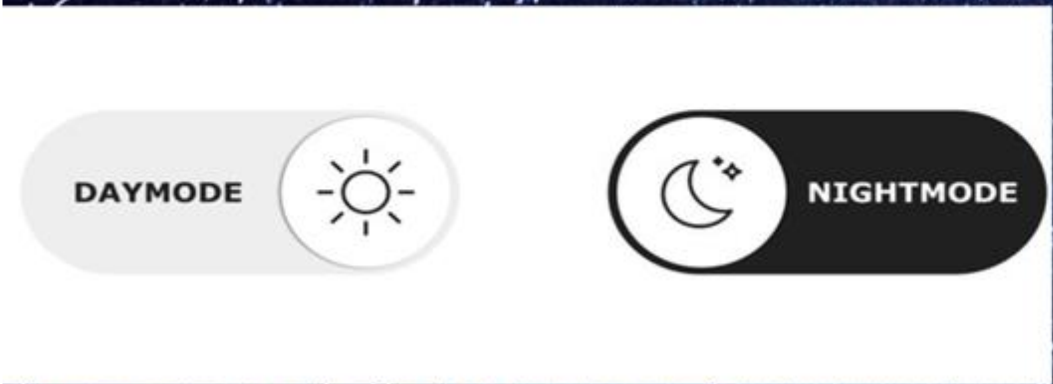
NIGHT MODE OPERATION OF PV INVERTERS

PAVAGADA ULTRA MEGA SOLAR PARK



January 2022

Southern Regional Load Despatch Centre

REPORT

on

NIGHT MODE OPERATION (TRIAL)

of

PV INVERTERS

(PAVAGADA ULTRA MEGA SOLAR PARK)

January 2022

Revision - 1

Southern Regional Load Despatch Centre
Power System Operation Corporation Limited
(A Government of India Enterprise)

Message from Executive Director

India has been integrating Renewable Energy at an exponential pace in line with our country's commitment to a cleaner and greener planet. The last 5 years have seen a phenomenal improvement in RE capacity addition. The integration of RE has come with its own sets of challenges while managing the power system. One such challenge is managing reactive power and maintaining voltages within the IEGC prescribed range.

The prime responsibility of RLDC is to maintain the power system in an efficient and economical way. Efficient use of existing resources would be a prerequisite in running the system in an effective way. In this regard, SRLDC has made a pilot study to explore the reactive power capability of solar PV inverters during night hours to control high voltages. It was indeed a privilege and proud moment for SRLDC to conduct this test at one of the largest solar parks in the world.

SRLDC sincerely acknowledges the invaluable support of SRPC, CTU and SR constituents. SRLDC is also thankful to KSPDCL and SPDs of Pavagada Ultra Mega Solar Park for their participation and cooperation in the pilot study

With Best Wishes

V. Suresh
Executive Director
SRLDC, POSOCO

Foreword

Quote:
We should not get into the mindset that RE is the intruder and conventional energy is the main player. Why not consider RE to be the main occupants of the 'house' and then work out the rest of the system around RE, essentially, because RE is the future?
Un-quote:
— Former Member (Energy), erstwhile Planning Commission of India

India has committed to integrating RE on an exceptional scale - 175GW by 2022 and 500GW by 2030. The Southern Region, being blessed by Mother Nature with a lot of potential of wind and solar resources, has been a front runner in the integration of Renewable Energy. Renewable Energy Management Centre (REMC) has been operationalized at SRLDC for integrating and managing RE. Several initiatives have been taken up during the process to overcome the challenges associated with RE.

The team has initiated a pilot study to understand the reactive power capability of PV inverters during non-solar hours at Pavagada Ultra Mega Solar Park for a period of two months starting from 01-08-2021. The results were encouraging as the maximum of 456MVAr could be absorbed in 220kV.

At this juncture, I would like to congratulate the REMC team for this unique initiative and for bringing out an exhaustive report highlighting various learnings during the pilot study. I hope this report would go a long way from the system security point of view by limiting high voltages in the associated transmission system of Solar Power Parks.

M. K. Ramesh
Sr. General Manager
(REMC & Construction)
SRLDC, POSOCO

Acknowledgement

REMC, SRLDC would like to thank SRPC Secretariat, various forums of SRPC, CTU, SR constituents, KSPDCL and RE developers at Pavagada for encouraging, participating and supporting SRLDC in this experiment on Night mode operation.

REMC, SRLDC would like to thank NLDC & POSOCO management for the valuable support and guidance during this experiment as well as continuous encouragement and motivation for the initiatives on the technological experiments/advancements.

REMC, SRLDC would like to thank everybody concerned and all departments of SRLDC for their valuable support and guidance in preparing this report.

The support is highly appreciated and acknowledged.

REMC Team, SRLDC

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Acronyms

AC	Alternating Current
APC	Average Power Consumption
BJT	Bipolar Junction Transistor
CB	Circuit Breaker
CEA	Central Electricity Authority
DC	Direct Current
DCDB	Direct Current Distribution Box
EHV	Extra High Voltage
FSC	Fixed Series Compensation
GIS	Gas Insulated Substations
GW	Giga Watts
HMI	Human-Machine Interface
HV	High Voltage
ICR	Inverter Control Room
ICT	Inter Connecting Transformer
IDT	Inverter Duty Transformer
IEGC	Indian Electricity Grid Code
IGBT	Insulated Gate Bipolar Transistor
ISTS	Inter State Transmission System
JNNSM	Jawaharlal Nehru National Solar Mission
KREDL	Karnataka Renewable Energy Development Limited
KSPDCL	Karnataka Solar Power Development Corporation Limited
LV	Low Voltage
MCT	MOS Controlled Thyristor
MOSFET	Metal Oxide Silicon Field Effect Transistor
MPPT	Maximum Power Point Tracking
MU	Million Units
MVAr	Mega volt amps (reactive)
MVArh	Mega volt amps (reactive) hour
MW	Mega Watts
NLDC	National Load Despatch Centre
NTPC	National Thermal Power Corporation
OCCM	Operation Coordination Committee Meeting
OEM	Original Equipment Manufacturer
PF	Power Factor
PGCIL	Power Grid Corporation of India Limited
PLC	Programmable Logic Controller
PLCC	Power Line Carrier Communication
PoC	Point of Common Coupling
PPC	Power Plant Controller
PS	Power Station

PSS	Power System Stabiliser
PV	Photo Voltaic
PWM	Pulse Width Modulation
RE	Renewable Energy
RLDC	Regional Load Despatch Centre
SACU	String Array Communication Unit
SCADA	Supervisory Control and Data Acquisition
SECI	Solar Energy Corporation of India
SEM	Special Energy Meter
SPD	Solar Power Developer
SR	Southern Region
SRLDC	Southern Regional Load Despatch Centre
SRPC	Southern Regional Power Committee
SS	Sub-Station
STATCOM	Static Synchronous Compensator
SVG	Static VAR Generator
VGF	Viability Gap Funding
WTG	Wind Turbine Generator

Executive Summary

असतो मा सद्गमय । तमसो मा ज्योतिर्गमय ।
मृत्योर्मा अमृतं गमय । ॐ शान्तिः शान्तिः शान्तिः ॥

Renewable Energy (RE) generation at the ISTS system is being integrated at fast pace in the Indian grid. As of 31.10.2021 ~4.8 GW RE is connected at ISTS level and being scheduled by SRLDC. Many high voltage transmission lines are built for evacuation of these RE stations and these lines are lightly loaded during the lean/NIL RE generation period. The issue gets aggravated during monsoon period when demand is low and nearby sub-stations would also experience high voltages beyond the IEGC band. Many transmission lines are being taken out of service to address high voltage at night hours. The transmission line/bus reactors (35 No. with a capacity of around 4570MVAr) have been approved in various Standing Committees of the Southern Region (SR). These include 125MVAr reactors each at Madhuguri & Hiriyur. These bus reactors are yet to be commissioned as on the start date of trial operation.

Initially, SRLDC had conducted reactive power capability tests of inverters at Pavagada Ultra Mega Solar Park during non-solar hours for two days in February 2021. The results were shared with the constituents of SR in 176th OCC Meeting of SRPC. Subsequently, SRLDC circulated a detailed note along with NLDC communication on the results of the experiment and requested for trial operation for a period of two months. The trial operation was initiated with the concurrence of SRPC forum for utilization of inverters at Pavagada Ultra Mega Solar Park in night mode for controlling high voltages from 01.08.2021 to 30.09.2021.

This report is an attempt to capture the experience on night mode operation of solar inverters for providing reactive power support. The report covers various aspects viz. introduction about Pavagada Ultra Mega Solar Park, technical capabilities of inverters, experience gained during two days study and two months trial operation on reactive power capabilities of inverters during night mode operation, analysis of active power consumption and reactive power absorption , commercial aspects and way forward.

The important observations of the trial operation are –

A. Reactive Power Capability

i. Inverters are having reactive capability of 33%, 66% and 88%, or in some case up to 100% of active power depending upon the manufacturer and model.

ii. 986MVAr dynamic reactive capability is available in the PV inverters at Pavagada Ultra Mega Solar Park.

iii. Night Mode facility is available in 1575MW out of 2050MW installed capacity.

iv. Maximum reactive absorption of 456MVAr has been observed at 220kV end of POWERGRID 400/220kV Pavagada Substation during the trial period from 01.08.2021 to 30.09.2021.

B. Enabling Night mode/SVG mode feature and Reactive Power set point Control

i. For 775MW having reactive power capability of 441.5MVAr, the night mode/Static VAR Generator (SVG) feature can be enabled during generation hours only and cannot be enabled during non-generation hours. Whereas Night mode/SVG Feature can be enabled at any time of the day for 800MW of installed Capacity of inverters having the reactive capability of 544.5MVAr.

ii. In some of the inverters, reactive power could be controlled remotely by SCADA, only during generation hours. However, during night mode / SVG mode, inverters could not be controlled remotely by SCADA and could be controlled at Inverter HMI only. The issue was resolved subsequently.

C. Factors affecting reactive absorption during the trial period

i. Planned / forced shutdown of 33 or 66kV Substation / feeder.

ii. Low voltage has been reported at the LV side of the Inverter Duty Transformer (IDT) due to high MVAr absorption.

iii. False alarm/tripping indication hardware failure and unbalanced current faults have been observed due to low voltage at LV side of IDT. Additionally there were issues like increase in speed of inverter cooling fan / fan failures that were reported and have been taken up with respective OEM for root cause analysis.

iv. Communication issues were reported by developers having string inverters. The issue was expected to overcome after implementation of PPC.

v. Delay in getting the OEM consent for the test.

D. Auxiliary Consumption

i. Normally, the inverters enter into sleep mode after generation hours; however they would be functioning if the night mode is enabled. There is a marginal increase in active power consumption after enabling night mode. Further as reactive power absorption Q increases, active power consumption also would increase. It is pertinent to mention that the marginal increase could not be measured because of measurement limitation at inverter level.

ii. It is understood that normally OEM indicates the normal auxiliary consumption without the night mode feature enabled. There is no mention of auxiliary consumption with the night mode feature in technical manuals

iii. A total of 4.16MUs of energy has been consumed for this exercise which was included in regional loss during the two months trial period.

E. Reactive Energy

i. Maximum reactive absorption of 456MVAr has been observed at 220kV end of POWERGRID 400/220kV Pavagada Substation during the trial period from 01.08.2021 to 30.09.2021, which is almost equivalent to 4 x 125MVAr reactors.
ii. Total of 1,64,970MVArh of reactive energy was absorbed by Pavagada Solar Park at Point of Common Coupling (PoC) viz. 220kV end of POWERGRID 400/220kV Pavagada Substation.
iii. There was active power consumption of ~4.5 to 5MW from the grid by the Solar Power Developers (SPD) for their auxiliary consumption when not operating in night mode.
iv. Maximum active power of 14.5MW was consumed from the grid at 220kV level during the trial operation when maximum 456MVAr was absorbed at 220kV level PoC. Additional power consumption of ~9.8MW was drawn from the grid, excluding power consumption during normal operation, during the night mode for providing 456MVAr.
v. The active power consumption per 100MVAr of reactive power absorption is in the range of ~2 to 2.5MW which is ~2% to 2.5%.

F. Commercial analysis

i. **Impact of active energy loss**: A total of 4.16 MUs of energy is spent for this exercise as regional transmission loss for reactive power absorption of 164970 MVArh. The cost based on frequency rate as per DSM regulations 2014 works out to ~ ₹ 173.99 Lakhs for the two months viz ~ ₹ 2.85Lakhs per day for ~450+ MVAr absorption.
ii. **Impact on Annual Maintenance Cost:** The following was understood from the developers / OEM orally.
    a. Normally only a technician is available at night along with security staff for each 50MW. However, 1or 2 additional executives were posted for each 50 MW block during the night mode.
    b. Inverters are operating for 12 hours in generation and then enter to sleep mode during non-generation hours. However, inverters would be running continuously for 24 hours when inverters are put in night mode. Hence the periodicity of maintenance may increase and additional spares may be required resulting in increase in maintenance expenditure.
    c. No specific impact could be traced, except for few cooling fan failures for which root cause is yet to be established to this night mode exercise and there is no history available for long term impact analysis. The annual expected expenditure in terms of maintenance and manpower could not be obtained from the developers considering it as confidential information.
    d. POSOCO report on Reactive Power Management and Voltage Control Ancillary Services (VCAS)[4] mentions typical additional maintenance cost of ₹ 0.02 / kVArh for operating solar inverters in SVC mode during

“no generation” period. This is in addition to absorbing real power consumed for reactive power support as region loss.

e. Further POSOCO has suggested 5 paise/kVArh in the feedback on CERC (Draft) Ancillary Services Regulations, 2021 while emphasising the introduction of Voltage Control Ancillary Services (VCAS) in India [5]. POSOCO suggestions regarding the reactive power capabilities w.r.t RE is summarised in section **7.5.** This is in addition to absorbing real power consumed for reactive power support as region loss

ii. **Cost analysis with other reactive sources:** The cost of equivalent reactive sources both dynamic reactive sources viz STATCOM and fixed reactive source bus reactor is deliberated in section **7.5.**

G. High Voltages of PSS could effectively be controlled with the reactive capability using the night mode of inverters. This helps in reducing line openings. It was observed that all lines at 400kV Pavagada were in closed condition during this experimental period except on a few occasions which were due to issues at other connected stations.

H. Apprehension was expressed about the life of inverters/components by developers but there was no historical record. However, this experiment has indicated enough confidence.

Way forward

A. With huge amount of RE plants in the pipeline, dynamic reactive capability available at all RE plants needs to be harnessed.
B. The SVG / Night mode facility of PV inverters can be utilized by specifying a suitable mechanism for the following.
    a. Compensation for incremental real power consumed during the night mode / SVG operation of plant for reactive support.
    b. Compensation to cover increased annual maintenance in the form of additional manpower, spares, increased frequency of maintenance etc.
C. SVG / Night mode feature may be made mandatory by including the requirement of facility in the CEA Technical Standards for Connectivity.
D. Developers may define the performance guarantee clause & the warranty period for SVG / Night mode operation. The developers may mention the requirement in their bidding as well mandate OEMs to necessarily demonstrate the capability as part of commissioning test.
E. All the alarm and trip settings may need to be rechecked for correct indication.
F. The provision of 'night mode' operation whereby the inverters can act as STATCOM have been successfully demonstrated in field trials carried out by SRLDC at Pavagada solar park. The provision of voltage control ancillary services by renewables through var control may enable enhanced grid support. POSOCO has submitted a report on Reactive Power Management and Voltage Control

Ancillary Services (VCAS) in India to Hon’ble CERC. Further POSOCO has submitted it suggestions on CERC (Draft) Ancillary Services Regulations, 2021 emphasising the introduction of Voltage Control Ancillary Services (VCAS) in India. Hence Voltage Control Ancillary Services (VCAS) framework, whereby the night mode operation of inverters is incentivised, needs to be enabled at the earliest.

Chapter 1: Introduction

1.1 Background

The need for green power has led to an increase in renewable energy generation in the energy portfolio of the power systems of India and across the world. The government of India has scaled up the target of renewable power capacity to 175GW, which includes 100GW from Solar, 60GW from wind, 10GW from bio-power, and 5GW from small hydro power, to be achieved by 2022. Further Hon'ble Prime Minister of India has set a renewable installed capacity target of 500GW by 2030. Wind and Solar energy would be the major contributors.

With a high RE addition target set by India, ultra-mega solar and wind power parks are getting commissioned as the need of the hour. RE generation at ISTS system is being integrated at fast pace. As on 31.10.2021 ~4.8GW RE is being scheduled at ISTS level by SRLDC. Many high voltage transmission lines are built for evacuation of these RE stations and these lines are lightly loaded during lean/NIL RE generation period. The issue gets aggravated during monsoon period when demand is low and nearby sub-stations would also experience high voltages beyond IEGC band. Many transmission lines are being taken out of service to address high voltage at night hours. The transmission line / bus reactors (35 No. with capacity of around 4570MVAr) have been approved in various Standing Committees of Southern Region. These include 125MVAr reactors each at Madhuguri & Hiriyur. These bus reactors are yet to be commissioned as on date of trial operation.

SRLDC had conducted study for two days on reactive power capability of inverters at Pavagada Ultra Mega Solar Park during non-solar hours in February 2021. The results were shared with the constituents of SR in 176th OCC Meeting of SRPC. Subsequently, SRLDC circulated a detailed note along with NLDC communication on results of the study on typical days and had requested for trial operation for a period of two months. The trial operation was initiated with the concurrence of SRPC forum for utilization of inverters at Pavagada Ultra Mega Solar Park in night mode for controlling high voltages from 01.08.2021 to 30.09.2021. The report captures the experience and findings from the trial operation.

1.2 Pavagada Ultra Mega Solar Park

The Pavagada Ultra Mega solar park is located in the state of Karnataka with a total installed capacity of 2050MW.

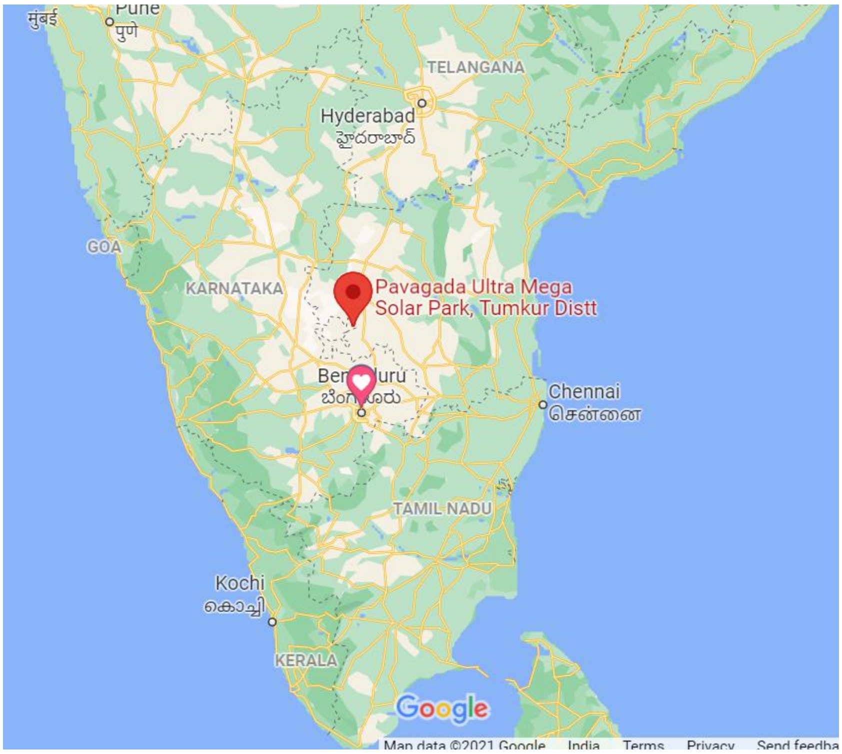


Figure 1 Geographical location of Pavagada Ultra Mega Solar Park

The solar park is developed in 8 segments of 250 MW each. One pooling substation of 220/66kV or 220/33kV is connected to each 250MW segments for onward transmission of solar power. 250MW segments is further subdivided into 5 blocks each having capacity of 50MW. Each 50MW block is connected to the solar park first at either 220/66kV or 220/33kV pooling substation through 66kV/33kV double circuit underground cables wherein the voltage is stepped up to 220kV which is further stepped up to 400kV at the 400/220kV PGCIL station at solar park. Additionally, KREDL 50 MW is connected to 4 Sub Pooling stations.

The entire Pavagada Solar Park has been divided into 40 blocks each of 50MW. KREDL 50 MW is connected to 4 Sub Pooling stations. The plot allocation in Pavagada Solar Park is as under:

Scheme	Capacity in MW
NTPC under JNNSM	600
SECI under VGF	200
KREDL	1200
KREDL (Own)	50
Total	**2050**

Table 1 Capacity Distribution among various schemes

1.3 Layout of Pavagada Ultra Mega Solar Park

The Pavagada ultra mega solar park is situated in Tumkur district with a cumulative capacity of 2050MW spread across 11,000 acres in 5 villages viz., Tirumani, Rayacherlu, Vallur, Balasamudra and Kyataganacherlu of Nagalamadike Hobli, Pavagada Taluk, Tumkur district [3].

Area Statement of Each Block			
Block No.	Area in Acres (Approximate)	Block No.	Area in Acres (Approximate)
1	257	22	250
2	257	23	257
3	252	24	263
4	251	25	252
5	254	26	250
6	258	27	252
7	254	28	263
8	280	29	255
9	256	30	280
10	253	31	262
11	254	32	250
12	244	33	256
13	253	34	253
14	260	35	252
15	257	36	258
16	Does not exists	37	268
17	254	38	276
18	263	39	275
19	260	40	269
20	319	40A	272
21	250		
Sub-total	5190		5216
Total area	10406		

Substation	Block No's
220/33Kv	
1	B1, B2, B3, B4, B5
2	B6, B7, B8, B9, B10
3	B11, B12, B13, B14, B19
4	B15, B17, B18, B20, B21
220/66Kv	
5	B22, B23, B24, B25, B26
6	B27, B28, B29, B30, B31
7	B32, B33, B34, B35, B36
8	B37, B38, B39, B40, B40A

Figure 2 Layout of Pavagada Ultra Mega Solar Park

1.4 Pavagada Solar Connectivity

The overview of the connectivity of the solar park showing the different blocks is depicted in below figure

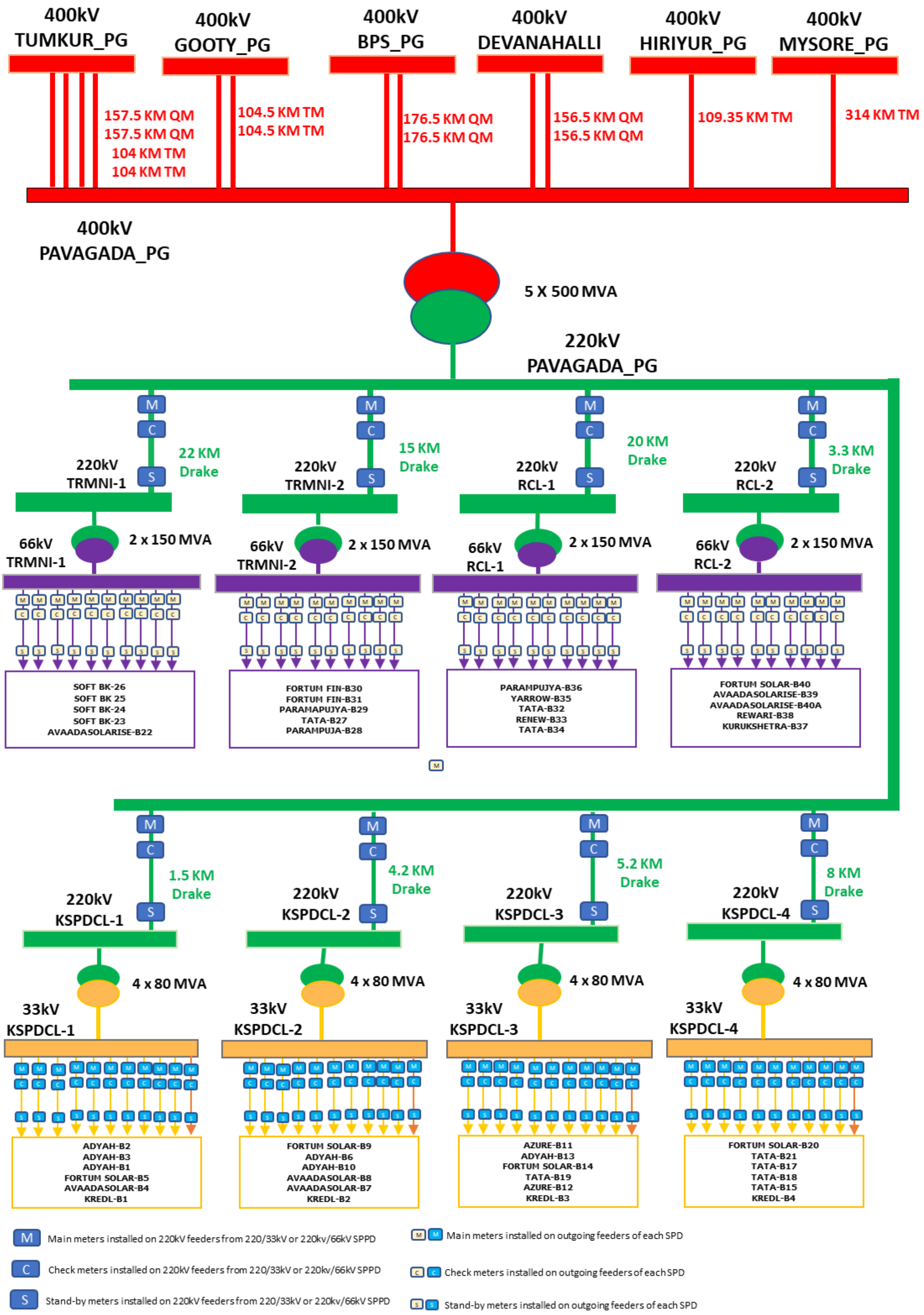


Figure 3 Overview of the Connectivity of the solar park showing the different blocks

The connectivity of 400kV POWERGRID Pavagada substation is shown below.

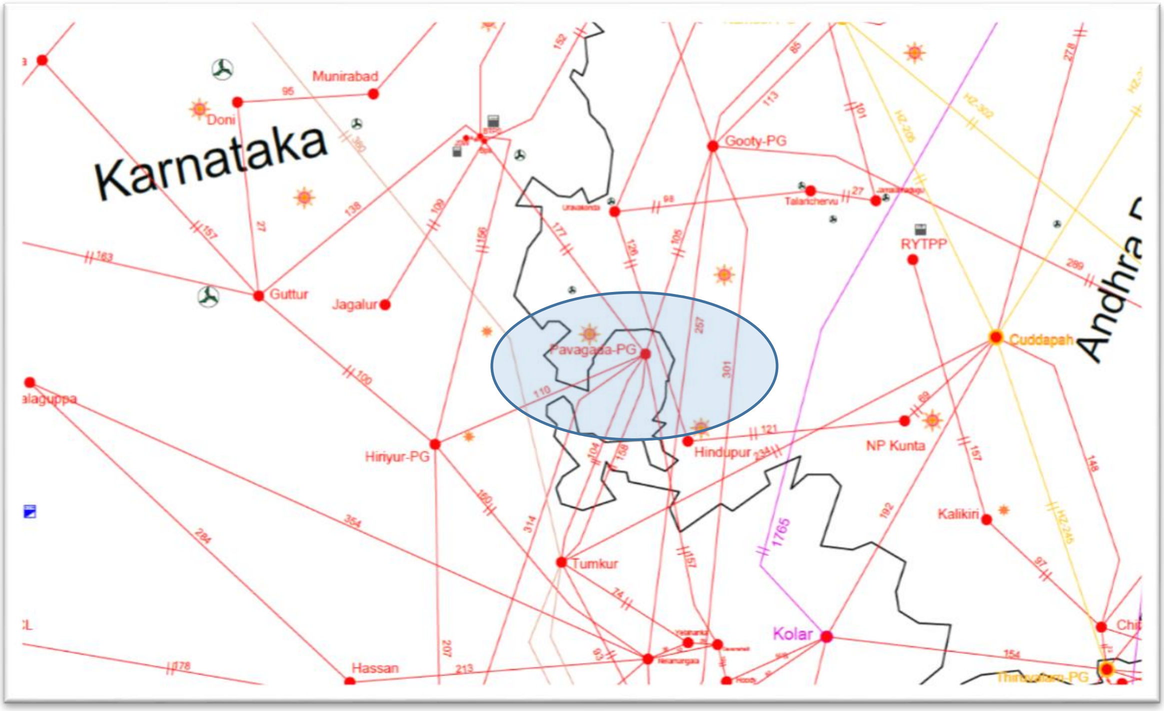


Figure 4 Transmission connectivity of Pavagada

The Pavagada Solar Park is evacuated through twelve 400kV lines as below.

Sl. No	Pooling Substation	Conductor Type	Kms
1	400kv Pavagada-Tumkur-1 with FSC 40%	Quad Moose	157.5
2	400kv Pavagada-Tumkur-2 with FSC 40%	Quad Moose	157.5
3	400kv Pavagada-Tumkur-3	Twin Moose	104
4	400kv Pavagada-Tumkur-4	Twin Moose	104
5	400kv Gooty Pavagada-1	Twin Moose	104.5
6	400kv Gooty Pavagada-2	Twin Moose	104.5
7	400kv Bellary PS-Pavagada-1	Quad Moose	176.5
8	400kv Bellary PS-Pavagada-2	Quad Moose	176.5
9	400kv Pavagada-Hiriyur	Twin Moose	109.35
10	400kv Pavagada-Mysore	Twin Moose	314
11	400kv Pavagada-Devanahalli-1	Quad Moose	156.5
12	400kv Pavagada-Devanahalli-2	Quad Moose	156.5

Table 2 400kV evacuation lines of Pavagada

The Pavagada Solar Park is evacuated through eight 220kV lines as below.

