Operating DC input voltage range ($V_{dcmin}$…$V_{dcmax}$) : 360…1000 V
Rated DC input voltage ($V_{dcr}$) : 620 V
Rated DC input power ($P_{dcr}$) : 102 000 W
Number of independent MPPT : 6
MPPT input DC voltage range at ($V_{MPPTmin}$…$V_{MPPTmax}$) $P_{acr}$ : 480…850V
Maximum DC input power for each MPPT ($P_{MPPT,max}$) : 17500 W
Maximum DC input current for each MPPT ($I_{dcmax}$) : 36 A
Maximum input short circuit current ($I_{scmax}$) for each MPPT : 50 A
Maximum Number of DC input pairs for each MPPT : 4

4.2.2 Output side.
AC Grid connection type three phase : 4W+PE
Rated AC power ($P_{acr}$ @cosφ=1) : 100 000 W
Maximum AC output power ($P_{acmax}$ @cosφ=1) : 100 000 W
Maximum apparent power ($S_{max}$) : 100 000 VA
Rated AC grid voltage ($V_{ac,r}$) : 400 V
AC voltage range : 320…480 V
Maximum AC output current ($I_{ac,max}$) : 145 A
Rated output frequency ($f_{r}$) : 50 Hz
Output frequency range ($f_{min}$…$f_{max}$) : 45…55 Hz
Total current harmonic distortion : < 3%
Nominal power factor and adjustable range : > 0.995

Inverter has RS 485 communication port and the plant data from the inverter is linked to PC and the campus network for remote monitoring.

4.3 Under Ground Cable
Two runs of 240 sq.mm, three and a half core, Aluminium conductor, PVC insulated, steel strip armoured and PVC sheathed cable (AYFY) is used for power transmission from plant to the substation. The length of the cable is around 250 m and one end is connected to a SFU installed in the switch board near inverter. From inverter copper cable is laid and connected to the switch board. Other end of the cable is connected to another SFU at the substation.

5. Installation and commissioning
Solar Modules are installed at an angle of 11 degree in the east-west direction. Installation of module structure had been done based on analysis carried out with geographical coordinates as input and ensured that there will not be any shade on any of the panels between 6 AM to 6 PM on any day in
the year. Galvanized structural steel is used for support structural works. Columns of the support structure are made of 120 x 50 x 2.5 mm size, lipped C channels and are welded to the base plate of 120 x 120 x 6 mm size. These base plates are anchored to the roof slab. Concrete blocks are provided surrounding the column over the base plate. Rafters used for support structure are also lipped C channels of size 100 x 40 x 2 mm size. Purlin used for fixing the module is 80 x 40 x 2 mm size lipped C channels. Entire support structure with module is analyzed for a wind speed of 150 km/h and found fit. Pathway is provided in between arrays of modules to ensure approach for water spray and cleaning of the modules. Entire Structure and solar modules are electrically earthed at different locations to two separate earth pits using GI flats of 3 mm thickness and 25 mm width. Switch gears and surge protection devices (SPD) are provided wherever needed as per standards. Lightning arrestors provided for the building were adequate for the solar panel too.

Cables from the plant are laid underground to the substation. The cables are terminated to SFU at substation using suitable legs and glands. Energy meter is provided to read the amount of energy generated. In the common output line, a moulded case circuit breaker (MCCB) is provided. Reverse Power Relay (RPR) installed in DG power line circuit is linked to the MCCB. On reverse power to DG, the MCCB will trip and isolate solar plant. MCCB output is connected to MSB where loads are connected. Parallel to MSB six capacitor banks of total capacity 125 kVAR is connected in parallel. Capacity of banks ranges from 25 kVAR to 15 kVAR. These capacitor banks are automatically switched on/off based on the value of power factor which is monitored real time. After completing the installation, inspection and after receiving clearance from the state electrical inspectorate, the plant was commissioned by switching on the inverters. The voltage and current at different points of the plant were monitored to ensure that the functioning is as per design. Energy meter reading was observed and confirmed the feeding of power to the MSB panel. The remote monitoring system was activated and plant parameters could be obtained through mobile phones.

6. Plant performance evaluation
In order to evaluate the performance of the plant various plant parameters were measured. Measurements were carried out at two conditions of irradiance of 578 W/m² and 1088 W/m². The first one corresponding to evening and mornings and the second one corresponds to peak power density during noon period. Solar 100 Irradiance Meter, Fluke 438-II Power Quality Analyzer and Fluke 62 MAX IR thermometer are used for the measurements. The accuracy of the instruments used were better than 1%.