Line No	220 PSS	Conductor Type	Kms
1	KSPDCL-1	Drake	1.5
2	KSPDCL-2	Drake	4.2
3	KSPDCL-3	Drake	5.2
4	KSPDCL-4	Drake	8
5	Tirumani-1	Drake	22
6	Tirumani-2	Drake	15
7	Rayalcheru(RCL)- 1	Drake	20
8	Rayalcheru(RCL)- 2	Drake	3.3

Table 3 220kV evacuation lines of Pavagada

The details of each 33kV feeder / 66kV feeder emanating from each 50 MW block is summarised below. There would be three cables of equal length wherever 1C (single core) is mentioned in the below table.

Substation	SPD's Name	Block No.	Feeder No.	Size of Cable	Cable Distance (mtrs)
SS-01	Renew Power	1	1	33kV 1Cx500Sqmm	1410
			2		1190
	Renew Power	2	3	33kV 1Cx500Sqmm	600
			4		370
	Renew Power	3	5	33kV 1Cx500Sqmm	1160
			6		765
	Avaada	4	9	33kV 3Cx300Sqmm (Double run)	1500
			10		
	Fortum	5	7	33kV 1Cx630Sqmm	1500
			8		
SS-02	Renew Power	6	3	33kV 1Cx500Sqmm	506
			4		181
	Avaada	7	9	33kV 3Cx300Sqmm (Double run)	1200
			10		
	Avaada	8	7	33kV 3Cx300Sqmm (Double run)	1200
			8		
	Fortum	9	1	33kV 1Cx630Sqmm	1900
			2		
	Renew Power	10	5	33kV 1Cx500Sqmm	678
			6		451

Substation	SPD's Name	Block No.	Feeder No.	Size of Cable	Cable Distance (mtrs)
SS-03	Azure Power	11	1	33kV 3Cx300 Sqmm (Double run)	2300
			2		
	Azure Power	12	9	33kV 1Cx400 Sqmm (Double run)	170
			10		
	Renew Power	13	3	33kV 1Cx500Sqmm	353
			4		492
	Fortum	14	5	33kV 1Cx630Sqmm	500
			6		
	TATA Power	19	7	33kV 1Cx300Sqmm (Double run)	3500
			8		
SS-04	TATA Power	15	9	33kV 1Cx300Sqmm (Double run)	2900
			10		
	TATA Power	17	7	33kV 1Cx300Sqmm (Double run)	1500
			8		
	TATA Power	18	5	33kV 1Cx300Sqmm (Double run)	1500
			6		
	Fortum	20	1	33kV 1Cx630Sqmm	2200
			2		
	TATA Power	21	3	33kV 1Cx300Sqmm (Double run)	3500
			4		
SS-01	KREDL	Plot-8	11	33kV 3Cx300 Sqmm	2290
SS-02		Plot-6		33kV 3Cx300 Sqmm	2500
SS-03		Plot-1,2&3		33kV 3Cx300 Sqmm	4500
SS-04		Plot-7		33kV 3Cx300 Sqmm	2800
SS-05	Avaada	22	9	66KV 1Cx400 Sqmm	1950
			10		
	Softbank Energy	23	7	66KV 1Cx400 Sqmm	1092
			8		
	Softbank Energy	24	5	66KV 1Cx400 Sqmm	378
			6		
	Softbank Energy	25	3	66KV 1Cx400 Sqmm	1230
			4		
	Softbank Energy	26	1	66KV 1Cx400 Sqmm	238
			2		
SS-06	TATA Power	27	7	66KV 1Cx400 Sqmm	400
			8		
	Adhani	28	9	66kV 1Cx630 Sqmm	1570
			10		
	Adhani	29	5	66kV 1Cx630 Sqmm	90

Substation	SPD's Name	Block No.	Feeder No.	Size of Cable	Cable Distance (mtrs)
			6		
	Fortum	30	3	66KV 1Cx400 Sqmm	300
			4		
	Fortum	31	1	66KV 1Cx400 Sqmm	1200
			2		
SS-07	TATA Power	32	5	66KV 1Cx400 Sqmm	500
			6		
	Renew Power	33	7	66kV 1Cx630 Sqmm	700
			8		
	TATA Power	34	9	66KV 1Cx400 Sqmm	200
			10		
	Yarrow	35	3	66KV 1Cx400 Sqmm	400
			4		
	Adhani	36	1	66kV 1Cx630 Sqmm	1650
			2		
SS-08	ACME	37	9	66kV 1Cx400 Sqmm	1800
			10		
	ACME	38	7	66kV 1Cx400 Sqmm	1200
			8		
	Avaada	39	3	66kV 1Cx400 Sqmm	120
			4		
	Fortum	40	5	66kV 1Cx400 Sqmm	1900
			6		
	Avaada	40A	1	66kV 1Cx400 Sqmm	120
			2		

Table 4 66 & 33kV Evacuation lines of Pavagada

1.5 Voltage Profile

A typical day voltage profile of Pavagada Ultra Mega Solar Park is shown in Figure 4. It may be seen that high voltages are being experienced during night hours (no solar generation) at 400kV Pavagada Substation and nearby substations, despite utilising the available static reactive power support such as bus reactor and line reactors. Further, EHV lines are being opened to control high voltages, which compromises reliability / security, high duty cycles on CBs, reluctance by transmission licensees for regular switching off of lines etc. at GIS stations.

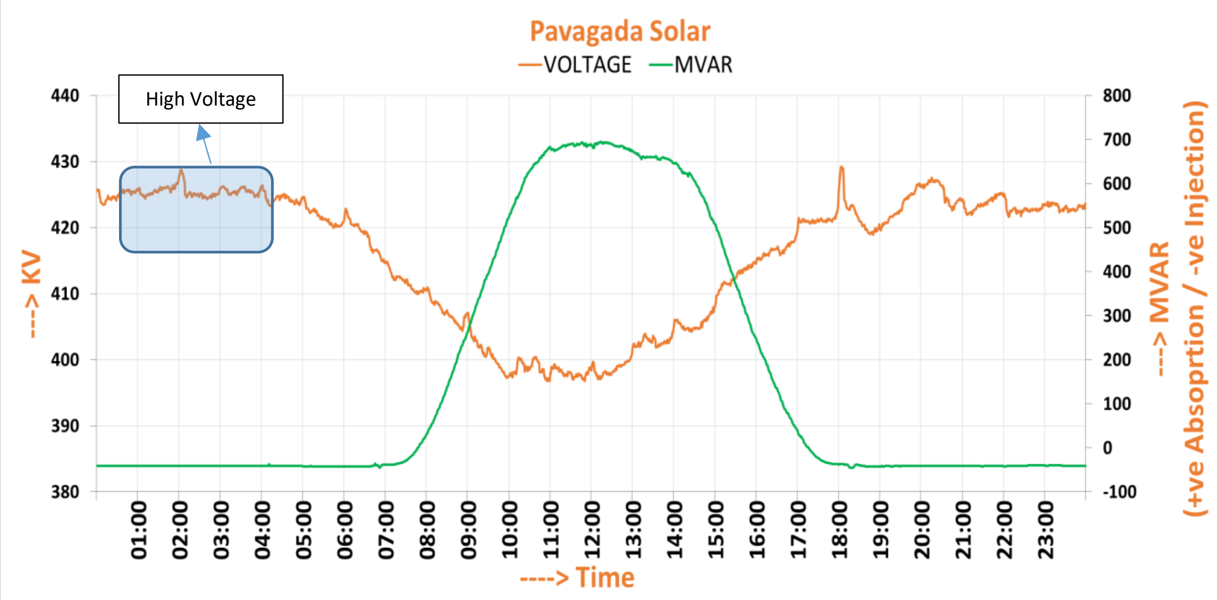


Figure 5 Typical Day Voltage Profile of 400kV Pavagada Substation

The situation gets worsened during monsoon and low load hours. The voltage duration curve of 400kV Pavagada Sub-station during monsoon period is shown in Figure 5.

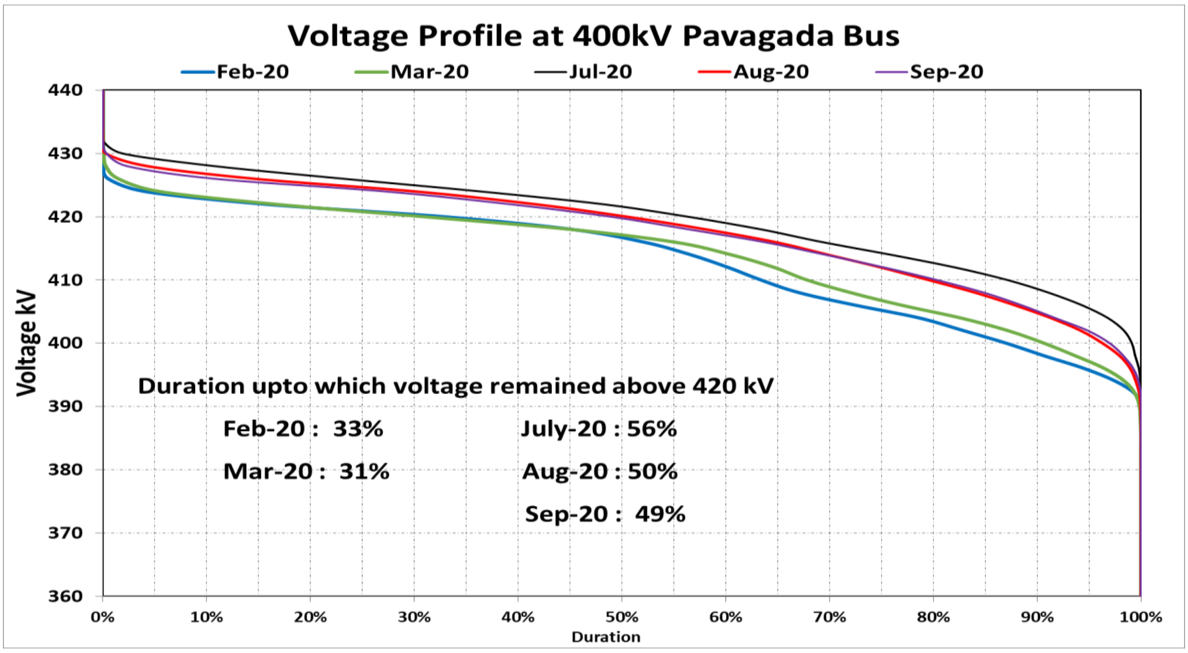


Figure 6 Voltage duration curves of 400kV Pavagada SS (Summer & Monsoon 2020)

The maximum Southern Regional load for the month of July 2020 and July 2021 was 43,176MW and 50,121MW. SR load has gone up by ~16% as compared to 2020. Hence there may be reduction in voltages due to ~7 GW increase in SR demand. The same can be seen in the figure below. However, the voltages were still on the higher side and number of lines were still kept out as can be seen in the subsequent sections.

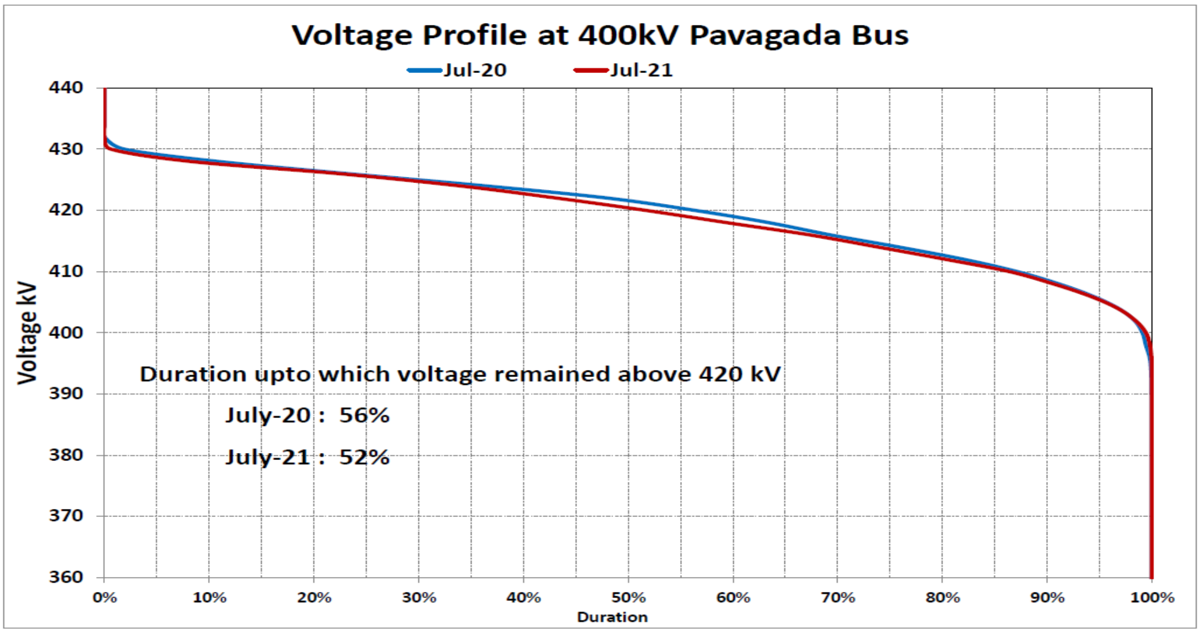


Figure 7 Voltage duration curve of 400kV Pavagada Sub-station (July 2020 & 2021)

The voltage duration curve for 400kV Pavagada sub-station for the entire year 2020-21 is shown below.

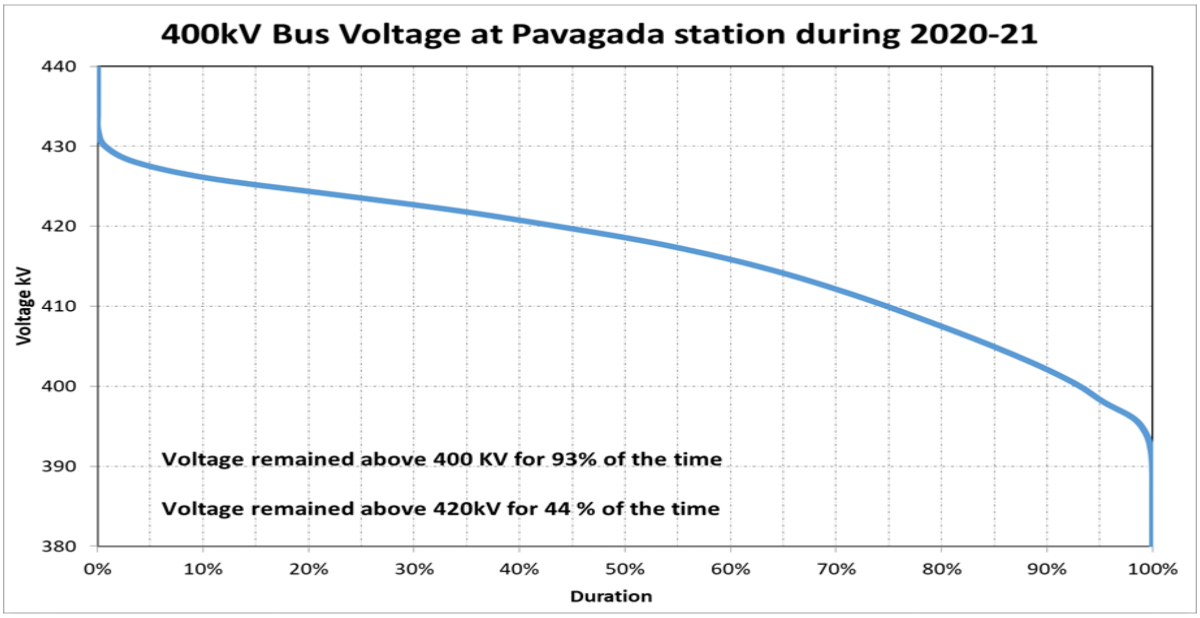


Figure 8 Voltage duration curve of 400kV Pavagada Sub-station (Annual 2020-21)

Currently, voltages are going to 390kV and low voltages are not significant at Pavagada. It is observed that during 5 to 10% of the time, voltage goes below 400kV particularly during peak RE generation. The reactive power absorption of solar plant increases with increase in active power generation that leads to low voltages during peak solar generation. Persistent low voltages could increase losses and can pose constraint in delivery of active power also.

The high voltages are predominant at night hours as compared to day time. The same can be observed in the box plot below plotted for financial year 2020-21

Figure 9 Box plot of 400kV Pavagada Sub-station (Annual 2020-21)

The system generally goes through period of high voltage due to low demand and lightly loaded lines. The reasons for persistent high voltage are listed below

- Evacuation lines for RE are built considering the potential generation, that leads to surplus capacity especially when the RE projects are in nascent stage. High voltages are arising due to lightly loaded lines during lean generation period from renewable generators and this issue gets further aggravated during monsoon period when loads are also low and nearby stations are also experiencing high voltages.
- Solar generation is available only during daytime and wind generation is available only during certain months of the year.
- The underlying network (220kV & below) is connected with wind / solar generators without any loads.
- Solar Panels / WTGs output are connected to pooling stations through underground cables.
- Delays in commissioning of reactors.

1.6 Line opening / tripping due to high voltage at Pavagada.

It can be observed that 3 to 4 lines are opened / tripped on daily basis at Pavagada to maintain the voltages below 430kV.

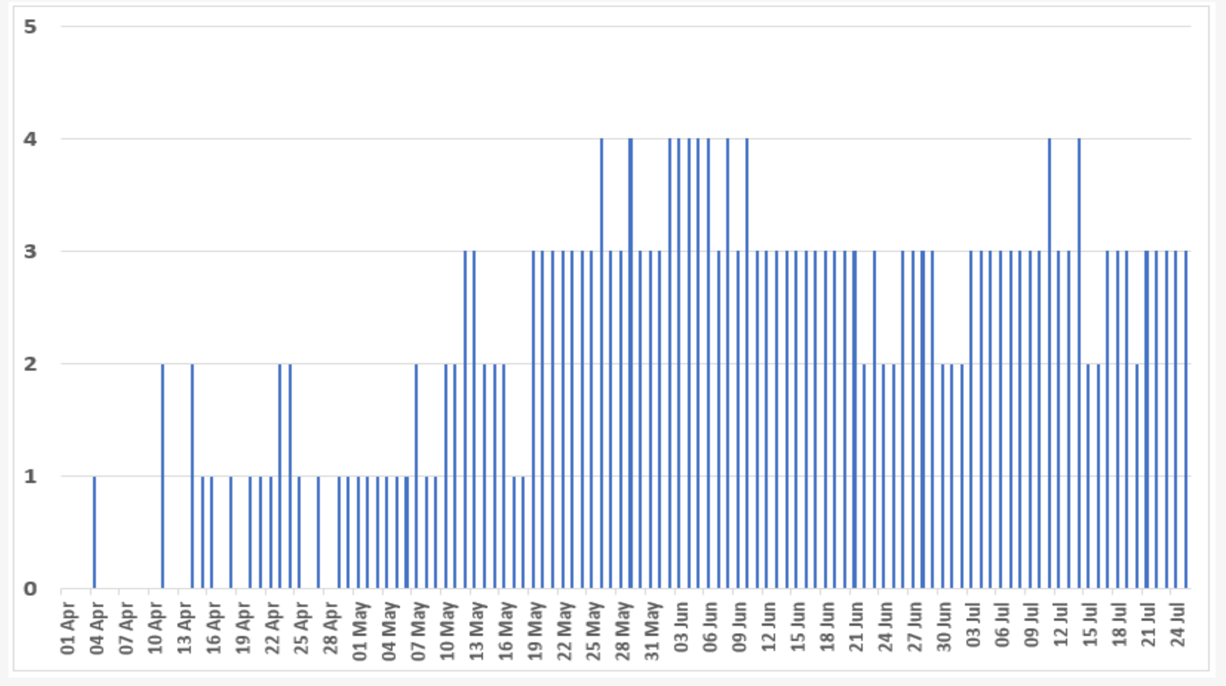


Figure 10 Line tripping for the period 1st April 2021 to 24th July 2021

1.7 Upcoming Reactors

Reactors (35 No. with capacity of around 4570MVAr) approved in various Standing Committees of SR which includes 125 MVAr reactors each at Madhuguri (Tumkur) & Hiriyur which were yet to be commissioned as on start date of trial operation. The upcoming reactors near Pavagada are shown geographically in the figure below. The 125 MVAr reactors at Madhugiri got commissioned on 30.08.2021.

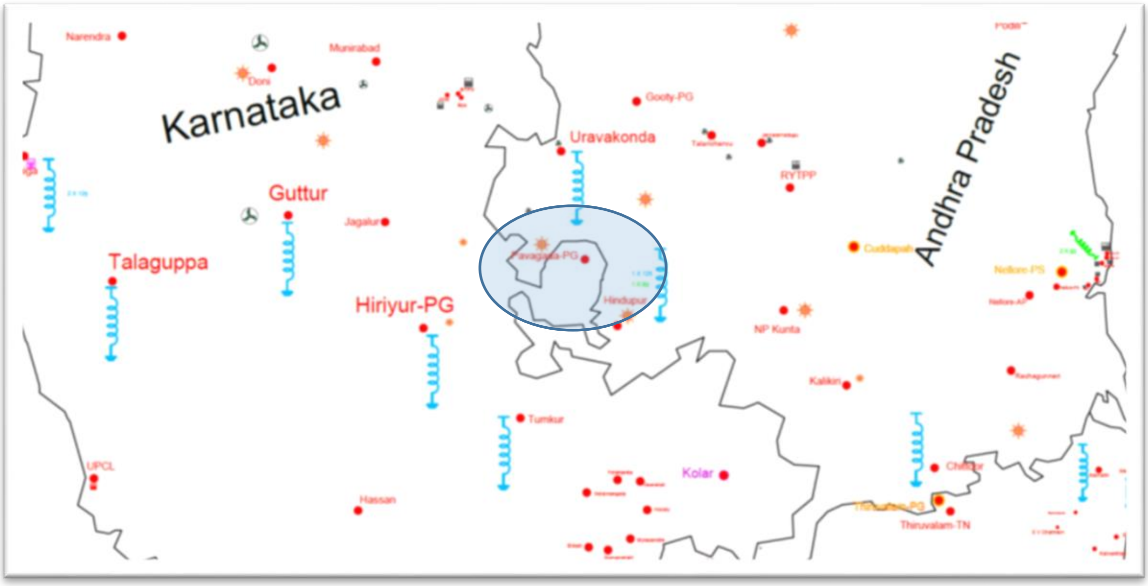


Figure 11 Upcoming reactors near Pavagada

Chapter 2: PV Plant and Inverters-Type, Modes of Operation and Control

2.1 Overview of photo voltaic plant

The single line diagram of a typical 50MW PV Plant is shown below.

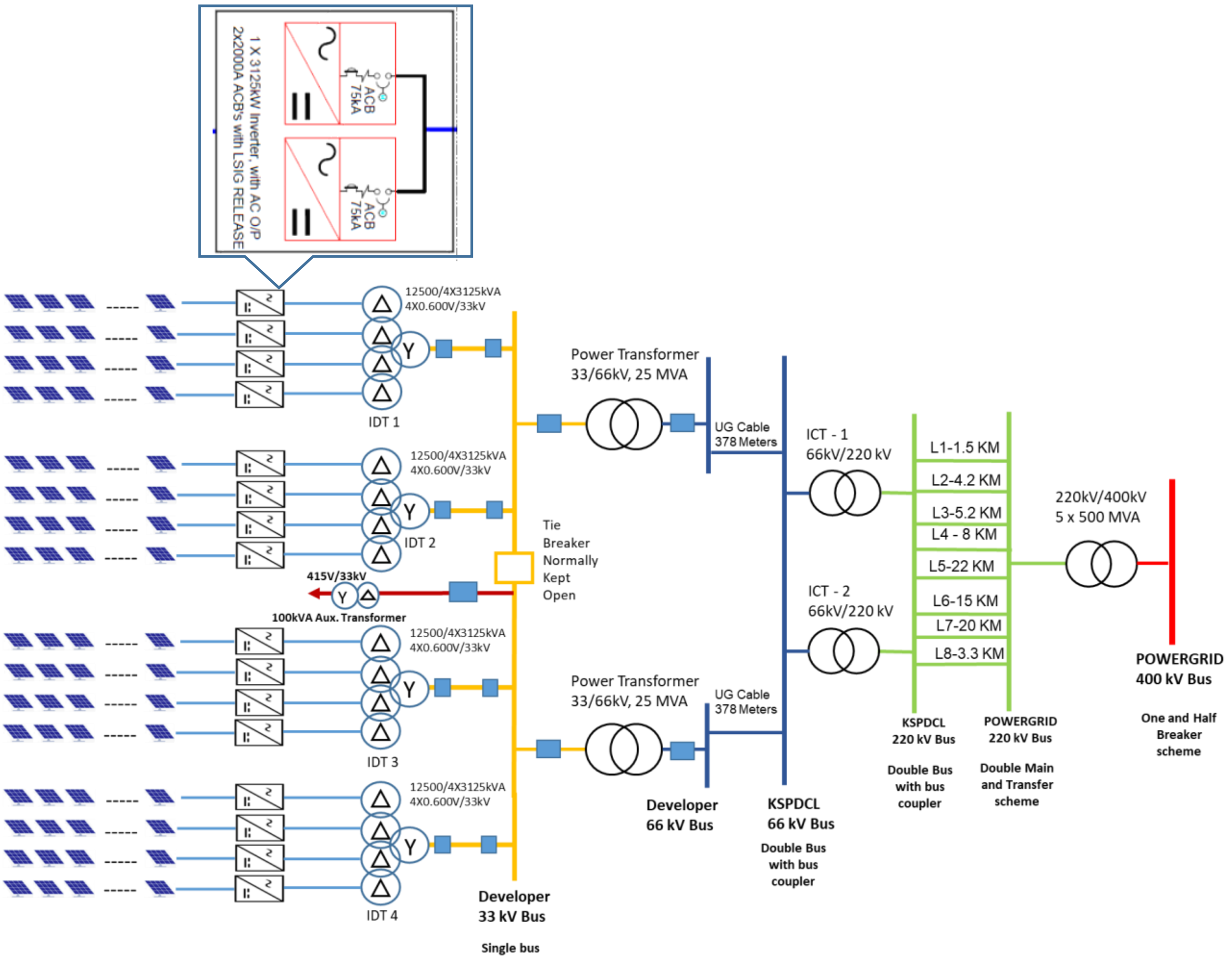


Figure 12 Single line diagram of a typical 50MW PV Plant

* All breakers (including ACB within inverter) except tie breaker at 33kV developer bus is normally in closed condition including non-generation hours. The DC breaker on the input side of the inverter would be in switched off condition during night mode and non-generation hours.

The important components of a PV plant are detailed below.

a. Photovoltaic cells: They work on the principle of the photovoltaic effect. When certain materials are exposed to light, they absorb photons and release free electrons. This phenomenon is called as the photoelectric effect. Photovoltaic effect is a method of producing direct current electricity based on the principle of the photoelectric effect. Based on the principle of photovoltaic effect, solar cells or photovoltaic cells are made. They convert sunlight into direct current (DC) electricity. Photovoltaic cells are connected electrically in series and / or parallel circuits to produce higher voltages, currents and power levels.

b. Photovoltaic module: A single photovoltaic cell does not produce enough amount of electricity. Therefore, a number of photovoltaic cells are mounted on a supporting frame and are electrically connected to each other to form a photovoltaic module.
c. Photovoltaic panel: Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit.
d. Photovoltaic String: In a larger PV array, individual PV modules are connected in both series and parallel. A series-connected set of solar cells or modules is called a 'string'.
e. Photovoltaic Array: A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels. Multiple solar modules and panels are connected in series to form a PV array to build the voltage up to proper levels for the inverter.

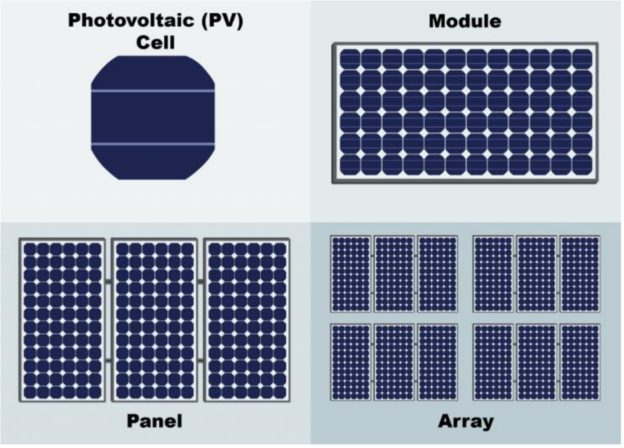


Figure 13 PV Cell, Module, Panel and Array

f. PV combiner box: The role of the combiner box is to combine the output of multiple array / strings of PV modules for connection to the inverter. Multiple strings of solar modules are combined together in parallel to multiply the string output currents to higher levels for input into the inverter.


Figure 14 PV combiner box

g. DC input distribution: DCDB box is a component of an electricity supply system which divides an electrical power feed into subsidiary circuits, which providing a protective fuse or circuit breaker for each circuit. DCDB controls the DC power from solar panel and with having necessary surge protection device (SPD) and fuses.
h. DC isolation switch: DC Break switch connects the PV array to the inverter, DC isolator switches are used to manually disconnect the solar panels for maintenance, installation or repair purposes. The same can be motorized also.
i. Inverters: Electric power from photovoltaic panels must be converted to alternating current by a power inverter if it is intended for delivery to a power grid. The inverter sits between the solar array and the grid, and may be a large stand-alone unit or may be a collection of small inverters attached to individual solar panels as an AC module
j. AC output switch: AC output switch connects the inverter unit with grid.
k. Inverter duty Transformer: The output of multiple inverters is connected to a transformer known as inverter duty transformer. It converts 600+ AC voltage output to 33kV or 66kV voltage.
l. Pooling Sub-station: The output from 33kV/66kV is connected to pooling transformer at pooling substation to next higher-level voltage. Normally it is 220/33kV or 220/66kV transformer.
m. Grid Sub-station: The pooling sub-stations are connected to the grid sub-station by 220kV lines for evacuation.

The electricity, generated by Photo Voltaic array, combines through the PV combiner box. The PV array produces DC voltage. The DC voltage is converted to AC voltage using inverters (3.125MVA inverters in the sample case). The AC voltage is typically around 600V.

Four inverters of 3.125MVA each are connected to 5 winding Delta-Star inverter duty transformer (12.5MVA) on the delta LV side. The voltage is stepped up to 33kV. Similarly the power from another set of 12.5 MVAr transformer is combined and a feeder of 25MW is achieved.

The voltage is stepped up from 33kV to 66kV using a 33/66kV, 25MVA power transformer. A single feeder of 25MW at 66kV line goes to the 220/66kV pooling substation. Similarly another feeder of 25MW stepped up to 66kV goes to 220/66kV pooling substation. Hence it can be seen that there are 2 feeders for each 50MW block.

5 Such 50 MW blocks is pooled at 220/66kV substation to form a 250MW pooling point. The pooled power is evacuated through 220kV lines to grid substation.

The auxiliary consumption is drawn from the 100KVA 415V/33kV auxiliary transformer. The general lighting load forms the majority of the auxiliary consumption during night hours. The other loads are consumption in AC, SCADA, watch tower lights etc. In addition, the losses in the inverter also gets added during generation hours.

The auxiliary consumption varies based on the variation in the network in terms of Inverter Make, line lengths, cable lengths, Transformer parameters etc. The average consumption of ISTS connected solar is found to be varying from 42 kW to 157 kW and the average of all ISTS connected solar plants stands at 113kW for 2020-21. The energy consumption per day for each plant is varying between 0.5 MWH to 1.87 MWH and the average energy consumption of all plants stands at 1.34 MWH.

In addition to the normal loads, there is an increase in auxiliary consumption which is elaborated in subsequent sections.

2.2 Typical inverter along with equipment

Basic sketch of a typical inverter in a solar plant showing the equipment on DC side and AC side is as seen below.

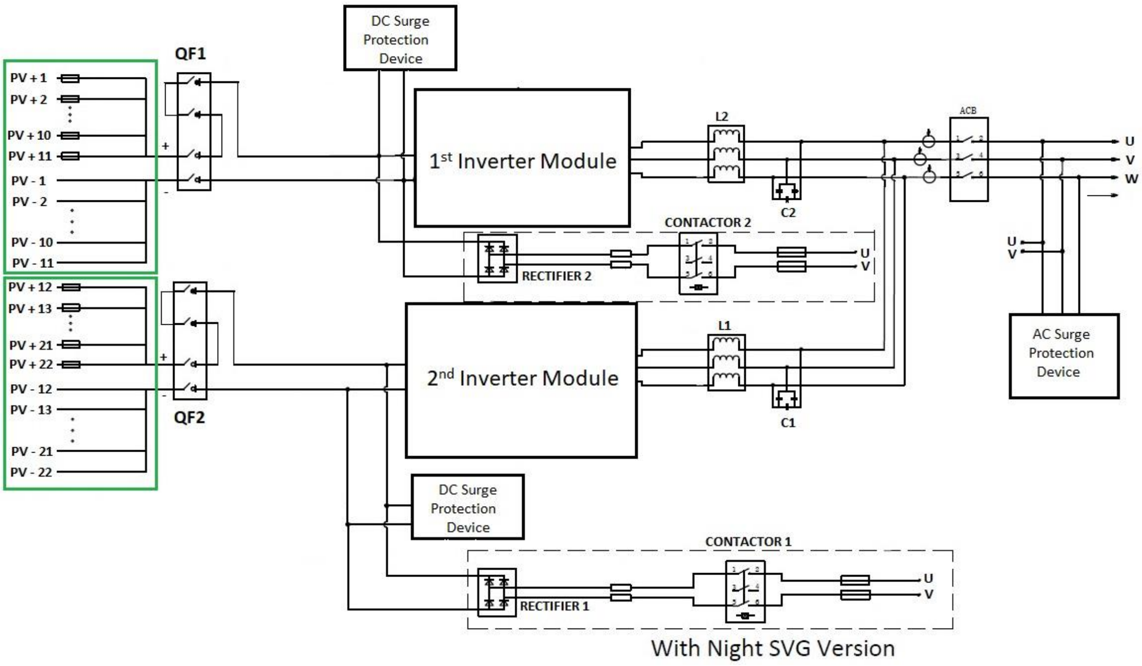


Figure 15 Basic sketch of the typical inverter in a solar plant

The electricity, generated by Photo Voltaic array, combines through the PV combiner box and then goes through Surge Protection Device and DC filter. The SPD absorbs the surge voltage of DC side, and DC filter restrains high-frequency signal conduction interference, and keep the DC voltage stable by storage capacitor.

Three-phase full bridge inverter unit will convert DC power into AC power with the same frequency and phase of grid, and filter generates sine wave AC power, and AC filter restrains high-frequency signal conduction interference, then the electricity will be delivered to grid by suitable transformer.

Currently, most PV inverters operate as grid- following (GFL) sources that regulate their power output by measuring the angle of the grid voltage using a phase-locked loop. Hence, they merely follow the grid angle/frequency and do not actively control their frequency output. It is observed that inverters installed in large solar plants are using IGBT based switching on the pulse width modulation technique.

It can be observed that the Insulated Gate Bipolar Transistor (IGBT) based inverter is connected as below

1. DC Side
   a. Solar panels / array through the DC motorised break switch QF1 & QF2 and necessary fuses.
   b. DC Surge Protection device.
   c. Night Mode Conversion circuit (wherever available) through contactor, fuses, resister and rectifier.

2. AC Side
   a. AC grid through smoothing reactor in series along with circuit breaker.
   b. Harmonic filtering capacitors in parallel to inverter output.
   c. AC Surge Protection device in parallel to AC grid side.
   d. Night mode conversion / rectifier circuit (wherever available) through contactor, fuses and resisters directly connected to grid.

Generation Hours

The DC breakers viz. QF1, QF2 and AC Breakers viz. ACB are in closed condition. The night mode contactor would be in open condition. The DC power generated by the solar panels would be converted to AC power.

Non-Generation Hours

The inverter converts DC to AC using IGBTs on pulse width modulation technique. DC voltage is required on input side DC bus of inverter for IGBT to trigger. PV voltage and DC Side voltage of inverter goes to zero during the night time hence IGBT would be switched off by default.

The following sequence is followed for night mode in general.

a) PV array is disconnected from inverter by using DC breakers QF1 and QF2.
b) AC side breaker ACB is switched off.
c) Night mode contactor gets closed. The night mode conversion circuit converts AC to 1100V DC or 600V DC based on Inverter DC rating viz. 1500V or 1000V respectively. This would make the DC supply availability at the input side of the inverter. The rectifier / converter can be made of diode, MOSFET or IGBT based on vendor. The night mode extra circuit of rectifier along with its components would increase the AC consumption marginally although reactive power is zero.
d) Inverter would produce its own voltage based on sampling after ACB. Once both voltages are matching, AC side circuit breaker ACB would be closed.
e) Reactive power varies based on the firing angle of IGBT. In some cases ACB would be in closed condition after step 'a' above. The implementation varies from vendor to vendor

Further details of night mode transition to generation hours and generation hours to night mode are explained in subsequent section.

2.3 Inverter mode of operation

It is observed that different inverter vendors use different nomenclature for the different mode of operation. Accordingly, one typical inverter is detailed below for understanding purpose. The inverter operation follows the state machine described below.

- Standby – inverter is not enabled.
- Initialize – inverter initializes the internal systems and performs self-tests.
- Disconnected – inverter waits for permission to connect to the grid.
- Connecting – inverter performs DC voltage and grid stability tests.
- MPPT – is the normal operational state during power generation.
- Standby or Night Q production – When the DC power level from panels is low, the inverter is in this state depending on the night mode settings (Night Q production).
- Disconnecting – disconnects the grid.
- Initialize – If inverter is not enabled or if fault occurs, inverter enters this state and waits to be reset.

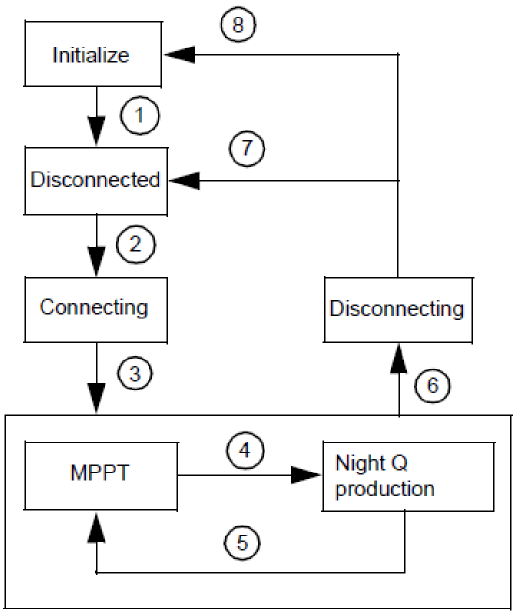


Figure 16 Inverter operational states

Transition number	Triggering condition
1	Inverter is enabled and initialized successfully, and not faulted.
2	Grid is stable and AC breakers are closed.
3	All power modules are ready for operation.
4	Reactive power compensation is enabled and PV power is below the pre-defined limit.
5	Reactive power compensation is disabled.
6	Inverter is faulted or shutdown is requested or grid is not stable or PV power is below the predefined limit.
7	Inverter is enabled and not faulted.
8	Inverter is disabled or faulted.

Table 5 Inverter transition status

2.4 Night Mode

During normal inverter operation, the inverter enters sleep mode when the sun sets since there is no active power available from the solar panels. This ends both active and reactive power production. However, reactive power production during the night may be of use to the solar plant / grid by eliminating the need for extra reactive power compensation at sites where it would otherwise be required.

Evening: Generation mode to night mode transition

1. The night reactive power (Night Q) production function is deactivated by default. It can be activated or forced on using a certain parameter in the inverter either through HMI or SCADA or PPC.

2. The operation of night Q production is as follows:
   - When the inverter enters sleep mode, the reactive power reference is checked. If the absolute value of the reactive power reference is larger than the value *Night Q low power*, the inverter disconnects from the DC side, but not from the AC side, and continues to generate reactive power.
   - If the mode is forced on, it stays connected to the AC grid even if the absolute value of the reactive power reference is smaller than the value *Night Q low power*.

- The shutdown procedure with and without the effect of reactive power is shown in the figure below. The figure shows the inverter shutdown operation and night Q transition operation when the active power is below the minimum power limit for the delay time that is *going to sleep time limit.*

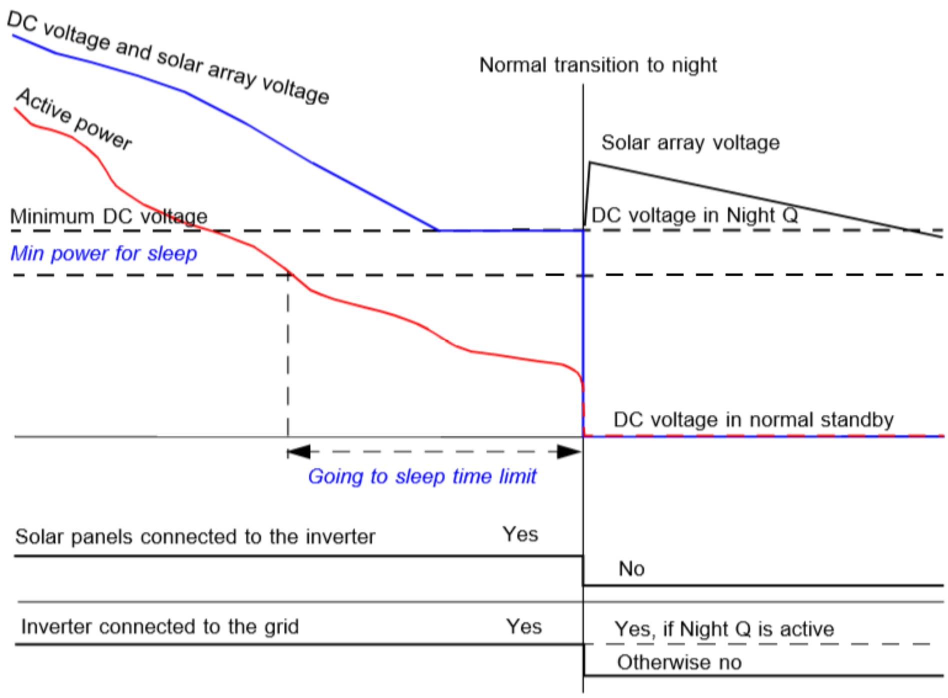


Figure 17 Power generation mode to Night Q mode transition curve

- If the absolute value of the reactive power reference decreases *Night Q low power* for duration of *Night Q delay*, the inverter disconnects from the AC side and proceeds to normal sleep mode.
- A separate reactive power reference can be set for Night Q production with parameter Night Q reference. If this reference differs from 0 kVAR, it is used. If the reference is 0 kVAR, the normal reactive power reference is used.
- If during the night, the absolute value of the reactive power reference increases above Night Q low power, the inverter connects to the AC grid and starts producing reactive power.

Morning: Night mode to generation mode transition

- In the morning, the inverter transfers smoothly from Night Q mode to power generation mode, when the panels produce enough power for the panel DC voltage to rise above the required limit, as seen in the figure below.

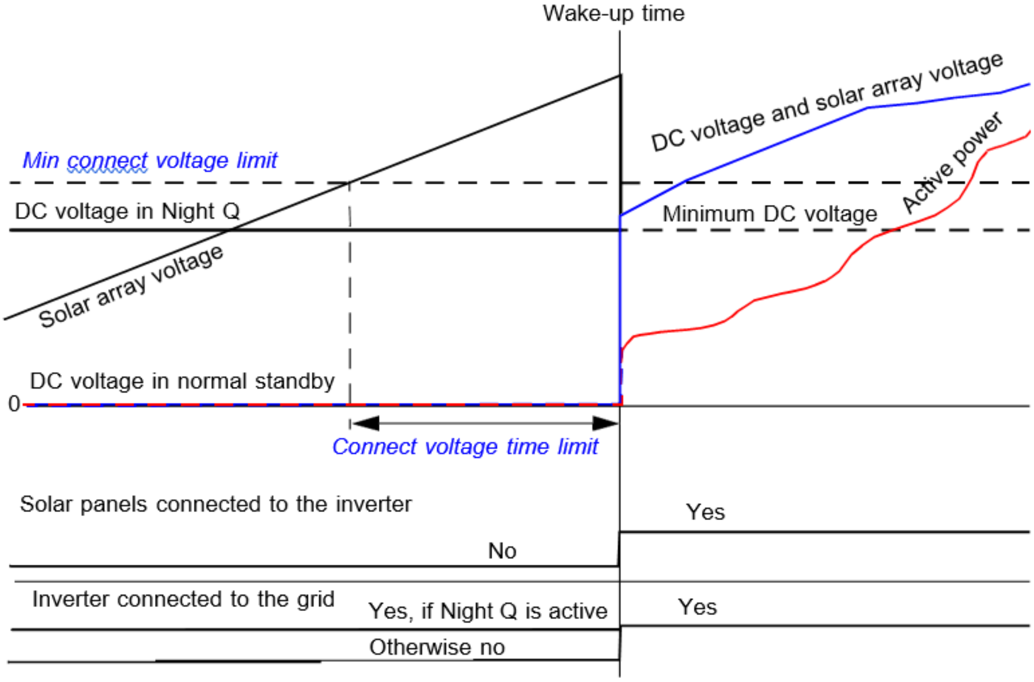


Figure 18 Night Q mode to power generation mode transition curve

2.5 Modes of Control

PV inverters generally have three modes of operation (Fast control through Power plant controller (PPC)):

i. **Voltage control mode** in which voltage of the reference point is monitored by inverters / PPC and reactive power drawl / injection is varied accordingly w.r.t. a voltage set point.

ii. **Reactive power or Q-control mode** in which inverter supplies / absorbs a fixed amount of reactive power from the grid.

iii. **Power factor control mode** is one in which inverter operates at a defined power factor.

Another important feature available in most of the inverters is the capability to absorb / generate reactive power using a feature known as Night mode or Static VAR generator (SVG) mode.

The status of voltage control mode as on 31.10.2021 at Pavagada Ultra Mega Solar Park is shown below.

Type	Capacity
	MW
Voltage Control	800
PF Control	1250
Reactive Power	0
Total	**2050**

Table 6 Type of Control

The status of night mode facility at Pavagada solar park is shown below.

Type	Capacity	
	MW	MVAr
Night mode available	1575	986
Night mode not available	475	0
Total	**2050**	**986**

Table 7 Status of Night Mode availability

2.6 Types of inverters

There are two types of inverters - Central type and String type of inverters. The snapshot of the central and string inverter is shown below.

Figure 19 Central Inverter

Figure 20 String Inverter

The detailed comparison is shown below based on various sources.

Description	Plant with Central Inverter	Plant with String Inverter
Land	No change in the land requirements with respect to inverter technology.	
IEC / EN certification :	Requirements are exactly same, except IEC - 62446 - 1 : 2016 and IEC - 61727 : 2004 certificates are required only for string inverters)	
Maximum technically viable block size	12.5MW	20MW
String connections :	Multiple module technologies cannot be mixed on SCB or SMB level	Multiple module technologies can be mixed on Inverter level (connections on different MPPT's)
MPPT range	Generally of order 945V-1300V	Generally of order 850V-1300V)
Output voltage	Lower as compared to string inverter (generally 630V)	Higher as compared to central inverter (generally 800V)
Noise level	Generally <60db	Generally <80db
Data logger	Not required	Required. Approximately 60 to 80 inverters can communicate to one data logger
Mobile application for monitoring :	Not available	Available
HMI	Available as a standard feature	Not available
Emergency switch	Available as a standard feature	Not available
		DC/AC Loading :
DC/AC Loading	Generally maximum loading allowed by any manufacture is up to 65%.	Generally maximum loading allowed by any manufacture is up to 80%.
IV curve monitoring :	Not possible	Possible
Anti-PID	Not applicable as inverter is negative grounded	Separate kit need to be procured as this will provide the virtual grounding
Monitoring	Zone level monitoring	String level monitoring
	Need additional cost investment if we want to opt for string monitoring within combiner box	Better from plant performance & monitoring point of view
Plant availability	Lower as compared to string as single failure can reduce	Higher as compared to central (generally >99.5%)

Description	Plant with Central Inverter	Plant with String Inverter
	the output 1MW to 3.125 MW (generally up to 99.5%)	
O&M : Inverter replacement	Difficult and time consuming (generally takes 8 to 10 hrs for complete replacement)	Easy (generally takes 1 to 2 hrs for complete replacement)
O&M: Maintenance	Overall time required is less as compared to string inverter (generally 3 hrs/inverter)	Overall time required is more since quantity is huge as compared to central inverter (15 mints/inverter)
AC losses	Approximately 0.25% average	Approximately 1.25% average
DC losses	Approximately 1.2% average	Approximately 0.35% average
DC String cable requirement	2.3 KM / MWp	2.6 KM / MWp
DC main cable requirement :	2.7 KM / MWp	0 KM / MWp
AC LT cable requirement	0.200 KM / MWp	1.5 KM / MWp

Table 8 Central vs. String type inverter comparison

Population of central vs. string at Pavagada Ultra Mega Solar Park is shown below.

Type	Quantity		Capacity	
	No.	%	MW	%
String	6544	90.4	420	20.5
Central	694	9.6	1630	79.5
Total	**7238**	**100.0**	**2050**	**100.0**

Table 9 Central vs. String inverter population

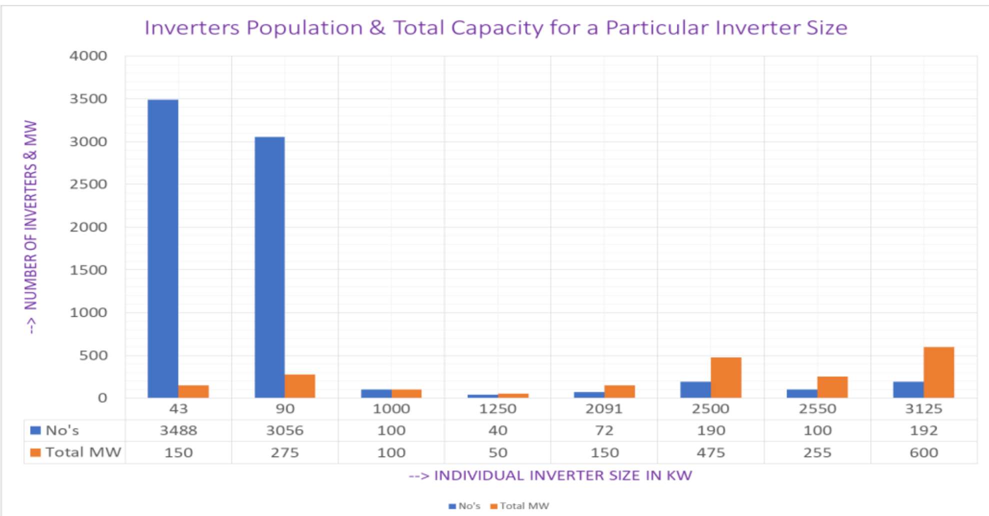


Figure 21 Inverter Population by size and number

2.7 Method of control

Solar power plant can be controlled through SCADA or Power Plant Controller. The active power and reactive power needs to be controlled during generation hours. Similarly reactive power needs to be controlled during night hours. The night / SVG mode needs to be enabled first for providing reactive support during non-generation hours. Subsequently desired Q can be set.

Type	Generation mode		Night mode
	P	Q	Enabling & Q change
HMI only	1700	1125	650
SCADA		575	575
PPC	350	350	350
Total	2050	2050	1575

*All types of controls can be done at HMI also

Table 10 Method of control at Pavagada Solar Park

2.8 Reactive Capability of Inverters

Most of the inverters are designed with capability to absorb / inject reactive power during generation period as well as during non-generation hours also. A typical invertor has a reactive power capacity of 33% capacity of active power capacity, which is available for absorption during night. Further, recently commissioned inverters have a reactive capacity of around 95% of active power capacity. Typical invertor reactive capability curves are shown in Figures 19 & 20.

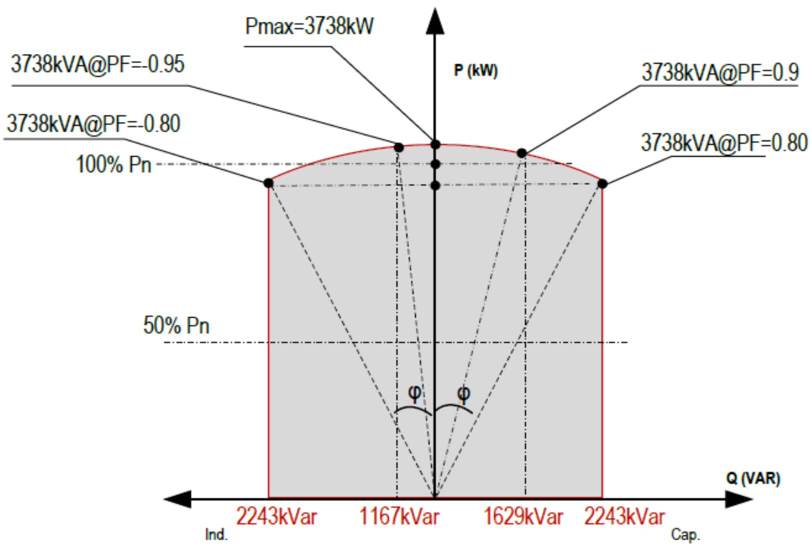


Figure 22 Typical inverter with 60% Capability curve

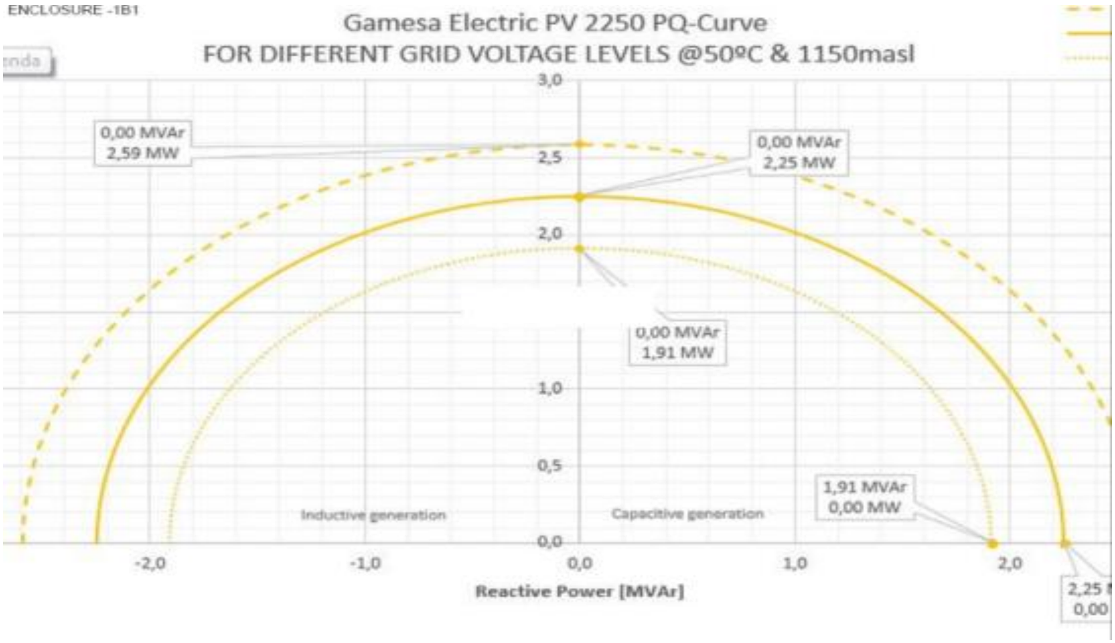


Figure 23 Typical inverter with 95% Capability curve

2.9 Regulatory framework

The current regulatory framework specifies RE generating station to be capable of supplying dynamically varying reactive power support so as to maintain power factor within the limits of 0.95 lag to 0.95 lead [1]. However, it does not specifically mention the requirement of capabilities of night mode operation. Further the 0.95 power factor as mentioned as per CEA regulation is a limitation on the harnessing full capability of the inverter.

Chapter 3: Night Mode Tests on typical days

SRLDC has conducted total of 3 typical day tests on night mode reactive power capability of which 2 tests were at Pavagada Ultra Mega Solar Park and 1 test at N P Kunta Ultra Mega Solar Park. The details of typical day test are briefed below.

3.1 Mock reactive power capability test: Pavagada Solar Park, Aug 2018

A field exercise was carried out to ascertain the MVAr absorption capability / night mode feature of inverters at Pavagada Ultra Mega Solar Park on 02nd and 03rd August 2018. The salient points of the tests are briefed below.

a) Out of the total capacity of 2050MW, 600MW capacity (Installed Capacity at that time of testing) has been tested for the MVAr absorption capability.
b) Maximum MVAr absorption recorded was 300MVAr at 400/220kV ICT level during day time.
c) Additional 150MVAr absorption was recorded in comparison to normal days.

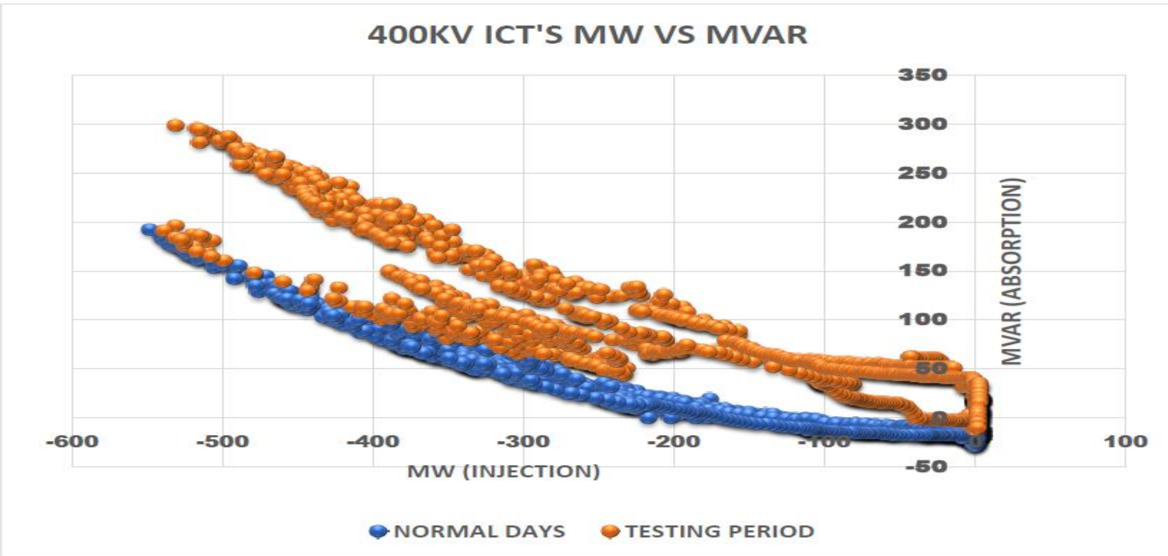


Figure 24 400kV ICT'S MW vs MVAr

d) 5kV voltage change was observed in the day time and 1 to 2kV change observed in night time with 30MVAr absorption was observed at 400kV.
e) Change in voltage was around 5kV at 220kV side.