6.1 PV module efficiency evaluation
Measurements are carried out for an array of 48 modules which are connected to one MPPT of the inverter. Details of measurement carried out are given in Table 1.

| Parameter                      | Measured Value | Measured Value |
|--------------------------------|----------------|----------------|
| Solar Irradiance(W/m²)         | 578            | 1088           |
| PV Module Area (m²)            | 1.9404         | 1.9404         |
| Total No of PV Modules         | 48             | 48             |
| Total PV Array Area (m²)       | 93.1392        | 93.1392        |
| I_DC (A)                       | 17.5           | 24.33          |
| V_DC (V)                       | 520            | 482            |
| PV Input Power(W)              | 53834.46       | 101335.45      |
| PV Output Power(W)             | 9100           | 11727.06       |
| Efficiency (%)                 | 16.90          | 11.57          |
| Module temperature             | 62.2           | 71.2           |
| Extrapolated power of the plant| 109.2          | 140.7          |
| kW(576 modules)                |                |                |
From the observations, the actual value of power per module at 1088 W/m\(^2\) irradiance is estimated as 244 W. The expected value of power per module as per specification is 277 W. Expected efficiency is 13.12 % against an actual efficiency of 11.57%. This is due to high value of temperature coefficient. The actual temperature coefficient is estimated as - 0.66%/°C against the specification of - 0.45%/°C.

6.2 Inverter Efficiency
Efficiency of the inverter 1 is computed here for two different loading levels as given in Table 2. Inverter 2 is identical to inverter 1.

| Parameter Measured Value | Measured Value |
|--------------------------|-----------------|
| Solar Irradiance(W/m\(^2\)) | 578 | 1088 |
| I\(_{DC}\) (A) | 17.5 | 24.33 |
| V\(_{DC}\) (V) | 520 | 482 |
| Input Power To PCU (W) | 54506.25 | 69629.41 |
| V\(_{RN}\) (V) | 241.02 | 245.92 |
| V\(_{YN}\) (V) | 239.02 | 243.68 |
| V\(_{BN}\) (V) | 240.26 | 243.26 |
| I\(_R\) (A) | 66.5 | 93.8 |
| I\(_Y\) (A) | 66.8 | 93.9 |
| I\(_B\) (A) | 67 | 94.3 |
| P\(_{Total}\) (W) | 47940 | 69629.41 |
| Power Factor | 0.99 | 1 |
| Efficiency (%) | 87.95 | 99 |

6.3 Overall efficiency
Overall efficiency of one string of 48 modules at two different irradiance conditions have been computed and presented in Table 3. Performances of the other strings are identical. Overall efficiency is also equal to efficiency of solar module x efficiency of inverter.

| Parameter Measured Value | Measured Value |
|--------------------------|-----------------|
| Solar Irradiance (W/m\(^2\)) | 578 | 1088 |
| Module Temp (°C) | 62.2 | 71.2 |
| PV Input Power (W) | 319642.092 | 601679.232 |
| Active Power L\(_{RN}\)(W) | 15900 | 23020 |
| Active Power L\(_{YN}\)(W) | 15880 | 22820 |
| Active Power L\(_{BN}\)(W) | 15960 | 22880 |
| Total (W) | 47740 | 68720 |
| Overall Efficiency (%) | 14.93 | 11.42 |
| Based on module and inverter efficiency (%) | 0.169 x 0.8785 | 0.1157 x 0.99 |
| | 14.84 | 11.45 |

6.4 Harmonics measurements
Solar inverter output should be harmonics free and should not cause increase in grid harmonic content when tied to local grid. Measurements are made to assess the value of harmonic injection by the inverter. Such measurements are complex in grid tied systems as a snap shot measurement at the point...
of common coupling (PCC) will not confirm whether the harmonics injection is from the inverter, from the local load or the one present in the supply grid. The harmonic content in the grid voltage without any load connected was measured first, using the power analyzer and was found that it is 2.3%. Then the harmonic content with load of the institution connected to the grid was measured and found that it was 2.7% and 8.6% in voltage and current respectively. Subsequently the capacitor banks were included in the circuit and it measured the harmonic content as 3.16% and 10.86% in voltage and current respectively. When the inverter is tied with grid, with all the system connected, the harmonic content in the voltage and current was 3.79 and 4.64 respectively. These measurements indicated that the rise in voltage harmonics injected from the inverter is negligibly small and the overall value is within the limits. Current harmonics is also found low with the inverter connected.