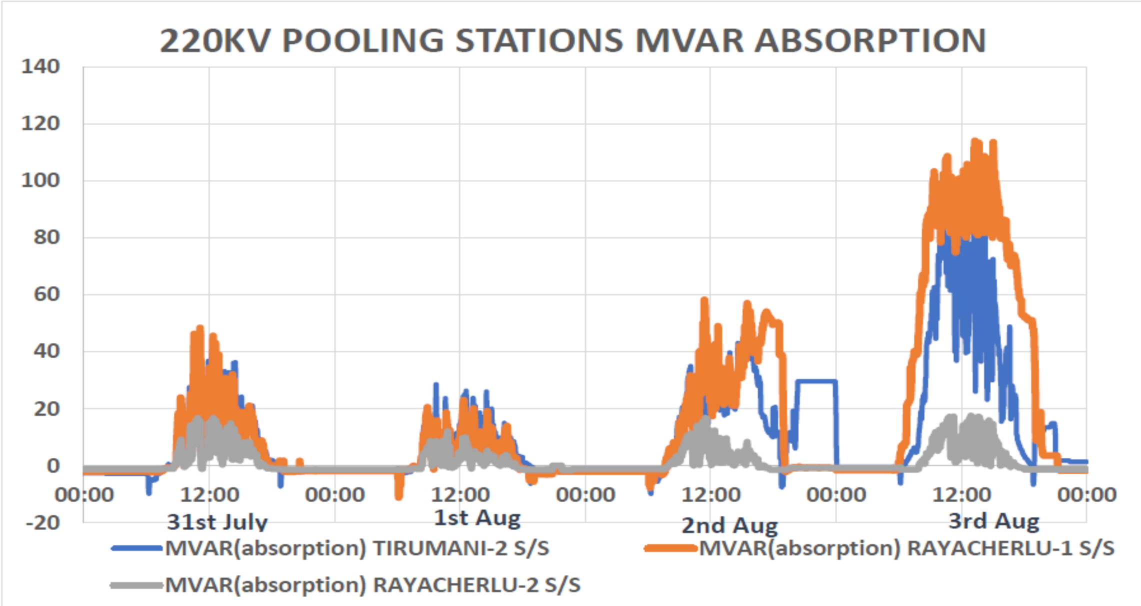


Figure 25 220kV Pooling station MVAr absorption

f) Night mode feature is available in certain blocks.

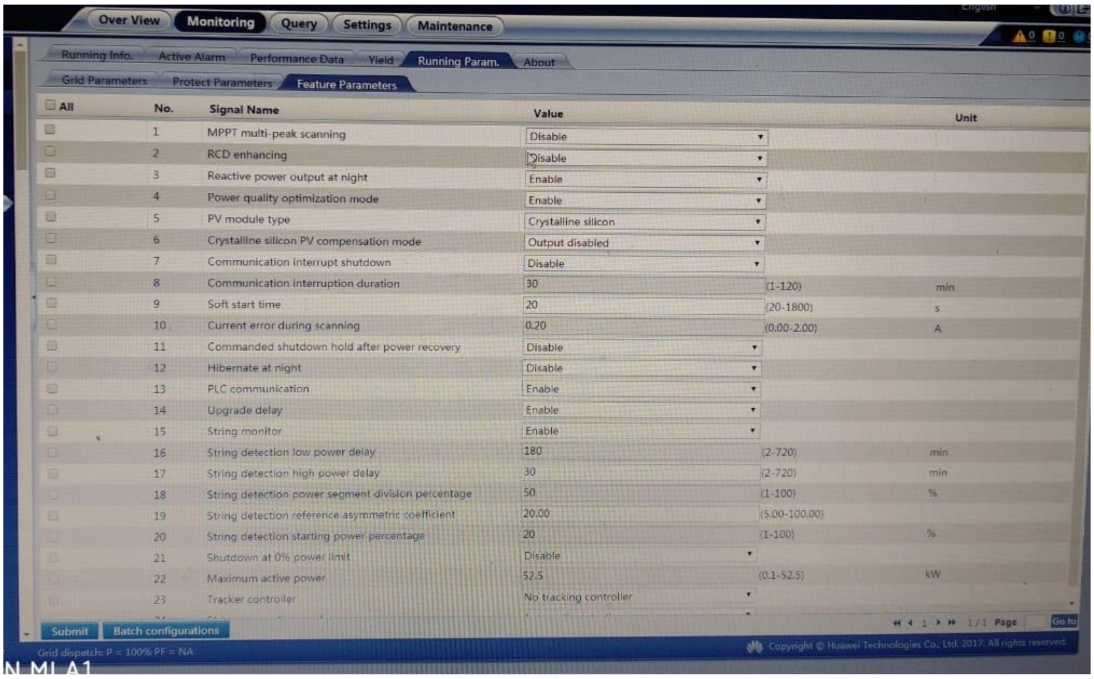


Figure 26 Night mode feature in inverter

g) The two blocks of Parampujya with capacity of 100MW could absorb 30MVAr in night mode operation.

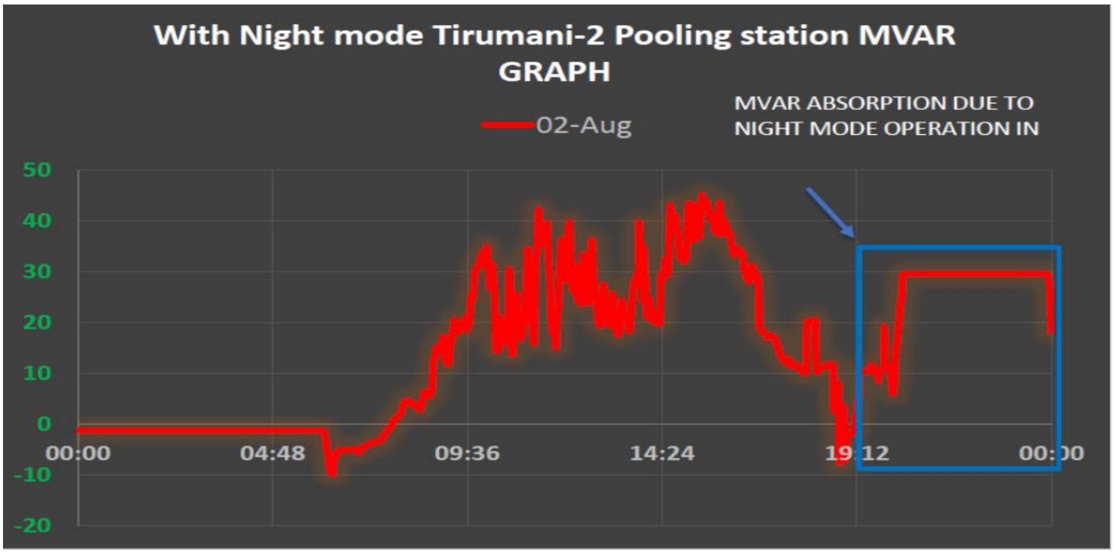


Figure 27 Tirumani-2 Pooling station MVAr Graph

Conclusion from Pavagada 2018 test

- Inverters have capability to provide reactive power support during night mode which could be further explored.

3.2 Mock reactive power capability test: Pavagada Solar Park, Feb 2021

A field exercise was carried out to ascertain the MVAr absorption capability / night mode feature of inverters at Pavagada Ultra Mega Solar Park on 16.02.2021 and 17.02.2021 to understand technical and commercial issues if any and its impact on the 400kV Grid. The salient points of the tests are briefed below.

a) A capacity of 1575MW out of total 2050 MW participated in the testing where night mode facility was available.

b) A total of 36MVAr (1MVAr absorption per 50MW block) was implemented on 16th February 2021 and 180MVAr absorption (5MVAr absorption per 50MW block) was implemented on 17th February 2021. It was observed that voltage reduction of 3kV was observed for 128MVAr support measured at grid end. No technical constraint was observed during the testing period.

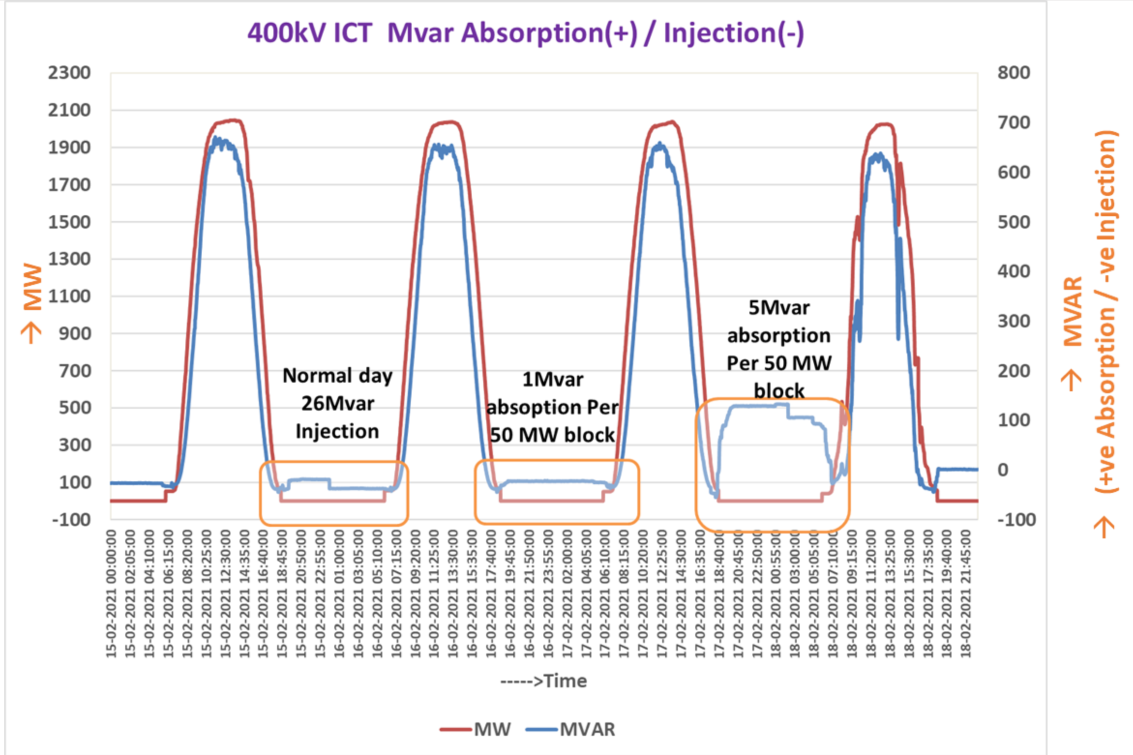


Figure 28 400kV ICT MVAr absorption vs injection Comparison

c) Around 2 to 3kV voltage drop seen as compared to normal day.

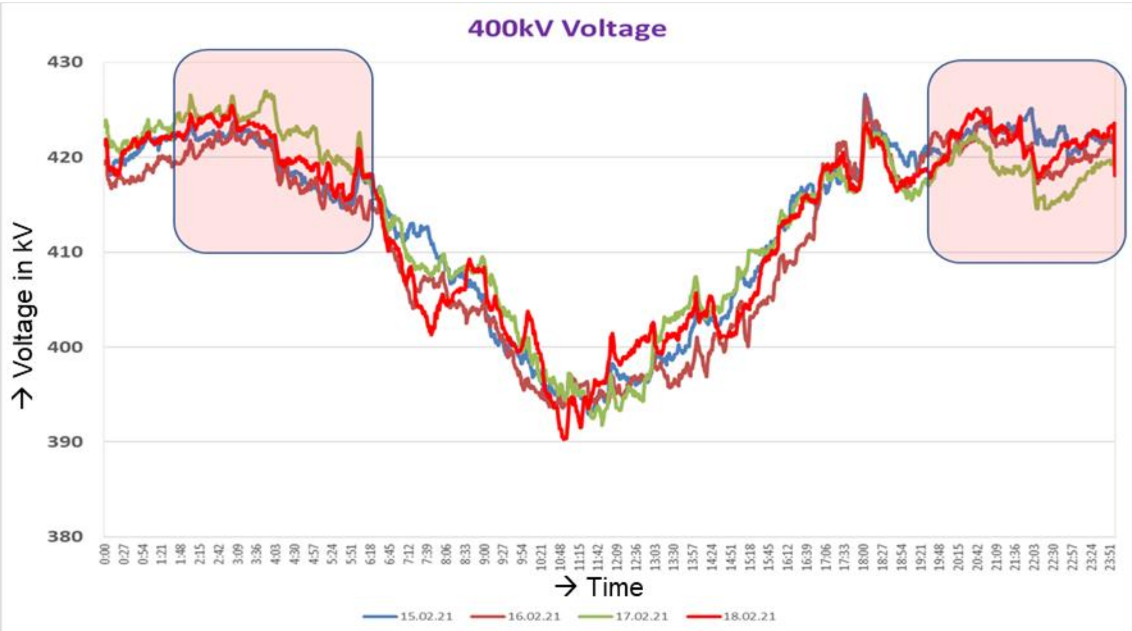


Figure 29 400kV Voltage profile during the testing period

d) 3 Lines were opened on 15.02.2021 (normal day) for controlling high voltage whereas only 1 line was opened on 16.02.2021 & 17.02.2021 (testing days) for controlling high voltage.

e) 0.026MU increase in auxiliary consumption was seen on 17.02.2021 as compared to normal day.

Conclusion from Pavagada 2021 test

- Sufficient reactive capability is available at Pavagada Solar Park.
- There is a possibility of total reactive absorption support of aprox. 900 MVAr.
- The MVAr capability can be utilised to bring the voltage say below 427kV to 425kV and avoid opening of lines.
- Actual requirement would be there only for 4 to 5 hours. Accordingly, the cost may go down.

3.3 Mock reactive power capability test: N P Kunta, Feb 2021

A field exercise was carried out to ascertain the MVAr absorption capability / Night mode feature of inverters at Sprng Agnitra Solar at NP Kunta Solar Park on 15.02.2021 and 16.02.2021 to understand technical and commercial issues if any and its impact on the 400kV Grid. The salient points of the tests are briefed below

a) Reactive capability of 2MVAr Capacity per 2.25MVA capacity is available.
b) Test was conducted with 50MVAr absorption. During the test, it was observed that LV voltage dipped significantly. Accordingly, the reactive absorption was revised to 25MVAr.
c) 0.005MU increase in consumption was observed.

Conclusion from N P Kunta 2021 test

- Around 80% + of active power is available as MVAr Capacity at Sprng Agntra.
- LV side voltage could go down when reactive absorption increases.

3.4 Conclusions and way forward from typical day tests

The tests have shown that sufficient reactive capability is available at Pavagada solar park. There is a possibility of reactive absorption of ~986MVAr. MVAr capability can be utilised to bring the voltage say below 427kV to 425kV and avoid opening of lines. Since requirement would be there only for 4 to 5 hours, the cost may go down. The following aspects need to be understood by carrying out a pilot project.

- Further understanding is required on aspect such as steps possible for controlling Q in night mode, technical feasibility of operating for 4 to 5 hours during night, tap change requirement if any etc.
- To work out commercial mechanism, if possible, by SRPC forum for a pilot project to study the monthly impact as well as gain to the grid.
- Pilot project could be taken for 1 or 2 months during monsoon.
- Whether energy loss can be made as part of regional transmission loss in line with reactors.
- Determining Plant wise energy above which energy loss could be charged and maximum energy allowed for reactive purpose for specified Q reactive.

Chapter 4: Trial Operation of Night Mode operation of Solar Inverters at Pavagada

4.1 Background

Based on the tests for typical days to ascertain night mode capability test of inverters described in Section 3, SRLDC had furnished a note to SRPC on reactive power capability of inverters, its utilization and way forward for implementation of pilot project. SRPC Secretariat had noted that all such pilot schemes in India should be implemented in consultation with NLDC with its national perspective and requested SRLDC to arrange for views of NLDC on the notes for facilitating deliberation in SRPC forums.

NLDC vide letter dated 06.07.2020 informed that the operation of solar inverters in night mode for controlling high voltage is a good initiative and would improve system reliability. In this regard, NLDC informed that similar usage of synchronous condenser mode of operation of hydro plants was being done in Northern Region historically at Tehri and Pong generating plants. The commercial settlement as agreed by all the regional entities is given below.

a. Active power consumed by the generating station during synchronous condenser operation is accounted in the regional loss account
b. Generating plants do not have to incur deviation charges for the same

Hence on similar lines, a suitable mechanism for night mode operation of solar inverters was suggested.

A special meeting was held on 27th July 2021 based on the SRLDC agenda to discuss modus operandi for utilization of inverters at solar parks in night mode for controlling high voltages. The following was concluded in the special meeting [2].

a. For controlling the high voltage, trial operation of solar inverters at Pavagada solar park (2050MW) to operate in night mode (voltage control mode) was to be implemented from 1st August 2021 for two months on pilot basis.
b. The incremental real power consumption during the night mode operation for voltage control would be treated as regional loss.
c. Incremental real power consumption by SPDs would be arrived by reducing the bench mark APC.
d. Block-wise Average Power Consumption (APC) of SPDs for the months of May 2021, June 2021 & July 2021 would be used as a reference for APC computation.
e. KSPDCL to inform all the SPDs about the implementation of trial operation from 01.08.2021.
f. KSPDCL to coordinate with SPDs at Pavagada Solar Park for facilitating the voltage control mode operation of Inverters.

g. KSPDCL / SRLDC to ensure no commercial issues to be raised by SPDs in future on account of trial operation.
h. SRLDC to furnish the following data to SRPC secretariat on weekly basis:
    i. Actual SEM data at 220kV bus of PGCIL Pavagada PS end & 33/66kV bus at KSPDCL SS end.
    ii. Computed data after removing the incremental real power consumption from blocks / substation at 220kV bus of PGCIL Pavagada PS end & 33/66kV bus at KSPDCL SS end.
i. SRLDC to share the updates / observations of the trial operation in monthly OCC meetings.
j. After completion of trial operation, SRLDC to submit a detailed report on trial operation of solar inverters at Pavagada solar park in night mode (voltage control mode).

4.2 Detailed procedure

A meeting was held with RE developers and KSPDCL for finalising the process and modalities during the trial operation. A detailed procedure was issued by SRLDC on 31.07.2021. Trial operation was conducted for two months duration i.e. August 2021 & September 2021 on pilot basis. Nodal officers were identified along with detailed responsibilities. The list of nodal officers is enclosed in Annexure – 1.

4.3 Developers and SPPD participation

KSPDCL along with Nine developers viz. Adyah, Avaada Solar, Avaada Solarise, Azure, Fortum Solar, KREDL, Parampujya, SBG Energy and Tata participated in the night mode operation (Trial) at Pavagada.

4.4 Inverters make and model participation

The following inverters make and model participated in the trial operation

Make	Model	Rating (KW)	Reactive Power Q	%
Fimer (ABB)	PVS980	2091	2007	96
HUAWEI	SUN2000-(90KTL-100KTL)	90	60	66
	SUN2000-43KTL-IN-C1	43	25.8	60
Kehua Tech	SPI3125K-B-H V1.1	3125	1875	60
Sineng	EP-2500-HA-UD	2500	1725	69
	EP-3125-HA-UD	3125	2000	64
Sungrow	SG2500	2500	-	-
	SG3125HV-20	3125	1875	60
TMEIC	PVH-L2500EQ-2	2500	1075	43
	PVH-L2550E	2550	1275	50

Table 11 Inverter details which participated in trial operation

4.5 Classification of blocks

The solar blocks of 50MW each were classified into three categories based on the availability of night mode facility in inverters and controllability of reactive power at night using PPC/SCADA as below.

a. Non-controllable Plants from central location: These Blocks have night mode capability but do not have Q control either through SCADA or PPC.
b. Controllable Plants from central location using PPC / SCADA: The Blocks having night mode capability & Q control through SCADA or PPC.
c. Blocks having no night mode facility or require manual intervention on daily basis.

4.6 Reactive power capability

The reactive power capability for each 50 MW block is different from block to block depending upon the make and model of the inverters. As discussed in the Section 2, night mode can be enabled only in generation hours and cannot be enabled in non-generation hours in certain inverters while night mode can be enabled even in non-generation hours also in remaining inverters. Similarly the reactive power can be controlled either at 50 MW block as a whole or 25 MW feeder wise using PPC / SCADA or at the inverter using HMI. The information provided in the below table is as on 01.08.2021. Certain developers have implemented PPC post trial operation. The developer wise capability and control is shown in the below table.

Developer	IC (MW)	Reactive Power Capability	Possibility of enabling night mode in non-generation hours	Level of control	Method of control for night mode
Adyah	275	183	No	25 MW Feeder	SCADA
Avaada Solar	150	144	Yes	Inverter	HMI
Avaada Solarise	150	96	Yes	25 MW Feeder	PPC
Azure Power	100	43	No	25 MW Feeder	SCADA
Fortum Solar	250	125	No	Inverter	HMI
KREDL	50	35	Yes	25 MW Feeder	SCADA
Parampujya	150	90	No	25 MW Feeder	SCADA
SBG Energy	200	120	Yes	25 MW Feeder	PPC
Tata Renewable	250	150	Yes	Inverter	HMI
Total	**1575**	**986**			

Table 12 Developer wise capability and control

The reactive power capabilities at night mode along with its controllability at Pavagada ultra mega solar park is summarised in below figure.

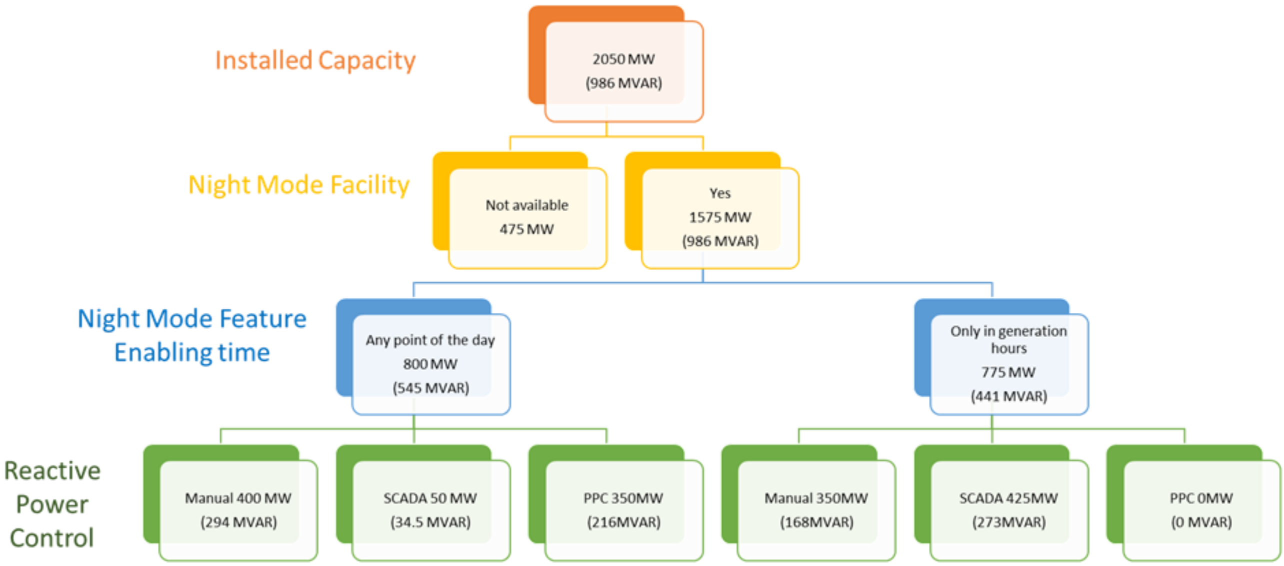


Figure 30 Reactive power capabilities and controllability of inverters

4.7 Addition of new elements at 400kV nearby substation during trial operation.

It was noted that 125MVAr bus reactor was commissioned on 30.08.2021

4.8 Reactive power absorption schedule

Based on the voltage profile and short circuit level of Pavagada substation, it was understood that around 500+ MVAr was required for avoiding the transmission line openings as well as to keep the voltages less than 425kV. Further as seen from the Section 2, Pavagada solar park had a total capacity of ~980 MVAr capability. Hence to achieve the 500MVAr, 16MVAr per 50MW block was planned for this trial exercise. It was also decided to limit to 16MVAr or 50% of maximum reactive power capability.

The following general guidelines were issued.

a. Each 50MW block is connected by two feeders. Q Schedule is equally split on both Feeders connected to 33kV/66kV Bus.
b. Necessary number of inverters on each feeder may be selected such that inverters are loaded up to 70% of their capability.
c. Avoid putting all inverters on night mode except on requirement to minimize the active power loss as well meet the Q schedule.

d. Reactive power absorption schedule of 16MVAr per 50MW block is used as reference to start with.
e. Non-controllable plants from central location would go into night mode operation with fixed Q automatically once there is no real power generation.

Controllable Plants from central location using PPC / SCADA was scheduled as below. The reactive power absorption schedule was revised based on the experience and challenges encountered.

The voltage profile for July 2021 was analysed and found that voltages were increasing from 22:30 hrs to 04:00 hrs. Accordingly the reactive power absorption schedule was given in three steps viz. 8MVAr from 22:30 hrs to 23:30 hrs, 16MVAr from 23:30 hrs to 04:00 hrs, 8MVAr from 04:00 hrs to 05:00 hrs w.e.f 01.08.2021. Subsequently developers have reported certain challenges as discussed in Section 5. Further, developers requested for reducing the three steps into one step considering human resource optimisation. Accordingly, the schedules were revised & reduced to 12MVAr from 16MVAr w.e.f 03.08.2021 with single timing from 22:30 hrs to 04:00 hrs. The night mode operation was found stable for a week. Accordingly the reactive absorption schedules were gradually increased to 14MVAr. Subsequently a committee comprising of SRLDC, SRPC, Telangana SLDC and KSPDCL visited the Pavagada site to understand the challenges expressed by the SPDs on 26.08.2021. After detailed discussion and taking SPDs into confidence, schedule was increased to 16MVAr. The summary of the reactive power absorption scheduled by SRLDC is given in the following table.

Period	Q timings	Q Schedule per 50MW Block
01.08.2021 to 02.08.2021	22:30 hrs to 23:30 hrs	8 MVAr
	23:30 hrs to 04:00 hrs	16 MVAr or 50% of reactive capability whichever is lower
	04:00 hrs to 05:00 hrs	8 MVAr
03.08.2021 to 08.08.2021	22:30 hrs to 04:00 hrs	12 MVAr or 50% of reactive capability whichever is lower
09.08.2021 to 25.08.2021		14 MVAr or 50% of reactive capability whichever is lower
26.08.2021 to 30.09.2021		16 MVAr or 50% of reactive capability whichever is lower

Table 13 Reactive Power Absorption Schedule and Timings

4.9 Data submission and observations.

KSPDCL, along with the nine developer's viz. Adyah, Avaada Solar, Avaada Solarise, Azure, Fortum Solar, KREDL, Parampujya, SBG Energy and Tata participated in the night mode operation (Trial) at Pavagada. Additionally, data was received from SRPC and POWERGRID SR2.

Data such as MW, MVAr, voltage, current, PF at all the points viz. inverter level, 33/66kV feeder level at both ends, 220kV feeder level at both ends was sought from developers/KSPDCL/POWERGRID/SRPC.

The following are the status on the data.

Table 14 Data Submission Status

Sl. No.	Entity	Quantum Participated in MW	Inverter	33/ 66kV Feeder @SPD End	33/66kV Feeder @KSPDCL End	220kV Feeder @KSPDCL End	220kV Feeder @PoC
1	Adyah	275	YES	YES	---	---	---
2	Avaada Solar	150	YES	YES	---	---	---
3	Avaada Solarise	150	YES	YES	---	---	---
4	Azure	100	NO	YES	---	---	---
5	Fortum Solar	250	YES	YES	---	---	---
6	KREDL	50	YES	YES	---	---	---
7	Parampujya	150	YES	YES	---	---	---
8	SBG Energy	250	YES	YES	---	---	---
9	Tata	200	YES	YES	---	---	---
10	KSPDCL	---	YES	YES	YES	YES	---
11	POWERGRID	---	---	---	---	---	YES
12	SRPC	---	---	---	YES	---	YES

Following are some of the specific observations.

- The developers having string inverters have submitted partial data due to communication issues.
- The 220kV Feeder @KSPDCL data submitted by KSPDCL was showing less value as compared to 220kV Values @POWEGRID by significant difference. Hence the information could not be utilised.
- The information provided by POWERGRID was utilised for computing reactive energy.
- The data received from SPD was used for understanding the inverter loading profile by various developers.
- The data received from SRPC was used for computing the incremental active energy on account of night mode operation. Meter recording issues were observed in 220kV line of PSS3. Hence the data of 33kV feeder was used for PSS3.

4.10 Reactive power capability & inverter loading at Pavagada solar park

The reactive power absorbed by each inverter in case of central inverter or inverter control room in case of string inverters is analysed. The distribution of reactive power absorption performance among developers is given below for 32 blocks (1575 MW) that participated in the night mode operation.

- 32 Blocks (1575 MW) blocks participated in the night mode.
- All inverters within a 50MW block were equally loaded across 19 blocks (925 MW).
- 50% of inverters within a 50MW block were swapped on a monthly basis in 6 blocks (300 MW).
- 50% of inverters within a 50MW block were swapped on alternate day basis in 2 blocks (100MW).
- Inverters within a 50MW block were utilised based on grid requirement in 5 blocks (250MW).

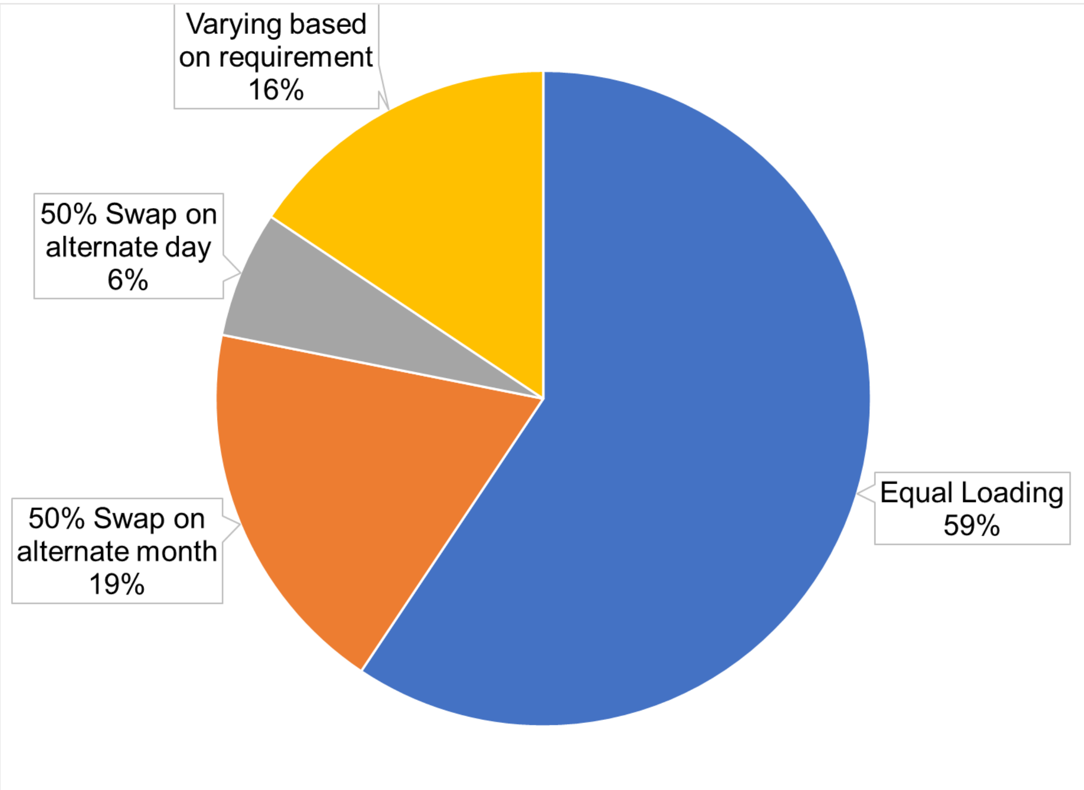


Figure 31 Inverter Loading Profile

The SPD wise detailed observations are summarised below.

a. Adyah

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
6.25	4.16	3.15	33.36	16

Table 15 MVAr absorption profile of inverters by Adyah

- Inverters are of string type.
- Typically, string Inverters connected to common feeder were equally absorbing reactive power to meet the desired reactive power schedule.
- In case of outage of particular string inverter or any transmission element, reactive absorption in remaining string inverters were maximised to meet the reactive schedule.
- The maximum loading on individual inverter during the trial period was 75% of its reactive power absorption capability.

b. Avaada Solarise

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
3.125	2.06	2.0	32	16

Table 16 MVAr absorption profile of inverters by Avaada Solarise

- Inverters are of central type.
- 50% inverters were equally absorbing to meet the desired reactive power.
- Swapping of inverters was carried out on monthly basis.
- The maximum loading on individual inverter during the trial period was 97% of its reactive power absorption capability.

c. Avaada Solar

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
2.091	2.0	0.91	48	16

Table 17 MVAr absorption profile of inverters by Avaada Solar

- Inverters are of central type.
- All inverters were equally absorbing to meet the desired reactive power.
- The maximum loading on individual inverter during the trial period was 45% of its reactive power absorption capability.

- Currently the reactive power is controlled manually. This difficulty is expected to be overcome after PPC implementation.

d. Azure Power

Inverter Rating in MVA	Reactive power MVAr			
	Inverter Level		50 MW Block	
	Capability	Instantaneous Max Achieved	Capability	Instantaneous Max Achieved
2.5	1.075	1	21.5	10

Table 18 MVAr absorption profile of inverters by Azure Power

- Inverters are of central type.
- 50% inverters were equally loaded to meet the desired reactive power.
- Swapping of inverters was carried out on alternate days.
- The maximum loading on individual inverter during the trial period was 93% of its reactive power absorption capability.
- There was no provision for reactor power control from SCADA till 15.09.2021. Subsequently the provision for reactive power control from SCADA was made w.e.f 16.09.2021 and 22.09.2021.

e. Fortum Solar

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
2.55	1.28	1	25	16

Table 19 MVAr absorption profile of inverters by Fortum Solar

- Inverters are of central type.
- All inverters were equally loaded to meet the desired reactive power.
- The maximum loading on individual inverter during the trial period was 78% of its reactive power absorption capability.

f. KREDL

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
2.5	1.73	0.34	34.5	1

Table 20 MVAr absorption profile of inverters by KREDL

- Inverters are of central type.
- Only 10MW out of 50MW participated in the trial exercise due to gateway issue.
- All inverters were equally loaded to meet the desired reactive power.
- The maximum loading on individual inverter during the trial period was 20% of its reactive power absorption capability.

g. Parampujya

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
5	3	3	30	16

Table 21 MVAr absorption profile of inverters by Parampujya

- Inverters are of string type.
- 50% of inverters were loaded for both months. However it was seen that the actual absorption was less than scheduled reactive power absorption for most of the days.
- The maximum loading on individual inverter during the trial period was 100% of its reactive power absorption capability.
- Typically, string inverters connected to common feeder were equally absorbing reactive power to meet the desired reactive power schedule.
- In case of outage of particular string inverter or any transmission element, reactive absorption in remaining String inverter were maximised to meet the reactive schedule.

h. Soft Bank

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50 MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
3.125	1.95	1.88	30	15

Table 22 MVAr absorption profile of inverters by Soft Bank

- Inverters are of central type.
- All Inverters were equally loaded to meet the desired reactive power absorption.
- The maximum loading on individual inverter during the trial period was 96% of its reactive power absorption capability.

i. TATA

Inverter rating in MVA	Reactive power MVAr			
	Inverter level		50MW block	
	Capability	Instantaneous Max achieved	Capability	Instantaneous Max achieved
3.125	1.875	1.38	30	16

Table 23 MVAr absorption profile of inverters by TATA

- Inverters are of central type.
- Reactive power absorption was set at 1MVAr / Inverter (51% of the setting) during the trial period. This was done to minimize the no. of participating inverters considering the manual operation, and also to keep the inverters at around 51% absorption as suggested by the OEM for the better life of the inverter.
- Max. of 16MVAr reactive power absorption per 50MW Block was performed, as there are only 16 inverters / block

- The maximum loading on individual inverter during the trial period was 73% of its reactive power absorption capability.

4.11 Reactive Power Absorption

The reactive absorption during non-solar hours for the period of 30.07.2021 to 30.09.2021 is plotted below. It may be observed that on a normal day, aprox. 35MVAr was being injected from the solar park into the 400kV system due to reactive power generated by the cables and lightly loaded 220kV lines. However, since start of trial operation, the reactive power injection has been nullified and absorption has started.

Certain developers had requested for enabling inverters in night mode during generation hours as well as for allowing reactive power absorption immediately after generation hours. This is due to the fact that night mode feature can be enabled in generation hours only and also to avoid manual operation during night hours. Hence it may be observed from the below graph that around 100MVAr absorption started just after generation hours. The reactive power absorption starts increasing from 22:30 hrs and gets maximised at 23:00 hrs in line with the reactive power schedule given by SRLDC. Similarly it can be observed that the reactive power absorption gets reduced to zero from 04:00 hrs.

The day wise reactive power absorption at 400 and 220kV from 19:00 to 05:00 hrs is shown below.

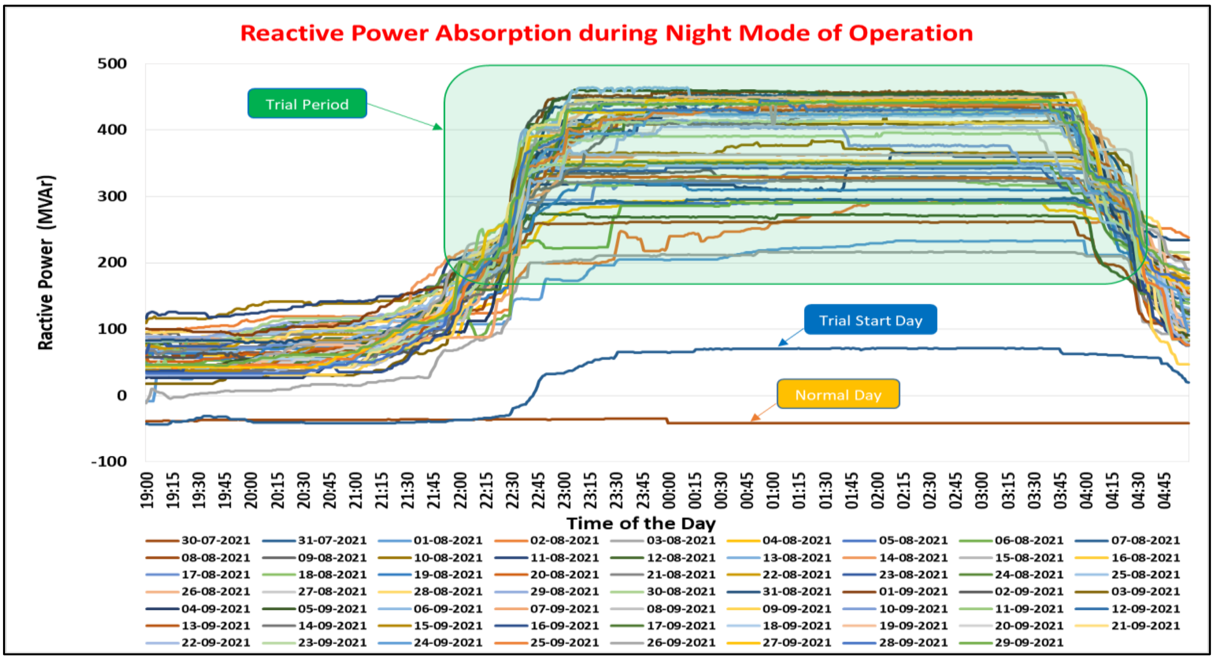


Figure 32 Reactive power absorption at 400kV Pavagada

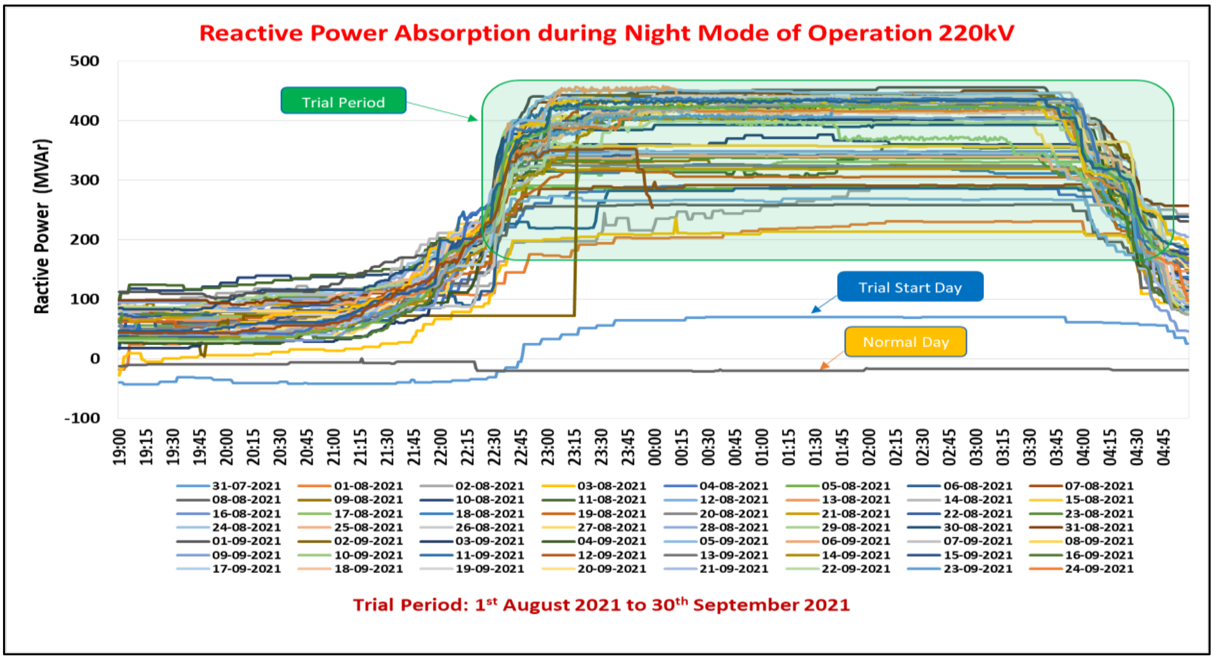


Figure 33 Reactive power absorption at 220kV Pavagada

The day wise maximum reactive absorption is plotted below. It was observed that maximum reactive power absorption of 465MVAr was observed at HV side of 400/220kV ICT on 06.09.2021 23:49 hrs and 458MVAr was observed at LV side of 400/220kV ICT on 07.09.2021 00:05 hrs.

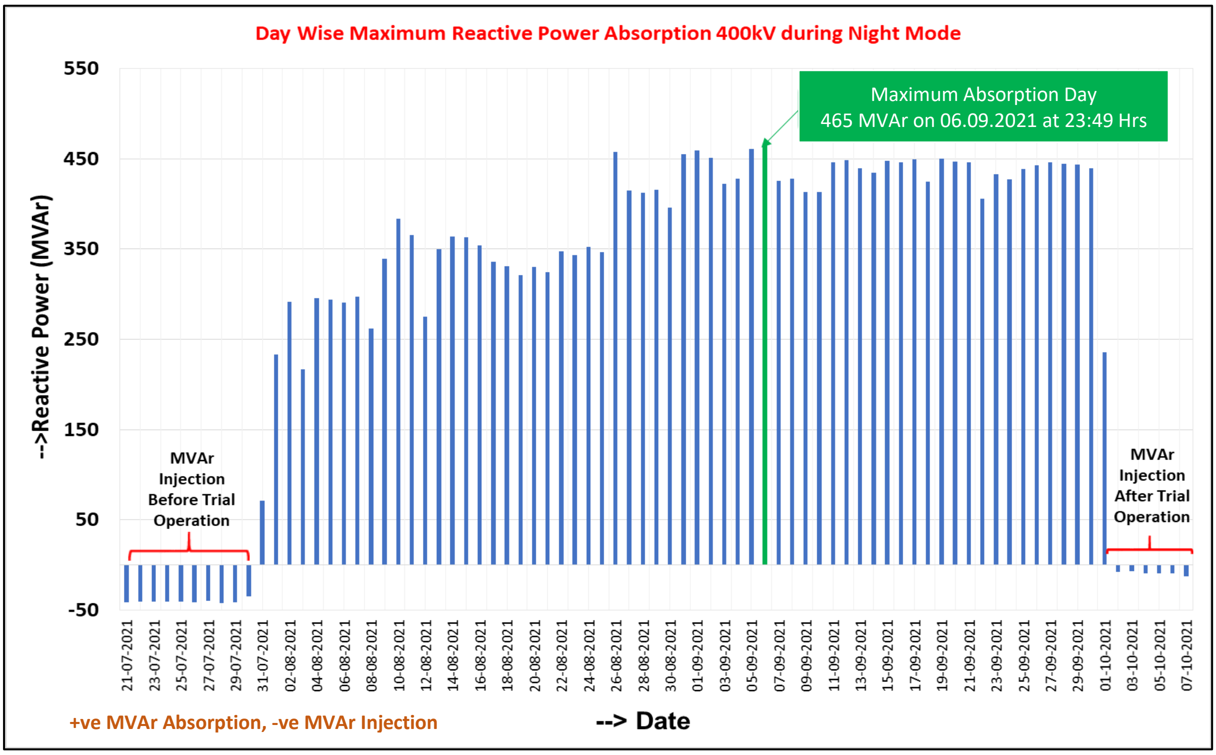


Figure 34 Day wise maximum reactive power absorption at 400kV Pavagada

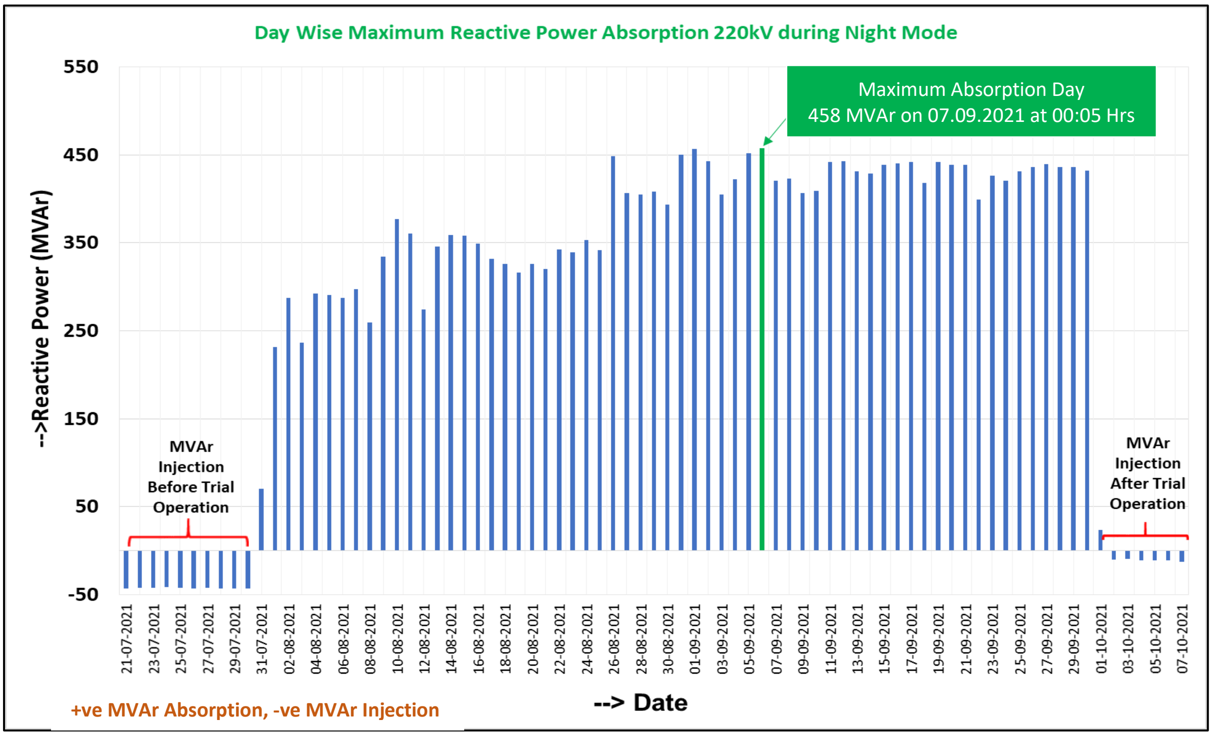


Figure 35 Day wise maximum reactive power absorption at 220kV Pavagada

*Date indicated in charts above shows that the timing from evening 18:00 Hrs to next day morning 06:30 Hrs

The voltage vs reactive power absorption is plotted for the maximum reactive absorption day. It may be noted from figure 31, 32 and 33, that there was reactive power injection of 25 to 35 MVAr due to lines and cables within the park on a normal day before the trial operation. However, the pattern has changed from reactive power injection to reactive power absorption during the trial operation.

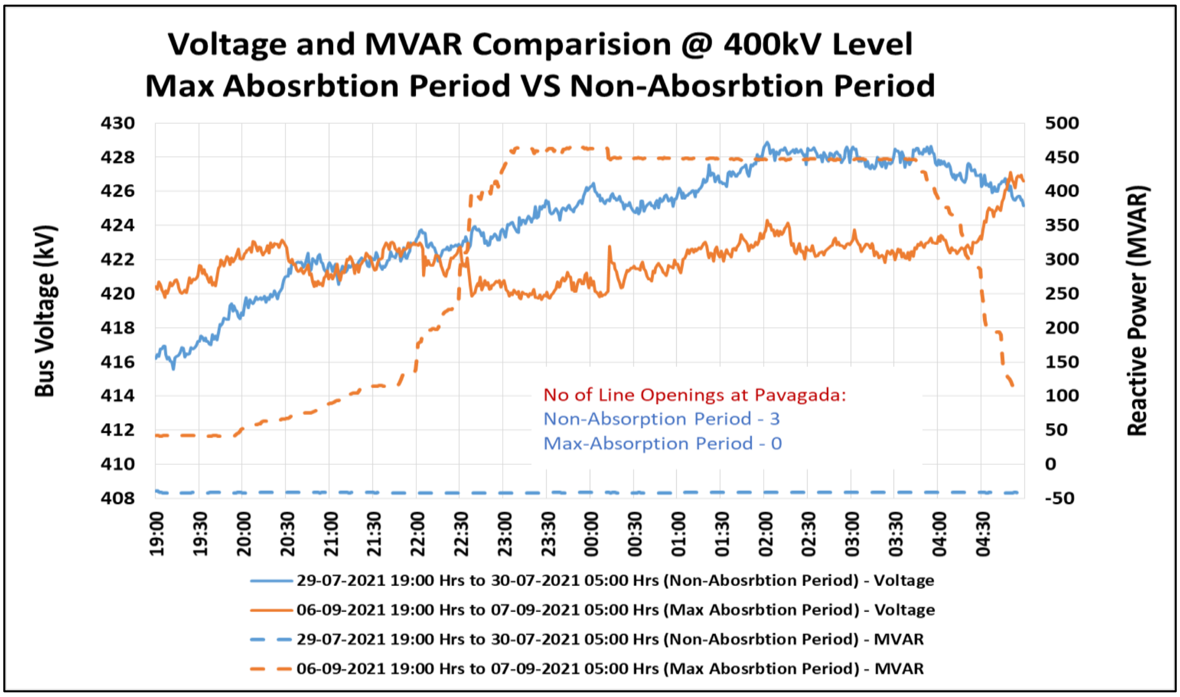


Figure 36 400kV Pavagada voltage vs. reactive power

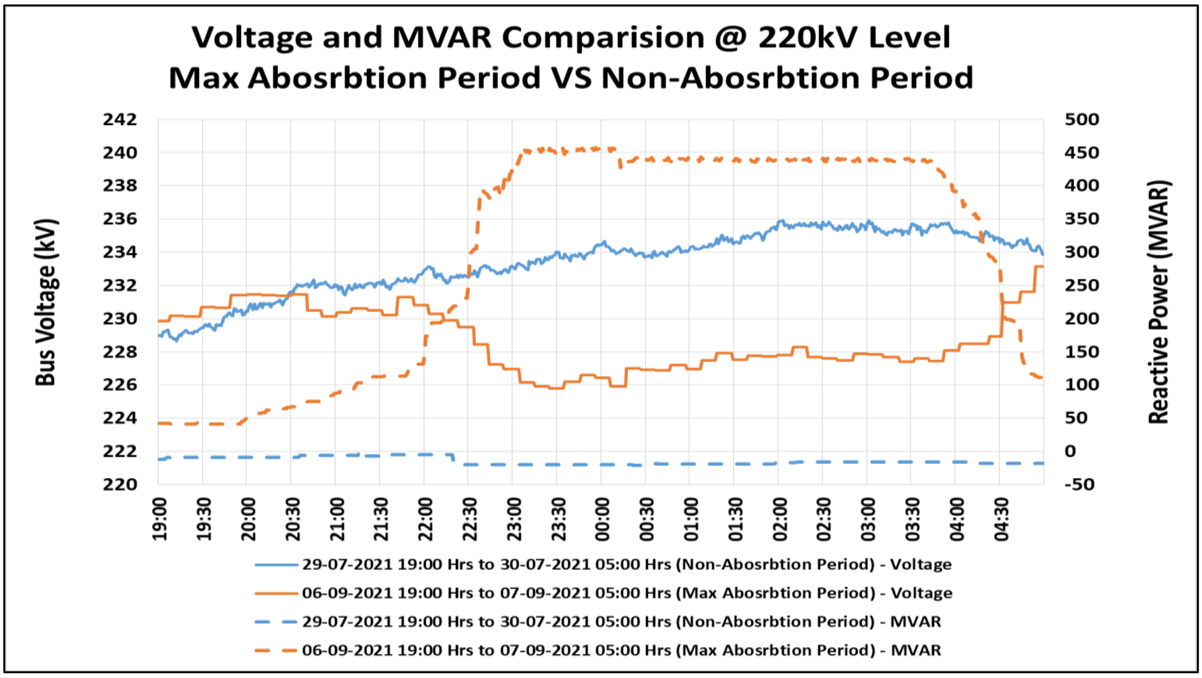


Figure 37 220kV Pavagada voltage vs. reactive power

The reactive power absorption schedule was actual is shown in below figure. There was less reactive power absorption as compared to schedule till 25.08.2021 due to issues expressed by developers deliberated in chapter 5. The deviation from schedule got reduced subsequent to the team visit on 26.08.2021.

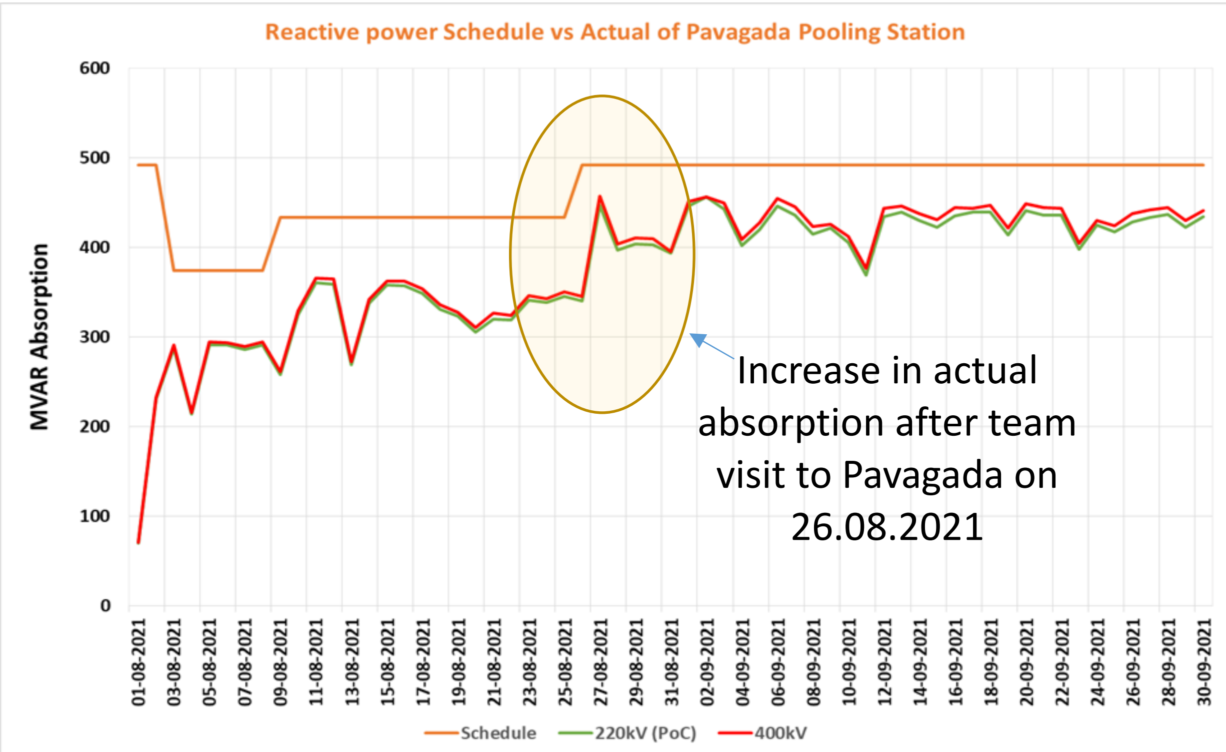


Figure 38 Reactive power schedule vs actual at 220kV and 400kV

The details of developer wise reactive power schedule vs actual is plotted in Annexure -3

4.12 Impact on voltage profile

It is observed that most of the time, 400kV Pavagada bus voltage was below 430kV during off-peak hours. The impact on voltage is shown below.

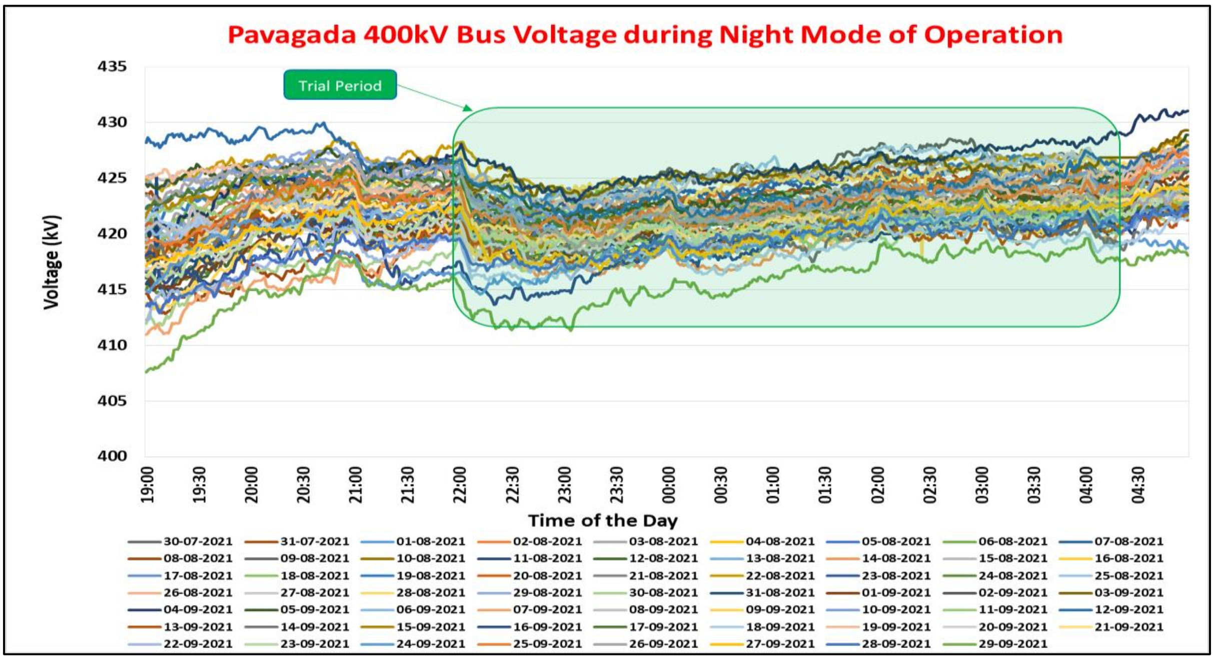


Figure 39 400kV daily voltage profile during trial period at Pavagada

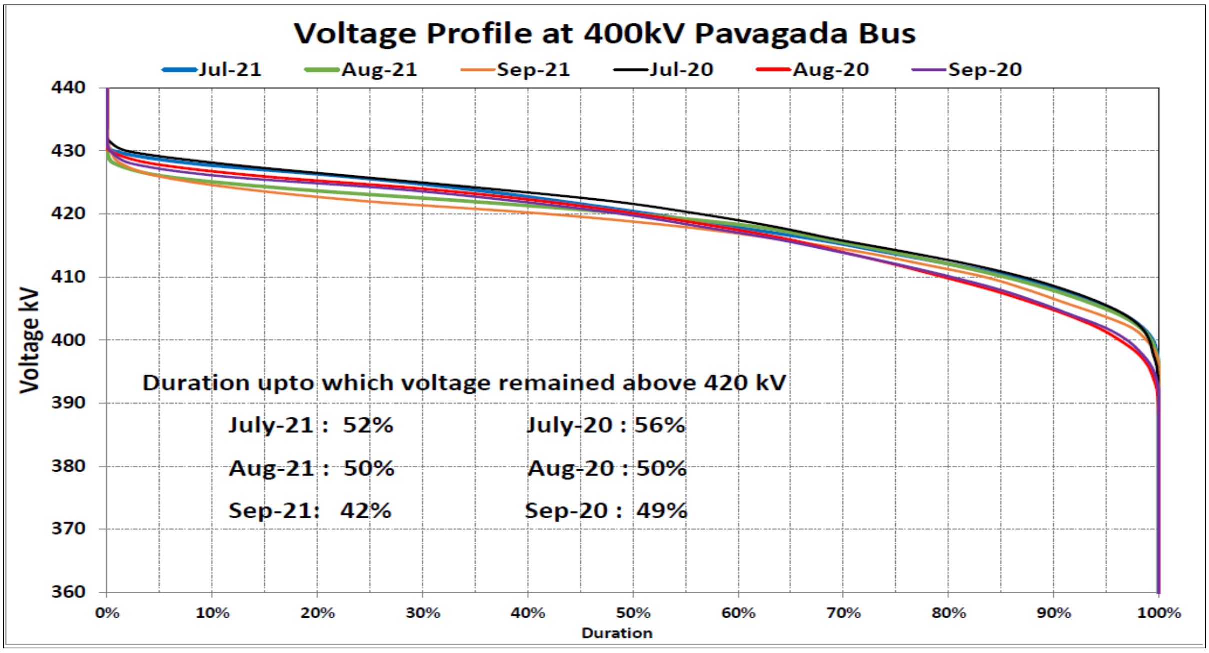


Figure 40 400kV Pavagada voltage duration curve for July, Aug & Sep 2020 and 2021

It is observed that most of the times voltage was below 230kV. The impact on voltage is shown in the following figure.