7. Experience on integrated operation

Integrated operation of the system was generally smooth and trouble-free apart from the few minor difficulties faced. The peak value of power generated was 140 kW. Energy upto a value of 906 kWh was generated on a sunny day, 18th of March 2020. The power generation profile of the plant on that day is given in Figure 3. Energy export is taking place on holidays when the load in the institution is low. All the operating data is stored in the inverter and it can be used for analysis and performance assessment. The plant is in operation since October 2019 and delivering power.

8. Difficulties faced and remedial measures adopted

The Inverter is designed to deliver power at unity power factor always. During integrated operation of the system the power factor monitored at the substation feeder was oscillating with change in inverter output. This oscillation was high at low loads. The response time of Automatic Power Factor Control (APFC) unit and contactor based capacitor bank switching system was much higher than the time taken for output change of inverter due to irradiance variation. This was causing a delayed APFC correction and resultant power factor oscillation. The phenomenon is explained with the phasor diagram in Figure 4. The problem was analysed in detail and concluded that the power factor should be monitored at the load level before the inverter is linked to the distribution bus [5,6]. The issue can be resolved by connecting the inverter at the transformer end of the main distribution bus in the substation and the CT of APFC positioned on the same bus between the inverter node and the load feeder node, as shown in Figure 5.
Figure 4. Phasor diagram of voltage and currents in the present scenario

V: grid voltage; I_L: load current; I_d: active component of I_L; I_q: reactive component of I_L; I_{qT} & I_{dT}: current components drawn from grid in the presence of PV generation; I_T: Line current drawn from grid in the presence of PV generation (it has a high power factor angle). \( \theta_1 \): Power factor angle without solar generation. \( \theta_2 \): Power factor angle with solar generation.

Figure 5. Required connection at substation

The operation of the plant along with DG supply during grid failure was giving problems. When the grid fails, the solar plant will trip automatically. As per the time settings, within 45 seconds the DG will start automatically and will be connected to the MSB and feed the loads. After 3 minutes of steady operation of DG, the inverter should switch on and solar plant should be connected to the MSB. During this condition, reverse power flow if any, from the solar plant to the alternator of DG set, the RPR will send signal to the MCCB, trip the solar power plant and isolate it from MSB. The generator will continue to operate and would take the complete load alone. However in most of the cases, the solar plant was not getting started on DG power. This was analysed and found that the frequency fluctuations in the DG supply is not allowing synchronisation of inverters to MSB and continue the operation of inverters with DG supply. This issue was overcome by changing the allowable frequency band of the inverter in tune with the DG power frequency and by implementing better control on DG engine speed. The operation of the system was smooth when the load is higher than the power generated by the solar plant. At low load conditions, the solar plant was getting tripped on RPR signal and it was as per design. The MCCB was not of auto reset type and because of that even after grid power resumes, the solar plant was not getting connected to the substation bus. Sharing of load between DG and solar plant was desirable at low loads. This was causing concern as operator intervention is required to resume solar plant operation and a delay in it was leading to loss of revenue. On analysis, it was found that this problem can be solved only by hardware modification in the system by introducing an additional control. The additional control needed is the monitoring of load on DG and restricting it around 20% of the rated capacity by controlling the inverter power output. The inverter manufacturer confirmed the feasibility of this scheme and implementation is being carried out.

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The overall efficiency of the plant was found lower than the specified value. This is because of the lower efficiency of solar module and also due to higher temperature coefficient of power of the module. Margin available for the input DC power is high and it is possible to add additional PV modules to system. Figure 6 shows the solar panel array at the roof top. Figure 7 shows the photo of inverter mounted on wall and the switch board positioned at substation near MSB.

9. Conclusion
PV array efficiency is good as per generally expected commercial standards, but is lower than the specified value. This is due to high temperature coefficient of power of the modules. The issue is being taken up with module manufacturer. Overall performance of the Inverter is very good and the efficiency is excellent. Though the installed plant injects little harmonics, it is negligibly small and very well within the limits. Present loading of inverters is only upto 70%, as the rated capacities of PV array and inverter are equal. The actual required inverter capacity is less than kWp rating of the PV array. The scope exists for addition of PV array of about 40 kWp without overloading the present inverters and cable. Grid tied solar power plant is well-suited for academic institutions and the suitability was demonstrated. All the problems faced during integrated operation were addressed and solutions are being implemented.

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