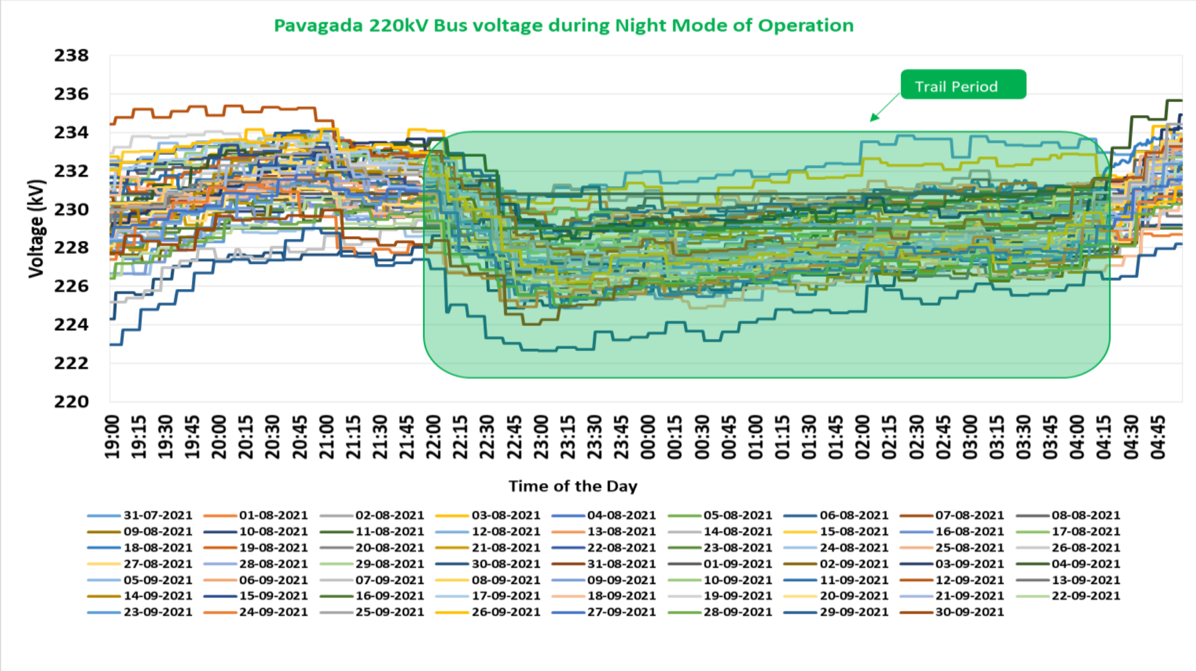


Figure 41 220kV daily voltage profile during trial period at Pavagada

The box plot of 400kV Pavagada Sub-station for the month of August & September 2021 is shown below. It can be observed that voltages started reducing after 22:00 hrs due to reactive power absorption by inverters in night mode. Similarly voltages are increasing from 04:00 Hrs subsequent to withdrawal of reactive power absorption support by inverters.

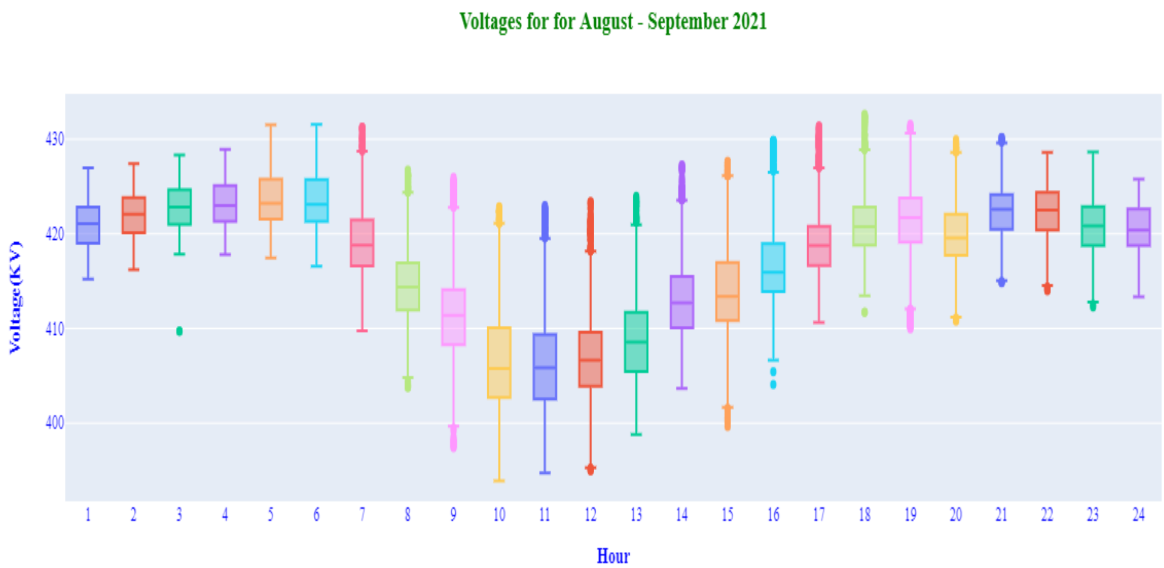


Figure 42 Box plot of 400kV Pavagada Sub-station (August & September 2021)

4.13 Impact on line opening/ tripping of lines due to over voltage.

During the night mode operation, there was a reduction in number of transmission lines opened as the voltage was below 430kV during the off-peak hours. However, only one transmission line at a time was opened to control the voltage at the far end station.

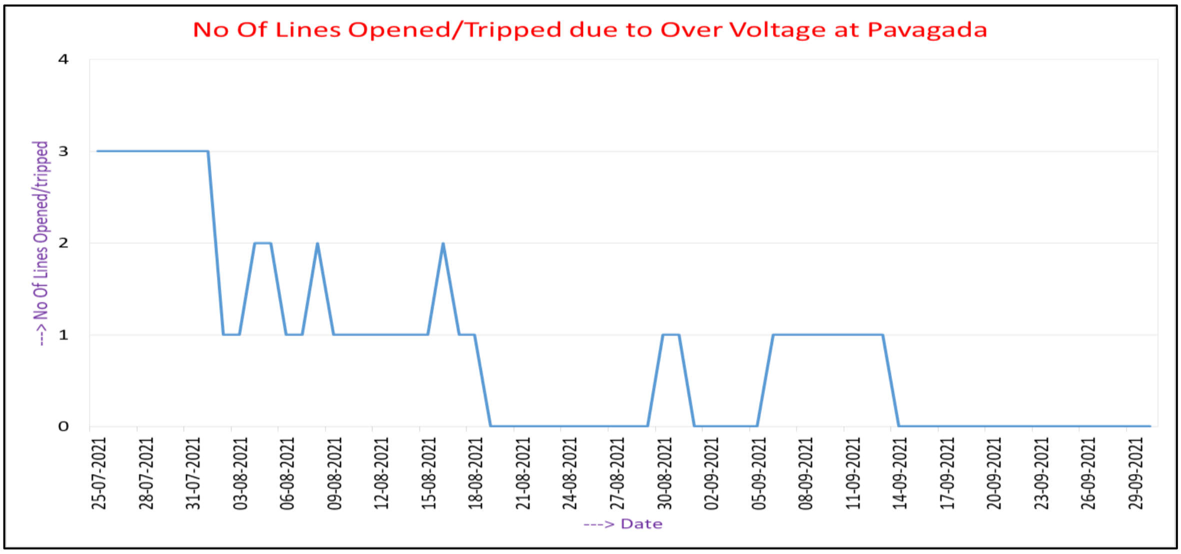


Figure 43 Line opening/ tripping of lines during trial period

Chapter 5: SPD wise challenges reported, observations and conclusions

Certain difficulties were expressed by the developers during the trial period. Further it was decided in the 181st OCCM that a team comprising of officials from SRLDC, SRPC and states would visit the solar park to experience the night mode operation as well to understand the difficulties expressed by the developers. Accordingly, a team of SRLDC, SRPC and Telangana visited solar park on 26.08.2021. The members of the team are attached as Annexure-II. The team visited SBG Energy, Azure, Tata, Adyah and Avaada on 26.08.2021.

Azure

Tata

SBG Energy

Adyah Avaada Solar

Figure 44 Committee visit to Pavagada Solar Park on 26.08.2021.

The observations during the visit and the trial period are summarized in the sub-sections below.

5.1 Developer 1

5.1.1 Challenges:

- Communication issues were reported during the Night Mode Operation.
- Reason was due to communication time differences between SCADA to SACU (String Array Communication Unit) and SACU to string inverters, communication failures are occurring in some of the inverters.
- Data pooling from string inverter to SCADA will be through SACU and all string inverters will communicate to SACU through PLCC.
- Due to huge data traffic flow from string inverters to SCADA for monitoring purpose, there will be some delay and some data will be missed; so reactive power consumption records are not accurate.
- During the trial period of reactive power absorption, it is observed that due to communication issues and non-availability of grid supply due to line / substation maintenance after generation hours, string inverters are going to sleep mode and never come on line until it gets DC power feedback, hence they are unable to absorb reactive power.

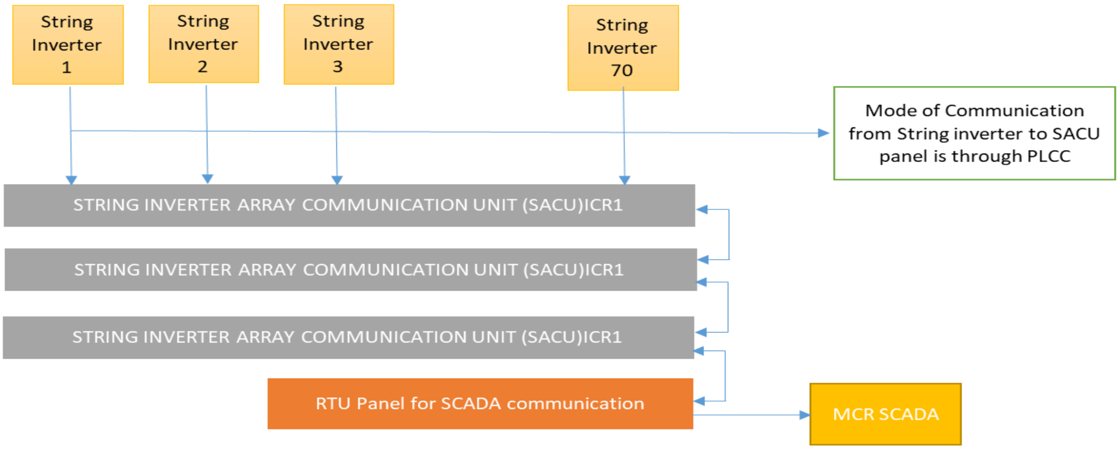


Figure 45 Communication SLD for String Inverters to SCADA system

5.1.2 Observations:

- Night mode and reactive power mode commands need to be given during generation hours as the inverters go into sleep mode under normal circumstances without night mode. Once the above commands are given during the generation time, reactive power settings can be changed during the night hours.
- Communication issues are still persisting but required MVAr was distributed among the inverters which were in service.
- PPC is under implementation. Once the PPC is implemented, the communication failure issue is expected to get resolved.

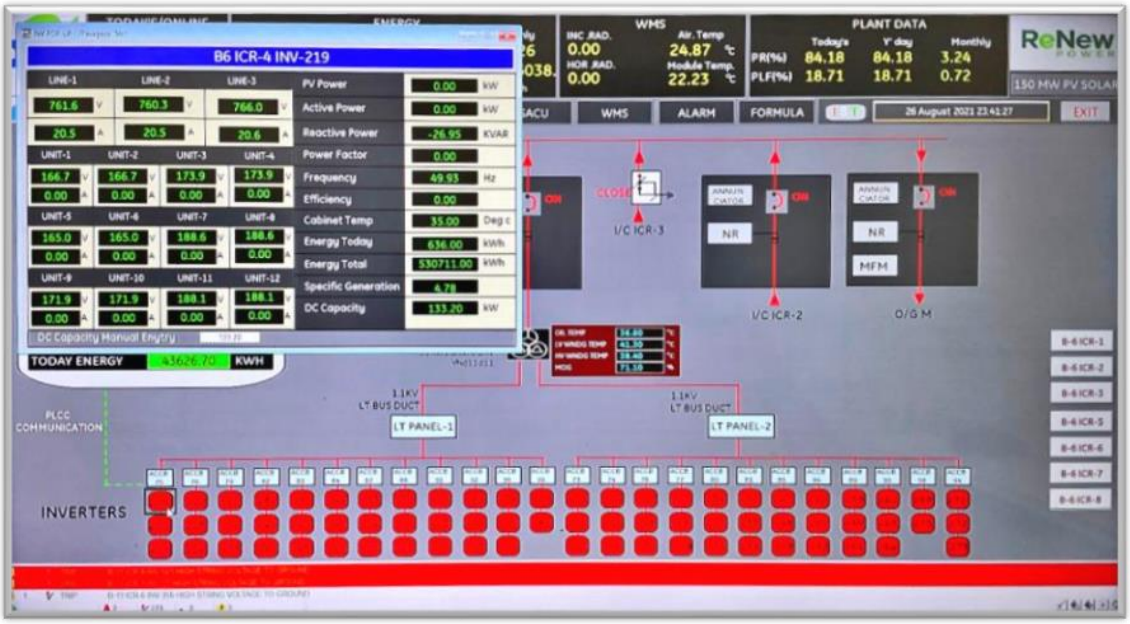


Figure 46 SCADA snap shot of inverter level controls

- Both block wise and incomer wise (6.25MVAr per ICR, 8 no. of ICR per block) real time active power controllability was available.

Figure 47 SCADA snap shot of inverter Block group level controls

5.1.3 Conclusion & Suggestions

- Currently SVG mode can be enabled only during generation hours. Developer to take up with OEM and understand the feasibility of enabling SVG mode after generation hours also.
- Q settings can be fed from SCADA.
- Communication issue to be checked after implementation of PPC.

5.2 Developer 2

5.2.1 Challenges:

- Developer expressed orally about the observation of increase in fan speed and few fan failures. The root cause analysis was requested to OEM and they were keeping Q lesser than the schedule advised to them. Accordingly visit was made to understand Fan Speed issues.

5.2.2 Observations:

- Out of 24 inverters (each of 2.1MVA capacity and 2.0MVAr reactive capability), 12 inverters were kept in service with a setting of 900kVAR per inverter in two out of 3 blocks whereas only 10 inverters were kept in service in another block due to IDT winding heating issues. This resulted in 29.6MVAr capacity out of requested 48MVAr. Developer could not demonstrate the difficulty expressed.
- Root cause analysis is yet to be completed and there is no direct establishment of fan failure to night mode operation.
- Subsequent to committee visit, remaining inverters were kept in night mode of operations.

5.2.3 Conclusion & Suggestions

- Developer could not demonstrate the difficulty expressed about the fan speed increase, till date root cause analysis is yet to establish the fan failure to night mode.
- Night mode can be enabled even after generation hours.
- Current operation of manual control may be converted to central control after PPC is implemented. Currently PPC implementation is under progress.

5.3 Developer 3

5.3.1 Challenges:

- Inverters were getting tripped due to which they were unable to reach the scheduled quantum. Software updation was made to overcome the issue.
- During the trial period, on some days inverter tripping was reported due to low voltage. 66kV bus voltages touched 63kV, which is plotted below.

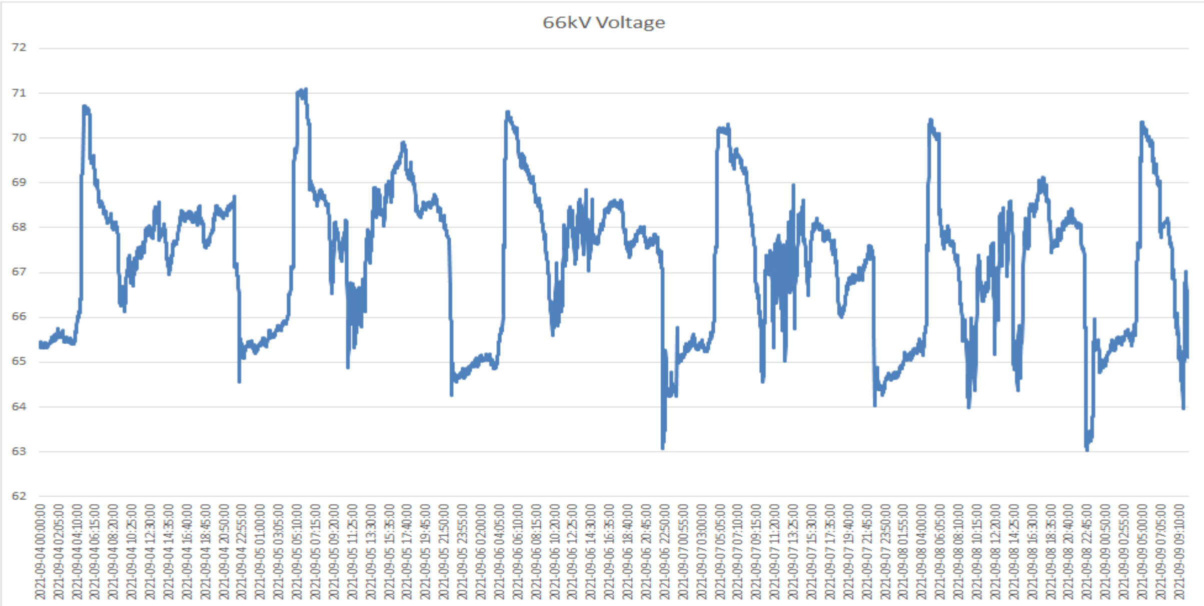


Figure 48 66kV voltage from 04.09.2021 to 09.09.2021

The Inverter under-voltage setting is kept at 90%.

Figure 49 Snap shot of under voltage relay settings at inverter

- Increase in voltage was seen after 4 AM (when reactive power absorption was getting stopped) and grid side voltages were going high (above 70kV) due to which over flux alarms.

5.3.2 Observations:

- LV side voltages generally are rated for 10% rating which means 66kV +/- 6.6kV which is general ranges from 59.4 to 72.6. Generally tripping would be set accordingly. Developer was requested to check the current settings of voltage on LV side at inverter for tripping and revert for further understanding.

- Based on the observation that the LV voltages are observed between 22:30 to 23:00 hrs, developer was advised to start absorption at their block from 23:10 hrs instead of 22:30 hrs subsequent to increase in voltage.
- Inverter AC side voltage tripping (over & under voltages) are set at 110% to 90% i.e. (660 Volts to 540 Volts). If any of the phase voltage goes below 540V, then this current unbalanced fault is expected in inverter. The explanation received for inverter AC side voltages & inverter trip (current unbalance) is shown below.

System Manual — 11 Troubleshooting

Fault name	Explanation	Fault severity	Measures
Current2 Unbalan-ced/ Current3 Unbalan-ced	AC current unbalance	Major	Measure the grid voltage, to check whether phase loss occurs.

Figure 50 Snap shot of current unbalance explanation

- Subsequent to the above shift in the timings the voltage constraint was overcome.

5.3.3 Conclusion & Suggestions:

- Constraint expressed by developer was due to voltage and inverters are capable of absorbing the required Q.
- Reactive power absorption can be increased by maintaining voltages above the trip limits by varying the tap change of pooling station / power transformer / IDT.

5.4 Developer 4

5.4.1 Challenges:

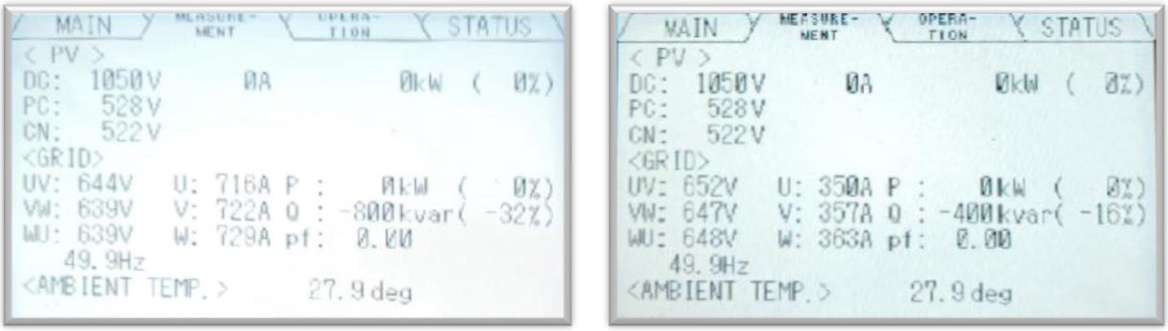
- Night mode cannot be turned on after generation period.
- Night mode / SVG mode option is not available in SCADA; it has to be turned ON from the inverter level. Further, the inverter was not able to take the Q settings from SCADA during SVG mode although Q settings from SCADA was possible during generation hours.
- SRLDC instruction of 16MVAr per 50MW was difficult since the maximum capability is aprox. 20MVAr per 50MW. They would like to go up to maximum of 50% (10MVAr /50MW Block) only.

5.4.2 Observations:

- To understand the above issues, night mode was enabled on 26.08.2021 in all the inverters. Inverter 4 of Inverter Control Room (ICR) #2 was tested with below 2 situations:
  a. VAR absorption was increased from 400 to 800kVAR in order to check whether the settings can be changed during off-generation hours or not at HMI which was tried through SCADA but was found not possible.

b. SVG mode was turned off and tried to turn on during the off-generation hours.

- The settings could be changed from 400 to 800kVAR and hence it was concluded that settings can be changed in the night hours. The sanp shot at 400kVAR and at 800kVAR reactive absorption.



Adyah Avaada Solar

Figure 51 Snap shot of Q settings at inverter with 400kVAR and 800kVAR

- During 2nd test, when SVG mode was turned off, AC side breaker got tripped which turns on automatically only when illumination and DC side voltage is above certain level.
- There was no feasibility of manual operation with which AC side inverter could have been taken into service. Night mode needs to be enabled during generation hours only as the inverter goes into sleep mode under normal circumstances without night mode. Once the above commands are given during the generation time, reactive power settings can be changed during the night hours.
- SVG mode option is not available in SCADA, it can be turned ON only from the inverter level. Further it was observed that the Q settings fed in SCADA during night mode were not taken by inverter however the Q settings set during generation were taken by inverters.

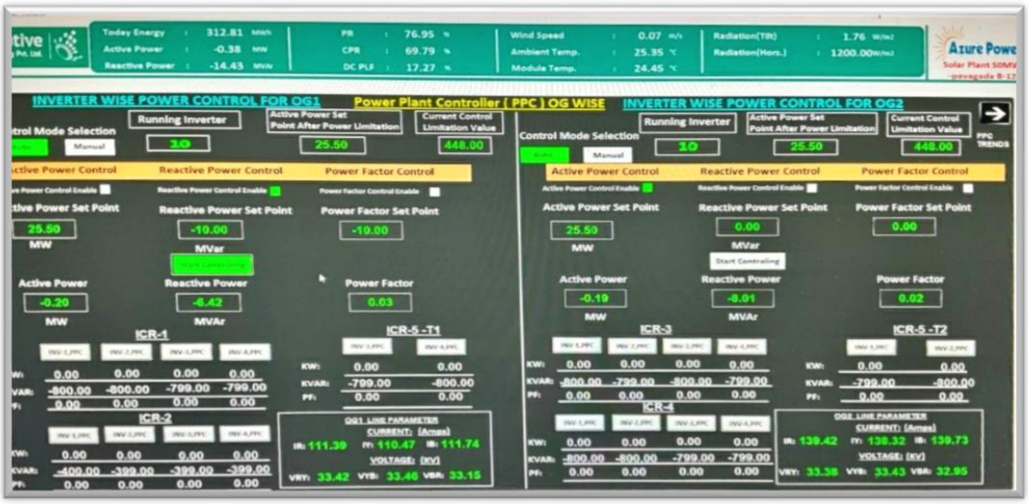


Figure 52 Snap shot of non-functioning of Q control during non-generation hours

5.4.3 Conclusion & Suggestions:

- Currently Night / SVG mode can be enabled only during generation hours.
- At present, active & reactive power can be controlled from SCADA only during generating hours. During SVG mode, SCADA doesn't have any control over inverters. The variation can be done only at inverter HMI during SVG mode.
- Developer was advised to take up with OEM and understand the feasibility of enabling SVG mode after generation hours also. Similarly, the feasibility of extending the Q control from SCADA to inverter in night mode may be understood.
- Subsequently, developer has implemented Q control in SCADA in night mode also from 16.09.2021 and 22.09.2021 for both the blocks.

5.5 Developer 5

5.5.1 Challenges:

- Developer could not join the exercise immediately from 01.08.2021 as they are dependent on OEM Service engineer availability at the plant for doing the necessary changes in the inverter and requested time of 7 to 10 days, subject to OEM confirmation for both feature & availability. After detailed deliberation, developer joined the exercise w.e.f 04.08.2021.
- Inverters SCADA control is applicable to PQ mode only. Therefore, inverters active & reactive power can be controlled from SCADA only during generating hours, as they are operating in PQ mode, and they can increase / decrease active power limit and also reactive power (injection / absorption) limit from SCADA during generating hours.
- During non-generation hours, increase or decrease of reactive power absorption / injection can be done only at inverter HMI during SVG mode.
- Allowed to operate as per Q schedule immediately after generation hours and up to start of generation next day instead of 22:30 hrs to 4:00 hrs. This was in lieu of changing the settings at the inverters & its HMI level.

5.5.3 Observations:

- Technical capability was already proved in February 2021 typical day experiment.
- Currently night / SVG mode can be enabled only during generation hours.
- During non-generation hours, increase or decrease of reactive power absorption / injection can be done only at inverter HMI during SVG mode.
- Developer was allowed by RLDC to operate as per Q schedule immediately after generation hours and up to start of generation next day instead of 22:30 hrs to 4:00 hrs.

5.5.3 Conclusion & Suggestions:

- Currently night / SVG mode can be enabled only during generation hours.
- At present, active & reactive power can be controlled from SCADA only during generating hours. During SVG mode, SCADA doesn't have any control over inverters. The variation can be done only at inverter HMI during SVC mode.
- Developer was advised to take up with OEM and understand the feasibility of enabling night / SVG mode during non-generation hours also. Similarly, the feasibility of Q control from SCADA to inverter in night mode may be understood.

5.6 Developer 6

5.6.1 Challenges:

- Developer expressed difficulty on joining the exercise immediately from 01.08.2021 due to non-availability of SCADA service engineer. Finally, joined the exercise w.e.f 03.08.2021 for block 1 connected to SS1 with 1MVAr.
- Remaining blocks were having issues in PLC and gateways through which control signals were given. As per their OEM, the manual option of enabling at inverter is not possible directly however the same can be enabled using laptop through a software which can be done only by the service engineer.

5.6.2 Observations:

- As per their OEM, the manual option of enabling at inverter is not possible directly however the same can be enabled using laptop through a software which can be done only by the service engineer. The same can be enabled though SCADA also. Currently the SCADA is unable to communicate with the inverter due to PLC/Gateways.

5.6.3 Conclusion & Suggestions:

- Developer to resolve the PLC and gateways issue at the earliest.
- Once communication issue is solved, then night mode can be enabled.

5.7 Developer 7

5.7.1 Challenges:

- Developer joined the exercise w.e.f 02.08.2021.

5.7.2 Observations:

- Changes in human resources delayed their Joining for the exercise.

- Lower levels of absorption were observed in comparison to schedule.
- No specific constraints were expressed.

5.7.3 Conclusion & Suggestions:

- No specific constraints were expressed.

5.8 Developer 8

5.8.1 Challenges:

- Inverter tripping was noticed and hardware failure indication was observed whenever the 16 MVAr / block absorption was attempted. The issue was taken up with OEMs along with relevant data by the developer. OEM informed that tripping was due to low voltages on AC side of inverters. It was found that AC side, which was rated at 600V, was reaching less than 540V resulting into breaching of 10% margins and causing the tripping of inverters. As a result, lower quantum (12MVAr / block) was being absorbed by developer and has shared the snapshot.

Figure 53 Snap shot of under voltage at inverter during reactive absorption

5.8.2 Observations:

- KSPDCL was requested to carryout tap change whenever voltages were going low during this trial operation. After tap change, developer raised the Q absorption to 16MVAr per 50MW block. The voltages were above 540V and No tripping was observed.
- On a query from the team, whether the 600V / 33kV IDT Tap operations can be done in order to maintain the 600V side voltages, it was informed that IDT is

having off load tap changer. Developer was requested to check with OEM of IDT transformer and power transformer about the feasibility of changing the tap change in night hours. Developer was requested to revert on the same.

- Developer informed that the voltage control mode of operation (during the day time) was implemented on a typical day and observed clipping of real power and hence stopped the operation. Developer informed that if all the developers participate then they may be able to participate and thus resulting into grid discipline related to voltages.

5.8.3 Conclusion and Suggestions:

- Constraint expressed by Developer is actually a voltage constraint and not a hardware issue and inverter was capable of absorbing the required Q.
- Voltage control mode is possible during generation hours and the same was advised to be enabled immediately.

5.9 Developer 9

5.9.1 Challenges:

- Visit was made to understand issues reported and to know how manual Operation was done during the Night Mode Operation. Developer is currently not having the SCADA facility for reactive power control, only manually controlled from each inverter. Reactive power mode / SVG mode is available only in 5 out of 8 blocks.

5.9.2 Observations:

- Reactive power is set at 1MVAr / inverter (51% setting) during the trial period. The strategy of operation is to minimize the No. of inverters considering the manual operation and keep the inverters at around 51% setting in line with the advice by the OEM.
- Developer informed that they are able to provide a Max of 16MVAr / block considering that there are only 16 inverters / block and maximum setting requested by the OEMs & for the better life of the inverter.
- The following sequence of operation was observed for keeping the inverters in night mode:
  a. Inverter is kept in local mode.
  b. SVG mode to be enabled. During enabling of night mode of operation, DC side breaker gets opened and AC side remains connected.
  c. Mode of control is then set to Q control.
  d. Once the DC Side voltage is developed (around 900 Volts), % settings is increased in steps 20%, 40% and 51% to finally absorb 1MVAr.
- The above sequence is followed in all 5 blocks for 16 inverters per block and in the morning the setting is reverted to P control mode of operation

- Inverter can be brought in SVG Mode even during the non-generation hours unlike other developer detailed above.
- Developer informed that they are trying to operationalize SVG mode and its settings through SCADA by making necessary modifications.

Conclusion & Suggestions:

- Night mode can be enabled even after generation hours.
- Current operation of manual control may be thought of controlling through SCADA.

Chapter 6: Active and Reactive power analysis

6.1 Impact on active power consumption during night mode

The forum had advised to analyze the active power consumption without reactive power (Q) absorption and active power consumption with reactive power absorption. This comparison study is expected to give an idea on the additional incremental active power requirement for reactive power absorption during night mode operation. Accordingly, the analysis is carried out and deliberated in the succeeding paragraphs.

The incremental power consumption for night mode operation was treated as regional loss. Block-wise average Auxiliary Power Consumption (APC) of SPDs for the months of May 2021, June 2021 & July 2021 was taken as bench mark APC for computing incremental power consumption on account of night mode operation of inverters for controlling high voltages. The loss is computed at the point of common coupling i.e. 220kV side of POWERGRID Pavagada station.

The inverters enter into sleep mode after generation hours normally however the inverter would be functioning if the night mode is enabled. It is understood that there is a marginal increase in active power consumption after enabling night mode. Further as Q increases active power consumption also increases. It is pertinent to mention that the marginal increase could not be measured because of measurement limitation. The extra consumption was considered as regional loss from 18:00 hrs to 06:30 hrs.

Developer	Total			
	IC	Active power consumption in MWh (at 220kV)		
		Actual during night mode trial period	Adjusted average consumption of SPD	Incremental
Adyah	275	940	240	701
Avaada Solarise	150	546	229	317
Avaada Solar	150	550	147	403
Azure Power	100	158	43	116
FortumSolar	250	1181	242	939
KREDL	50	30	24	5
Parampujya	150	831	127	705
SBG Energy	200	654	221	432
Tata Renewable	250	1095	556	540
01.08.2021 to 30.09.2021	**1575**	**5986**	**1828**	**4157**

Table 24 Active power consumption consumed during trial operation

Total of **4.16 MUs** of energy is spent for this exercise as regional loss for the two months trial period.

Note: * 220kV Line data of PSS3 was replaced with 33kV due to metering issues at 220kV.

6.2 Reactive energy absorbed during night mode

The reactive energy kVARH is worked from the SCADA / manual data submitted by POWERGRID. The MVAr considered for computation is measured at point of interconnection i.e. 220 kV feeder at POWERGRID end.

Period	Reactive Energy Consumed in MVArh	Active Energy Consumed in MWh	MWh per MVArh
01.08.2021 to 30.09.2021	1,64,970	4157	0.025

Table 25 Reactive power absorption during trial operation

Total of **1,64,970 MVArh** of reactive energy was absorbed by Pavagada solar park at Point of Common Coupling (PoC) i.e 220kV end of POWERGRID 400/220kV Pavagada Substation.

Developer wise reactive energy kVARH is worked from the SCADA / Manual data submitted by developers at their end i.e 33kV or 66kV respectively.

Developer	Total			
		Reactive Energy Consumed in MVArh @ 33kv/66kV KSPDCL End	Active Energy Consumed in MWh @ 220kV KSPDCL End	MWh per MVArh @ 33kv/66kV KSPDCL End
Adyah	275	25762	701	0.027
Avaada Solarise	150	12591	317	0.025
Avaada Solar	150	15411	403	0.026
Azure Power	100	8612	116	0.013
FortumSolar	250	42446	939	0.022
KREDL	50	1125	5	0.004
Parampujya	150	12575	705	0.056
SBG Energy	200	17007	432	0.025
Tata Renewable	250	29811	540	0.018
01.08.2021 to 30.09.2021	**1575**	**165339**	**4157**	**0.025**

Table 26 Reactive power absorption during trial operation by developers

6.3 Active power consumption vs. Reactive power in night mode

The auxiliary consumption for the night mode trial period August 2021 and September 2021 is analyzed and plotted below

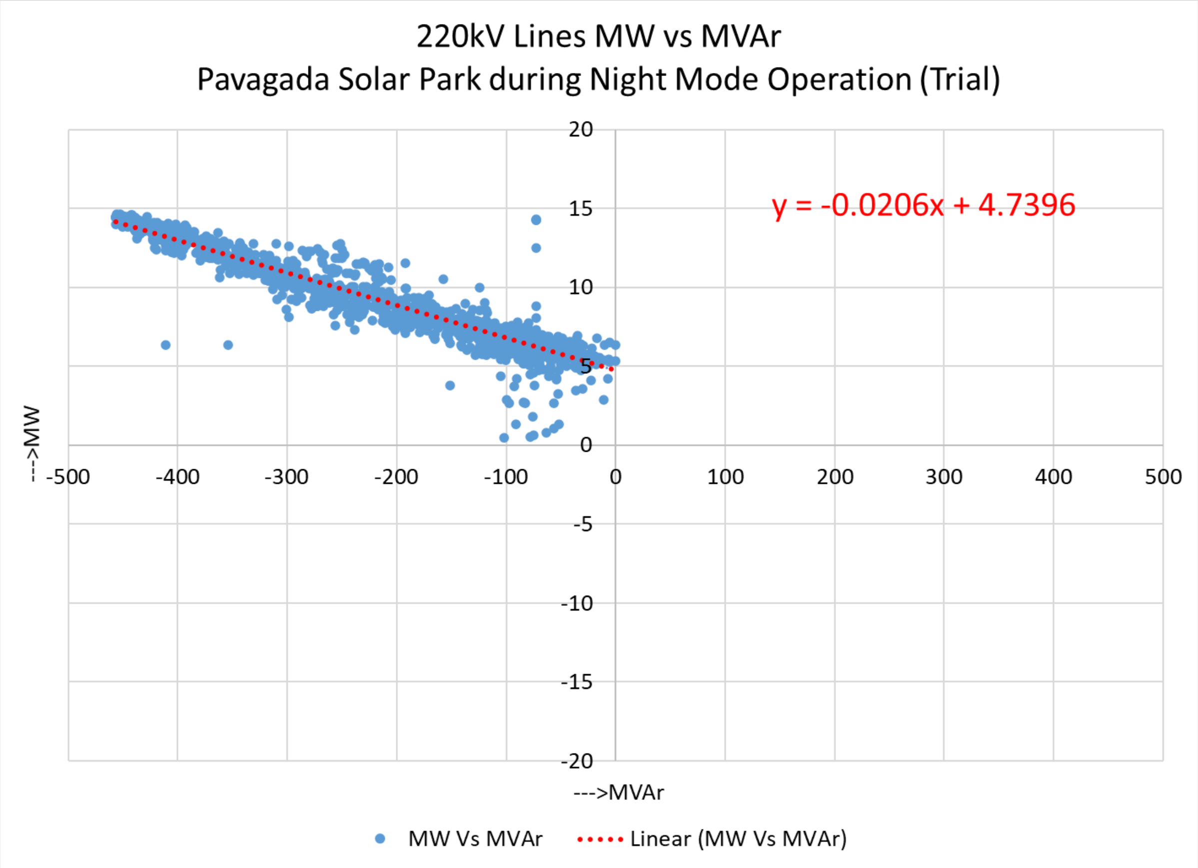


Figure 54 XY plot of Active Power consumption Vs Reactive Power in night mode

The following is observed -

- There is active power consumption of ~4.5 to 5MW active power from the grid by the developers for their auxiliary consumption when not operating in night mode.
- The maximum active power of 14.5MW was consumed from the grid at 220kV level during the trial operation when maximum 456MVAr was absorbed at 220kV level PoC. If the normal consumption is deducted, then the maximum of ~9.8MW was drawn from the grid for the night mode for providing 456MVAr support.
- Approximately 2.1% of active power was consumed for providing the reactive power support by utilizing the night mode / SVG mode of PV inverters during the said period.
- It can be concluded that the active power consumption per 100MVAr of reactive power absorption is in the range of ~2 to 2.5 MW.

6.4 Impact of night mode on manpower and spares

Developers have indicated the following additional expenditure during the interaction.

1. Normally only technician is available at night along with security staff for each 50MW. However, 1or 2 additional executives were posted for each 50MW block during the night mode.
2. Inverters are working for 12 hours in generation and then enter to sleep mode during non-generation hours. However, inverters would be running 24 hours when put in night mode. Hence the periodicity of maintenance may increase and additional spares may be required resulting in increase in maintenance expenditure.

The experiment was conducted for two months and no specific impact could be traced except for few fan failures for which root cause is yet to be established to night mode. There is no history available for long term impact. The annual expected expenditure in terms of maintenance and manpower could not be obtained from the developers considering it as confidential information. Hence the direct impact in rupees per kVArh could not be derived.

Chapter 7: Commercial analysis

7.1 Background

SRLDC presented the draft report on the night mode operation of inverters at Pavagada solar park during the 39th TCC meeting of SRPC which was held on 03.12.2021. During the meeting, it was suggested to SRLDC to work out commercial analysis of Night Mode operation of Inverters in comparison with reactor and STATCOM in association with SRPC and CTU.

The reactive power absorbed in night mode was ~450+MVAr absorption. This is equal to the installation of 4 x 125 MVAr [rated at 420kV] or 500MVAr STATCOM/ Reactor at 400kV Pavagada Substation. It is pertinent to mention that both inverters as well as STATCOM are providing dynamic reactive support whereas shunt reactors are providing fixed reactive support.

Accordingly, SRLDC has sought the following information from CTU.

- Capital Cost of Equivalent 500 MVAr STATCOM
- Annual Fixed Cost of Equivalent 500 MVAr STATCOM
- Active power consumption for Equivalent 500 MVAr STATCOM
- Capital Cost of 125 MVAr Reactor[rated at 420kV]
- Annual Fixed Cost of 125 MVAr Reactor[rated at 420kV]
- Active power consumption for 125 MVAr Reactor[rated at 420kV]

CTU submitted that the information sought was not available with CTU and the following information collected from POWERGRID was sent to SRLDC.

a. POWERGRID does not have the data pertaining to the capital cost of 500 MVAr STATCOM hence data for 300 MVAr STATCOM was submitted as below

Sl. No.	Element	Project name	Capital cost as on COD in Lakhs	Full year AFC for 2018-19 in Lakhs	DOCO	Petition no.	Order date
1	±300 MVAR STATCOM at 400 kV Aurangabad Sub-station	Installation of STATCOMs in Western Region	18674	3313.21	01/04/18	111/TT/2018	1/Nov/19
2	1 no. 400 kV, 125 MVAR Bus Reactor along with associated bay at Banaskantha SS	Green Energy Corridors-Inter State Transmission Scheme (ISTS) Part-B	1618	270.1	29/03/19	113/TT/2019	31/Jan/21

Table 27 Details of cost of STATCOM and Reactor

b. The guaranteed total losses of STATCOM Station is 1% of the Reactive Power Output for the cumulative highest reactive power output of STATCOM station i.e. Max 5 MW for 500 MVAr.
c. The guaranteed total loss of 420kV, 3 Phase 125 MVAr Shunt Reactor is 160 kW.

The guarantee total loss of 420kV, 3 Phase 125 MVAr Shunt Reactor is mentioned in page 279 of CEA Standard Specifications and Technical Parameters for Transformers and Reactors (66 kV & above voltage class) [6] https://cea.nic.in/wp-content/uploads/pse___td/2021/09/Transformer_Manual__Amendment_01.pdf

Accordingly, further analysis is carried out.

7.2 Reactive power testing at Pavagada

A total of **4.16** MUs of energy is spent for this exercise as regional loss for the two months trial period for reactive power absorption of 164970 MVArh. Since the energy is consumed as regional transmission loss, it would be more appropriate to work out based on the frequency rate as per DSM regulations 2014 which works out to ~ ₹ **173.99 Lakhs** for the two months viz ~ ₹ 2.85Lakhs per day for ~450+ MVAr absorption.

The total cost per kVArh without consideration of an increase in cost due to spares and additional manpower if any is $\frac{173.99}{164970} x10000 = $ 10.55 Paisa / kvarh.

Note.

- The average DSM rate during the trial period was 4.18 Rs/kwh., accordingly the 10.55 Paisa / kvarh was the expenditure. The expenditure 10.55 Paisa / kvarh may reduce or increase depending on the DSM rate during the period of usage.
- No explicit fixed cost incurred for operating inverters in night mode.

7.3 Equivalent bus reactor.

The reactive power absorbed in night mode was ~450MVAr absorption. This is equal to the installation of 4 x 125 MVAr reactor [rated at 420kV] at 400kV bus at Pavagada.

A. Capital Cost

The capital cost of a 125 MVAr bus reactor at 420kV is ₹1616 lakhs (as on COD filed in Petition No 113/TT/2019). Hence the capital cost of bus reactor for 500MVAr (4 x 125 MVAr) at 420kV reactor = 4 x 1618 Lakhs = ₹ **6472 Lakhs.**

Source:[7] https://cercind.gov.in/2021/orders/113-TT-2019.pdf

B. Annual Fixed Charges

The annual fixed cost of a 125 MVAr [rated at 420kV] Bus Reactor at 400kV is ₹270.1 Lakhs (as on COD filed in Petition No 113/TT/2019). Hence the annual fixed cost of bus reactor for 500MVAr (4 x 125 MVAr) at 420kV reactor = 4 x 270.1 Lakhs = ₹ **1080.4 Lakhs**.

Source: [7] https://cercind.gov.in/2021/orders/113-TT-2019.pdf

The fixed cost for two months trial operation would have been $\frac{1080.4}{12} * 2 =$ ₹ **180.06 Lakhs**

C. Losses

The guaranteed total loss of 420kV, 3 Phase 125 MVAr Shunt Reactor as per CTU/POWERGRID and CEA Standard Specifications and Technical Parameters for Transformers and Reactors (66 kV & above voltage class) is 160 kW. Hence the total losses of bus reactor for 500MVAr (4 x 125 MVAr) at 400kV bus = 4 x 160 kW = 640 kW.

The active power consumed for two months trial operation for 5.5 Hours (22:30 Hrs to 04:00 Hrs) would be 0.64 * 5.5 * 61 = 214.72Mwh. Considering the average DSM cost of 4.18 Rs/kwh, the expenditure works out to ₹ **8.98 Lakhs**

7.4 Equivalent STATCOM.

The reactive power absorbed in night mode was ~450MVAr absorption. This is equal to the installation of 500 MVAr STATCOM at 400kV bus at Pavagada. Currently CTU/POWERGRID do not have data pertaining to capital cost of 500 MVAr STATCOM and submitted the information for ±300 MVAr STATCOM at 400kV Aurangabad Substation based on information filed in 111/TT/2018(as on COD date). Further it is noted that the information pertaining to ±200 MVAr STATCOM at 400kV Gwalior Substation is also available in the same order *[8]* *https://cercind.gov.in/2019/orders/111.pdf*

A. Capital Cost

The capital cost of a 300 MVAr STATCOM at 400kV is ₹18674 lakhs (as on COD filed in Petition No 111/TT/2018) and the capital cost of a 200 MVAr STATCOM at 400kV is ₹14311 lakhs (as on COD filed in Petition No 111/TT/2018). Hence the capital cost of bus STATCOM for 500MVAr (300 MVAr + 200 MVAr) at 400kV = 18674+14311 Lakhs = **₹ 32985 Lakhs**.

B. Annual Fixed Charges

The annual fixed cost of a 300 MVAr STATCOM at 400kV is ₹3313.21 lakhs (as on COD filed in Petition No 111/TT/2018) and annual fixed cost of a 200 MVAr STATCOM at 400kV is ₹2560.96 lakhs (as on COD filed in Petition No 111/TT/2018). Hence the annual fixed cost of STATCOM for 500MVAr (300 MVAr + 200 MVAr) at 400kV = 3313.21 +2560.96 Lakhs = **₹ 5874.17 Lakhs.**

The fixed cost for two months trial operation would have been $\frac{5874.17}{12} * 2 =$ ₹ **979.02 Lakhs**

C. Losses

The guaranteed total losses of STATCOM Station as per CTU/POWERGRID is 1% of the Reactive Power Output for the cumulative highest reactive power output of STATCOM station i.e. Max 5 MW for 500 MVAr

The active power consumed for two months trial operation for 5.5 Hours (22:30 Hrs to 04:00 Hrs) would be 5 * 5.5 * 61 = 1677.5 Mwh. Considering the average DSM cost of 4.18 Rs/kwh, the expenditure works out to ₹ **70.12 Lakhs**

7.5 Summary.

The cost and losses for night mode, reactor and STATCOM is summarised below

Sl No	Description	Night Mode for 450+ MVAr	Equivalent 4 x 125 MVAr Reactor	Equivalent 500 (300+200) MVAr STATCOM
1.	Capital Cost	Nil	₹ 6472 Lakhs	₹ 32985 Lakhs
2.	Annual Fixed Cost	Additional costs due to spares and additional manpower could be there.	₹ 1080.4 Lakhs	₹ 5874.17 Lakhs
3.	Losses	~10 MW	640kW	5 MW
4	Fixed charges for two months pilot project (excluding spares and man power)	Costs due to spares and additional manpower was not envisaged for the exercise. However notional cost is worked out and shown below*	180.06 Lakhs	979.02 Lakhs
5	Cost for the active energy for two months pilot project	*173.99 Lakhs	8.98 Lakhs	70.12 Lakhs

Table 28 Summary of commercial analysis of night mode, STATCOM and reactor

Note

- SVC and Synchronous condenser are not compared.
- *The night mode of 450+ MVAr was from 22:30 to 04:00 Hrs. Around 100+ MVAr out of 450+ MVAr was operating from the start of non-generation hours viz appx 18:00 Hrs till 06:30 Hrs. Whereas reactor and STATCOM are considered for 5.5 Hours (22:30 to 04:00 Hrs) only
- POSOCO report on Reactive Power Management and Voltage Control Ancillary Services (VCAS) submitted to Hon'ble CERC in India [4] https://posoco.in/wp-content/uploads/2021/08/Reactive_Power_VCAS_CERC_22Mar2021-002.pdf mentions typical cost of operating solar inverters in SVC mode during "no generation" period: Additional maintenance cost = ₹ 0.02 / kVArh. If 50% of the same i.e ₹ 0.01 / kVArh was considered as notionally incurred for maintenance charges. The notional payment would have been $\frac{164970}{100000} x 1000\ x\ 0.01 = 16.5$ lakhs. This is in addition to absorbing real power consumed for reactive power support as region loss.
- Further POSOCO has submitted it suggestions on CERC (Draft) Ancillary Services Regulations, 2021 emphasising the introduction of Voltage Control

Ancillary Services (VCAS) in India
[8]https://cercind.gov.in/2021/draft_reg/comment_ASR/50.%20POSOCO-Comments-draft-AS-15.07.2021.pdf . The feedback w.r.t reactive power support by RE is detailed below

- Charge for VArh was suggested at the rate 5 paise/kVArh w.e.f. 1st January 2022 and to be reviewed periodically by the Commission. Any shortfall or surplus in the Reactive Energy Pool Account would be adjusted on quarterly basis through the Monthly Transmission Charges (MTC) as per the CERC (Sharing of Inter State Transmission Charges and Losses) Regulations 2020.
- All the Inverter Based Resources (IBRs) covering wind, solar and energy storage would need to ensure that they have the necessary capability all the time including night hours for solar. The active power consumed by these devices when operating under night-mode, would be treated as transmission losses in the ISTS. For IBRs of capacity 50 MW and below not coming directly to the point of interconnection but through the pooling at the Power Park Developer end, the Power Park Developer would act as aggregator for the Reactive Energy Charges for payments to and fro from the Pool Account at RLDC level. The de-pooling of Reactive Energy charges amongst the individual wind and solar would be done by the Power Park Developer."

Chapter 8: Summary of Observations

A. Reactive power capability

i. Inverters are having reactive capability of 33%, 66% and 88%, or in some cases up to 100% of active power, depending upon the manufacturer and model.

ii. 986MVAr dynamic reactive capability is available in the PV inverters at Pavagada Ultra Mega Solar Park.

iii. Night mode facility is available in 1575MW out of 2050MW installed capacity.

iv. Maximum of 456MVAr reactive absorption has been observed at 220kV end of POWERGRID 400/220kV Pavagada Sub-station during the trial period from 01.08.2021 to 30.09.2021.

B. Enabling night mode / SVG mode feature and reactive power set point control

i. For 775MW having reactive power capability of 441.5MVAr the night mode / Static VAR Generator feature can be enabled during generation hours only and cannot be enabled during non-generation hours. Whereas night mode / SVG feature can be enabled at any time of the day for 800MW of installed capacity of inverters having reactive capability of 544.5MVAr.

ii. In some of the inverters, reactive power can be controlled remotely by SCADA, only during generation hours. However during night mode / SVG mode, inverters could not be controlled remotely by SCADA and could be controlled at inverter HMI only. The issue has been resolved subsequently.

C. Factors affecting reactive absorption during the trial period

i. The planned / forced maintenance of shutdown of 33 or 66kV sub-station / line has limited the reactive absorption on some of the days. This is due to the fact that certain inverters can be enabled only in generation hours.

ii. Some of the inverters were showing hardware failure alarm and tripping after 4 MVAr per feeder although higher capability was available. Similarly, some of the inverters were tripping with an alarm indication as current unbalanced fault. Root cause analysis indicated that the tripping were due to inverter LV voltage touching the low voltage limit of -10%. Hence the alarm and tripping reasons may need to be re-checked to get confidence on the alarm and reasons for the alarm.

iii. One of the developer had orally expressed the observation of abnormal increase in fan speed and fan failure. There was no root cause analysis which pointed out fan failure to night mode. Developer was not able to demonstrate the abnormal fan speed during the team visit on 25.08.2021. However, fan quality needs to be ensured by the OEM and proper root because analysis needs to be carried out.

iv. Low voltage at LV side of the inverter were encountered due to increase in MVAr absorption.

v. Communication issues were reported by developers having string inverters. The issue was expected to overcome after implementation of PPC.
vi. Delay in getting the OEM consent for the test.

D. Auxiliary Consumption

i. The inverters enter into sleep mode after generation hours normally however the inverter would be functioning if the night mode is enabled. It is understood that there is a marginal increase in active power consumption after enabling night mode. Further as Q increases active power consumption also increases. It is pertinent to mention that the marginal increase could not be measured because of measurement limitation at inverter level.
ii. It is understood that normally OEM indicates the normal auxiliary consumption without the night mode feature enabled. There is no mention of auxiliary consumption with the night mode feature in technical manuals.
iii. A total of 4.16MUs of energy has been consumed for this exercise which was included in regional loss during the two months trial period.

E. Reactive Energy

i. Maximum reactive power absorption of 456MVAr was observed at 220kV end of POWERGRID 400/220kV Pavagada sub-station during the trial period from 01.08.2021 to 30.09.2021 which is almost equivalent to 4 x 125MVAr reactors.
ii. Total of 1,64,970MVArh of reactive energy was absorbed by Pavagada solar park at Point of Common Coupling (PoC) i.e. 220kV end of POWERGRID 400/220kV Pavagada sub-station.
iii. There was active power consumption of ~4.5 to 5MW from the grid by the Solar Power Developers (SPD) for their auxiliary consumption when not operating in night mode.
iv. The maximum active power of 14.5MW was consumed from the grid at 220kV level during the trial operation when maximum 456MVAr was absorbed at 220kV level PoC. Additional power consumption of ~9.8W was drawn from the grid, excluding power consumption during normal operation, for the night mode for providing 456MVAr.
v. The active power consumption per 100MVAr of reactive power absorption is in the range of ~2 to 2.5 MW which is ~2% to 2.5%.

F. Commercial Analysis

iii. **Impact of active energy loss**: A total of 4.16 MUs of energy is spent for this exercise as regional transmission loss for reactive power absorption of 164970 MVArh. The cost based on frequency rate as per DSM regulations 2014 works out to ~ ₹ 173.99 Lakhs for the two months viz ~ ₹ 2.85Lakhs per day for ~450+ MVAr absorption.
iv. **Impact on Annual Maintenance Cost:** The following was understood from the developers / OEM orally.

a. Normally only technician is available at night along with security staff for each 50MW. However, 1or 2 additional executives were posted for each 50 MW block during the night mode.
b. Inverters are operating for 12 hours in generation and then enter to sleep mode during non-generation hours. However, inverters would be running continuously for 24 hours when inverters are put in night mode. Hence the periodicity of maintenance may increase and additional spares may be required resulting in increase in maintenance expenditure.
c. No specific impact could be traced, except for few cooling fan failures for which root cause is yet to be established to this night mode exercise and there is no history available for long term impact analysis. The annual expected expenditure in terms of maintenance and manpower could not be obtained from the developers considering it as confidential information.
d. POSOCO report on Reactive Power Management and Voltage Control Ancillary Services (VCAS)[4] mentions typical additional maintenance cost of ₹ 0.02 / kVArh for operating solar inverters in SVC mode during "no generation" period. This is in addition to absorbing real power consumed for reactive power support as region loss.
e. Further POSOCO has suggested 5 paise/kVArh in the feedback on CERC (Draft) Ancillary Services Regulations, 2021 while emphasising the introduction of Voltage Control Ancillary Services (VCAS) in India [5]. POSOCO suggestions regarding the reactive power capabilities w.r.t RE is summarised in section **7.5.** This is in addition to absorbing real power consumed for reactive power support as region loss

iii. **Cost analysis with other reactive sources:** The cost of equivalent reactive sources both dynamic reactive sources viz STATCOM and fixed reactive source bus reactor is deliberated in section **7.5.**

G. High Voltages of PSS could effectively be controlled with the reactive capability using night mode of Inverters. This helps in reducing line openings. It was observed that all lines at 400kV Pavagada were in closed condition during this experiment period except on few occasions which was due to issues at other connected station.

H. Apprehension was expressed about life of the inverters / components by developers as there was no historical record. However, this experiment has indicated enough confidence.

Chapter 9: Way Forward

A. With huge amount of RE plants in pipeline, dynamic Reactive capability available at all RE plants needs to be harnessed.

B. The SVG / Night mode facility of PV inverters can be utilized by specifying a suitable mechanism for the following.

   i. Compensation for incremental real power consumed during the night mode / SVG operation of plant for reactive support.

   ii. Compensation to cover increased annual maintenance in the form of additional manpower, spares, increased frequency of maintenance etc.

C. SVG / Night mode feature may be made mandatory by including the requirement of facility in the CEA Technical Standards for Connectivity.

D. Developers may define the performance guarantee clause & the warranty period for SVG / Night mode operation. The developers may mention the requirement in their bidding as well mandate OEMs to necessarily demonstrate the capability as part of commissioning test.

E. All the alarm and tripping settings may need to be rechecked for correct indication.

F. The provision of 'night mode' operation whereby the inverters can act as STATCOM have been successfully demonstrated in field trials carried out by SRLDC at Pavagada solar park. The provision of voltage control ancillary services by renewables through var control may enable enhanced grid support. POSOCO has submitted a report on Reactive Power Management and Voltage Control Ancillary Services (VCAS) in India to Hon'ble CERC[4]. Further POSOCO has submitted it suggestions on CERC (Draft) Ancillary Services Regulations, 2021 emphasising the introduction of Voltage Control Ancillary Services (VCAS) in India [5]. Hence Voltage Control Ancillary Services (VCAS) framework, whereby the night mode operation of inverters is incentivised, needs to be enabled at the earliest.

Chapter 10: References

1. CEA (Technical Standards for Connectivity to the Grid) Amendment Regulations, 2013 https://cea.nic.in/wp-content/uploads/2020/02/grid_connectivity_12112013.pdf
2. SRPC Record Notes of the Special Meeting on Utilization of inverters at Solar Parks in night mode for controlling high voltages http://www.srpc.kar.nic.in/website/2021/meetings/special/rnsplnightmode-270721.pdf
3. KSPDCL http://www.kspdcl.in/sp_docs/Rev-4%20Layout%20plan.pdf
4. POSOCO discussion paper on Reactive Power Management and Voltage Control Ancillary Services (VCAS) in India https://posoco.in/wp-content/uploads/2021/08/Reactive_Power_VCAS_CERC_22Mar2021-002.pdf
5. POSOCO Suggestions on CERC (Draft) Ancillary Services Regulations, 2021https://cercind.gov.in/2021/draft_reg/comment_ASR/50.%20POSOCO-Comments-draft-AS-15.07.2021.pdf
6. CEA Standard Specifications and Technical Parameters for Transformers and Reactors (66 kV & above voltage class) https://cea.nic.in/wp-content/uploads/pse___td/2021/09/Transformer_Manual__Amendment_01.pdf
7. Bus Reactor Tariff Order https://cercind.gov.in/2021/orders/113-TT-2019.pdf
8. STATCOM Tariff order https://cercind.gov.in/2019/orders/111.pdf

Annexures

Annexure - 1 List of nominated nodal Officers

Nodal Officer	Name
SRLDC	
REMC HoD	Sh M.K.Ramesh, Senior General Manager
Main Officer	Sh Venkateshan.M, Deputy General Manager
Alternate Officers	• Ms Anusha Baruah, Chief Manager • Sh M V Pradeep Reddy, Assistant Manager • Sh Raj Ranjan, Assistant Manager • Sh Heet Unadkat, Assistant Manager • Sh Vinay Kumar Yadav, Executive Trainee
KSPDCL	
Main Officer	Sh Amarnath, DGM
Alternate Officers	• Sh Prakash, DGM • Sh Mahesh, AGM
Developers	

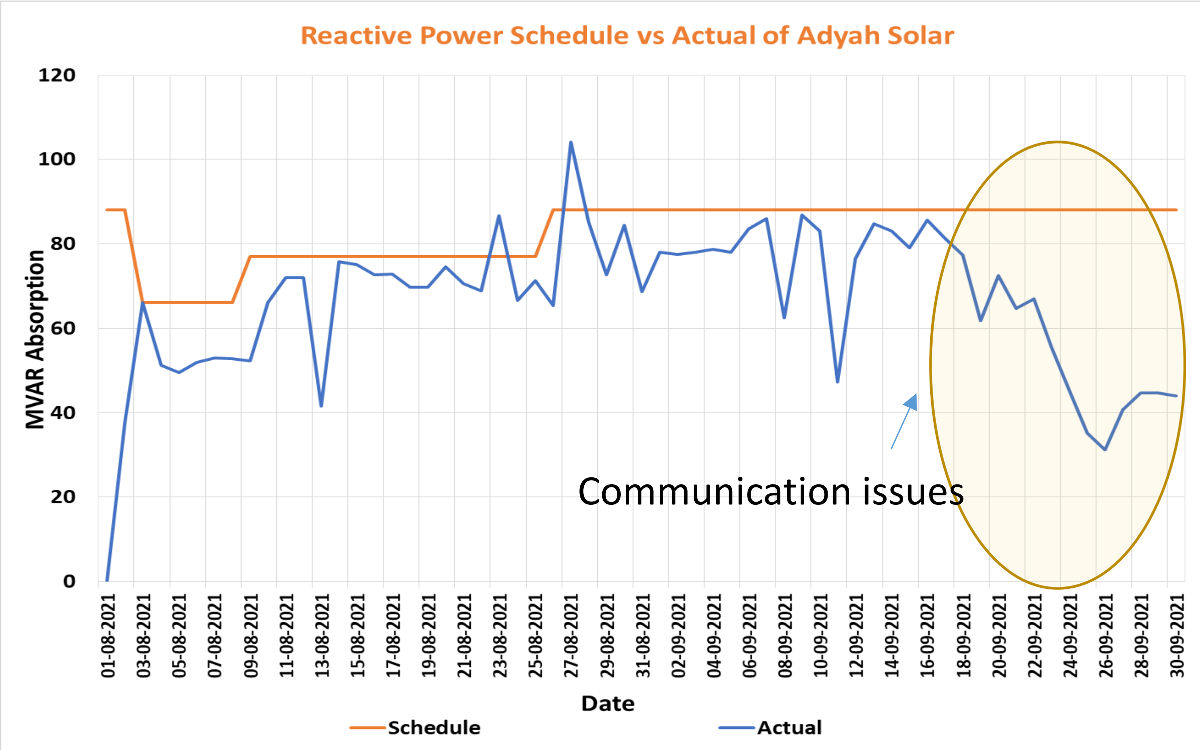
Block No	Developer		Officer Name
1	Adyah	Main Officer	Sh Raghunath, Deputy Manager
2			
3			
6		Alternate Officer	Sh Rajesh Poosa, Deputy Manager
10			
13			
4	Avaada Solar	Main Officer	Sh Nalluri Bhargav, Manager
7			
8		Alternate Officer	Sh Nalluri Bhargav, Manager
5	Fortum Solar	Main Officer	Sh Prabhu Ramasamy,AGM
9			
14			
20		Alternate Officer	Sh Ankur Singh, Deputy Manager
40			
11	Azure Power	Main Officer	Sh Shaik Johny Basha, Senior Engineer
12	Azure Power	Alternate Officer	Sh Prakash, Senior Engineer
15	TATA Renewable	Main Officer	Sh Revanth, Lead Engineer
17			
18		1st Alternate Officer	Sh Varuna, Lead Engineer
19			
21		2nd Alternate Officer	Sh Rutik Raul, Lead Engineer
22	Avaada Solarise	Main Officer	Sh Lakshman Naidu, Deputy Manager
		Alternate Officer	Sh Lakshman Naidu, Deputy Manager

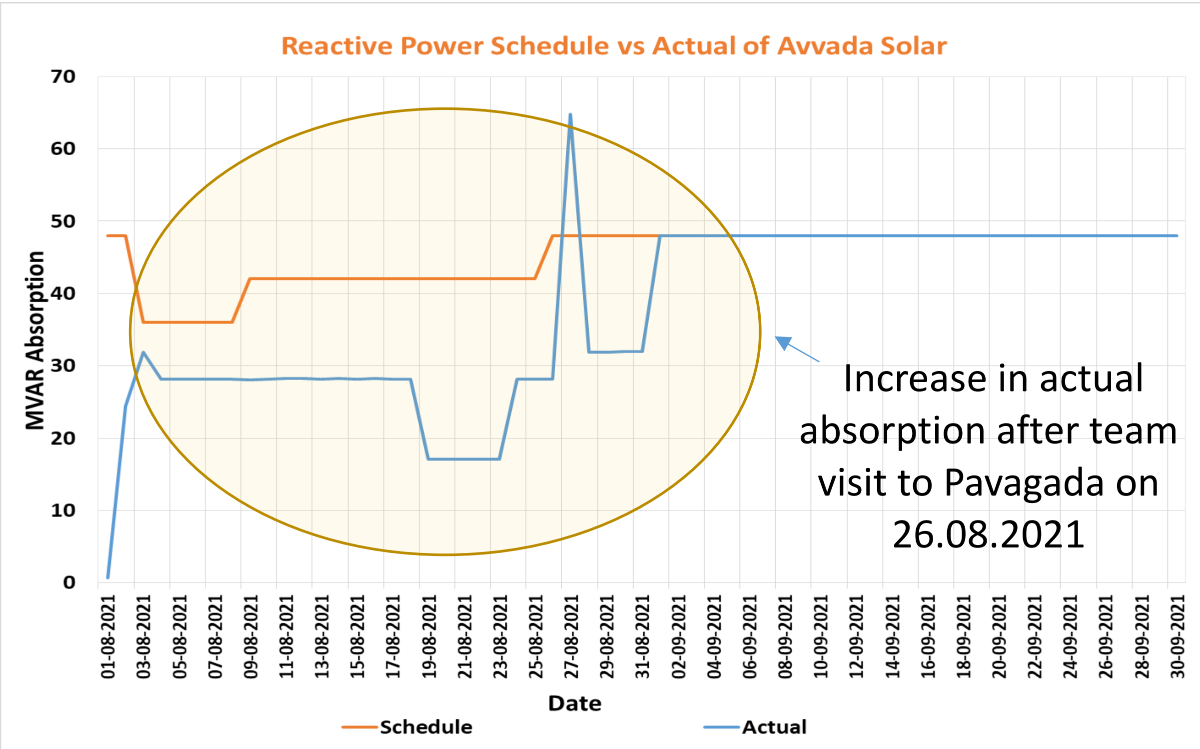
Nodal Officer		Name	
39	Avaada Solarise	Main Officer	Sh C.Mounish, Deputy Manager
40 A		Alternate Officer	Sh Venkataram Reddy, Deputy Manager
23	Soft Bank	Main Officer	Sh Puchakayala Venkateswarlu, Deputy Manager
24			
25		Alternate Officer	Sh Valliappan, Senior Engineer
26			

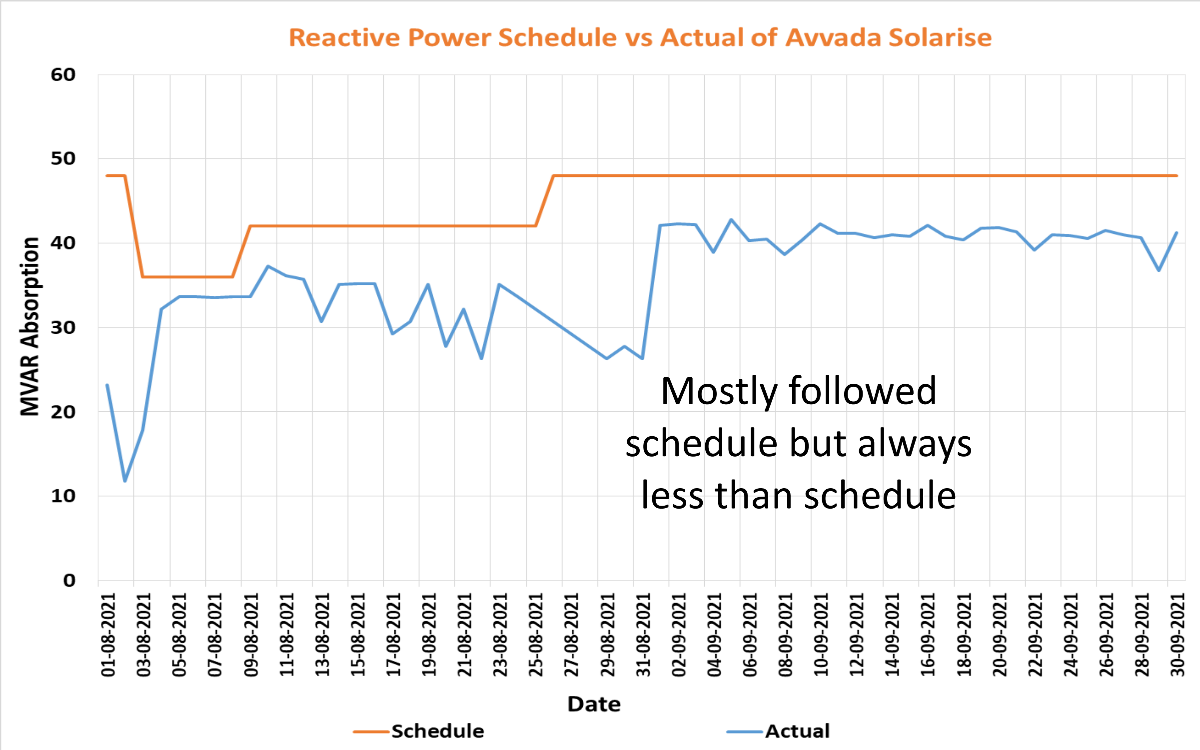
Annexure - 2 Committee

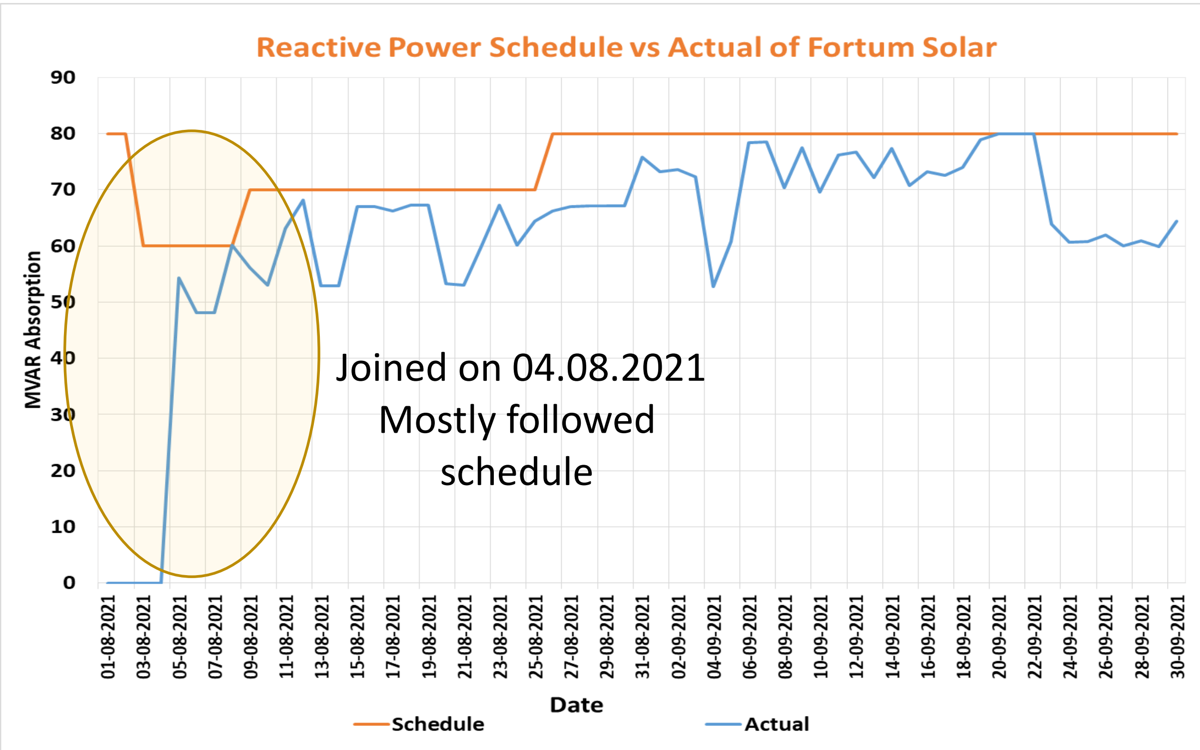
Name	Designation
SRLDC	
V Suresh	Executive Director
Sh M.K.Ramesh	Senior general Manager
Sh Venkateshan.M	Deputy General Manager
Sh Heet Unadkat	Assistant Manager
Sh Vinay Kumar Yadav	Executive Trainee
SRPC	
Sh A.C.Suresh	Executive Engineer(Commercial)
Sh Kesavan.A	Executive Engineer (Operation & Communication)
Ms Anusha Das	Executive Engineer(Commercial)
KSPDCL	
Sh Amarnath	Deputy General Manager
Sh Mahesh	Assistant General Manager
Telangana	
Sh C Mallikarjuna Chander	Divisional Engineer (RE-II),TS SLDC
Sh Sunil Kumar	Divisional Engineer, TS SPDCL
Sh N Rajasekhar	Assistant Engineer, TS SLDC

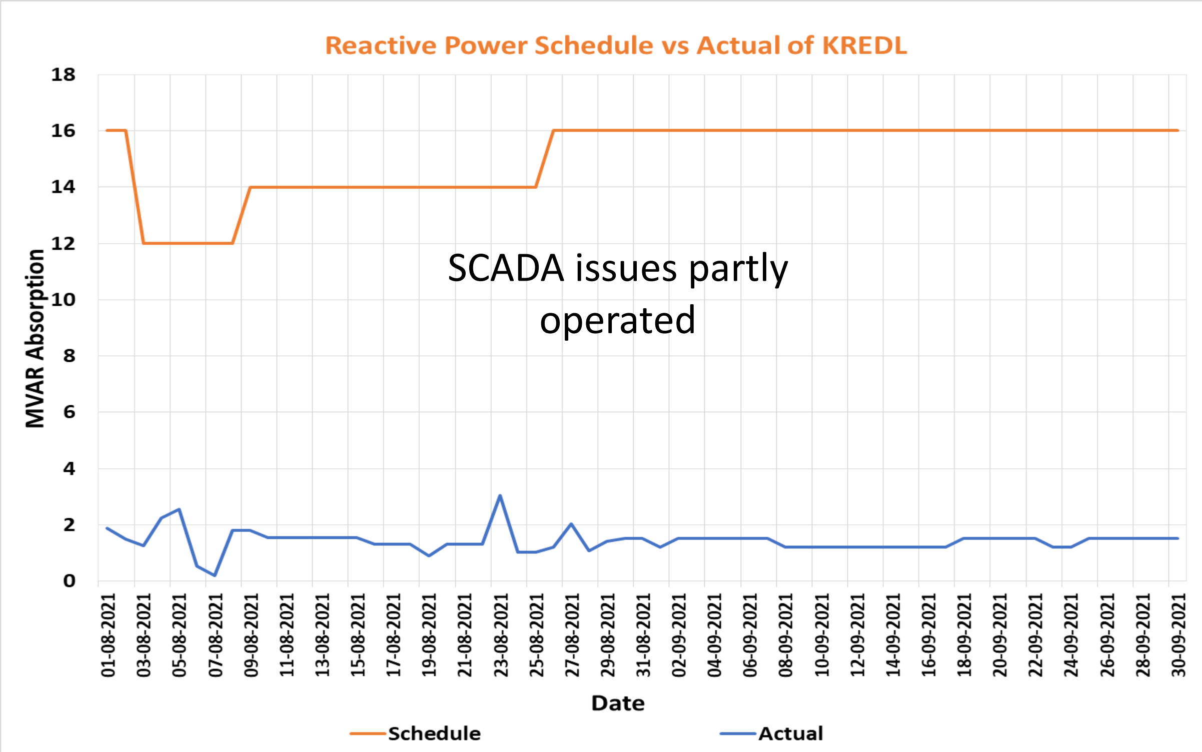
Annexure – 3 Reactive power absorption schedule vs actual

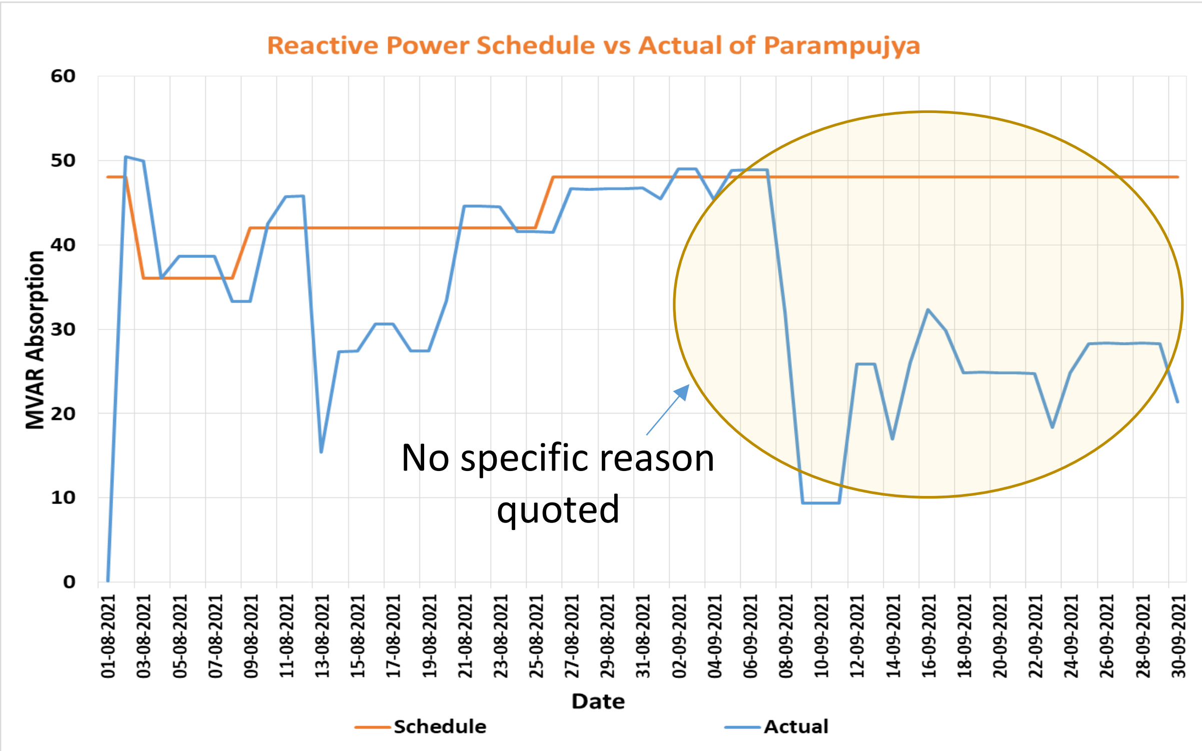


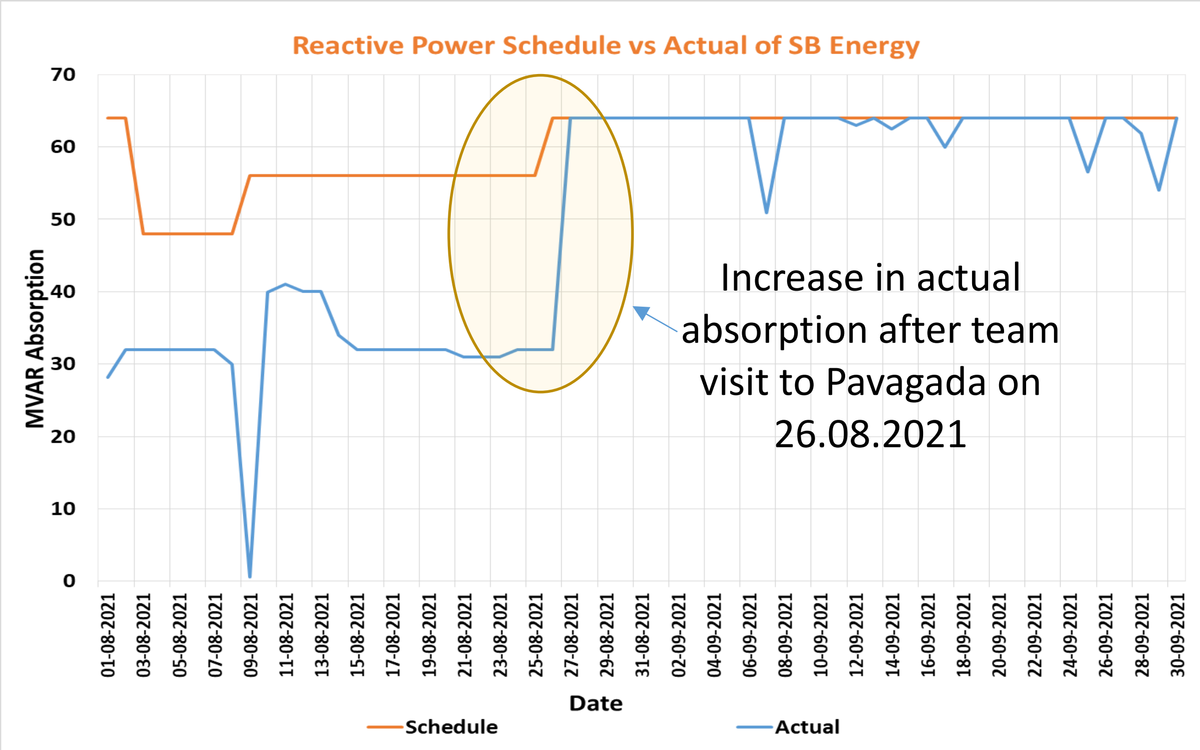


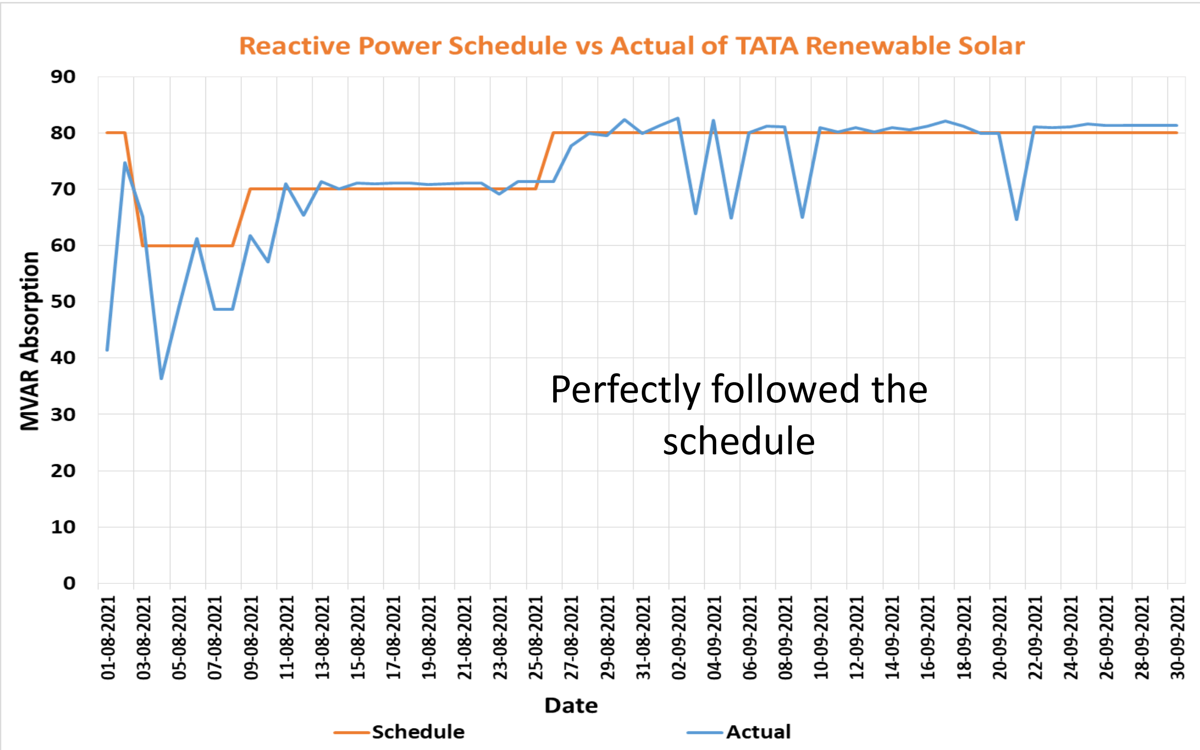

Reactive Power Schedule vs Actual of Avvada Solarise
MVAR Absorption
Date
Schedule
Actual
Mostly followed schedule but always less than schedule

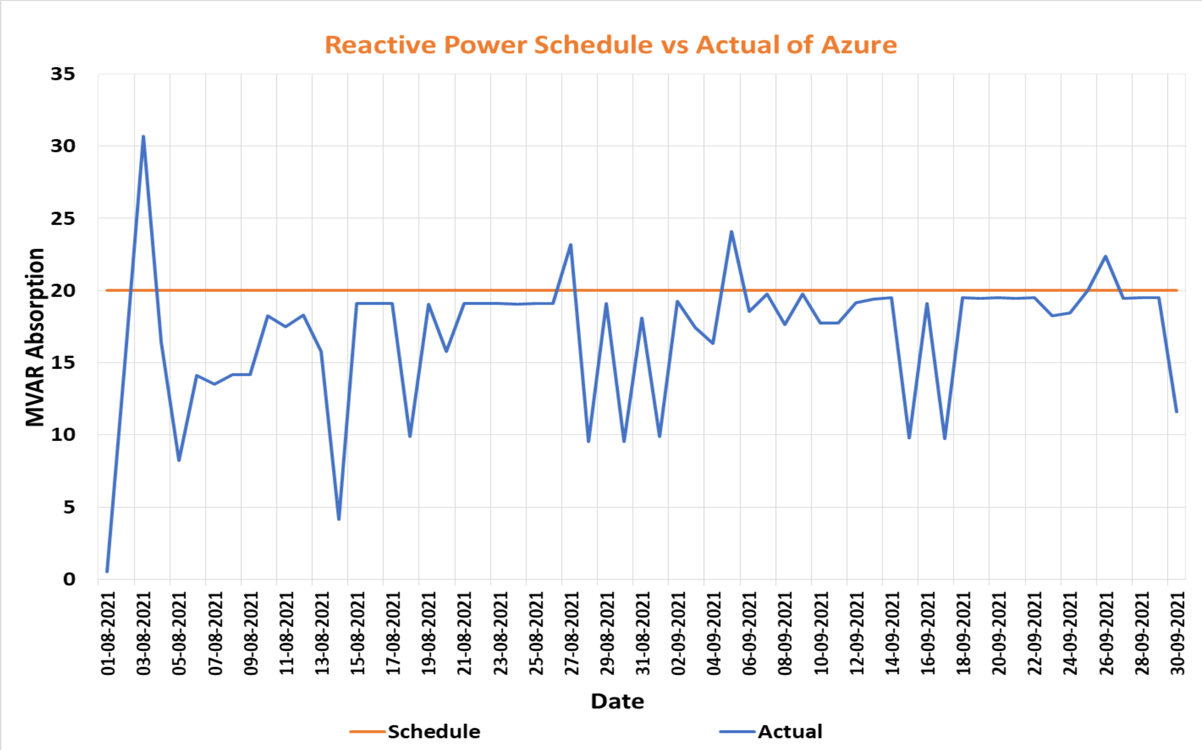

Reactive Power Schedule vs Actual of Fortum Solar
MVAR Absorption
Date
Schedule
Actual
Joined on 04.08.2021 Mostly followed schedule

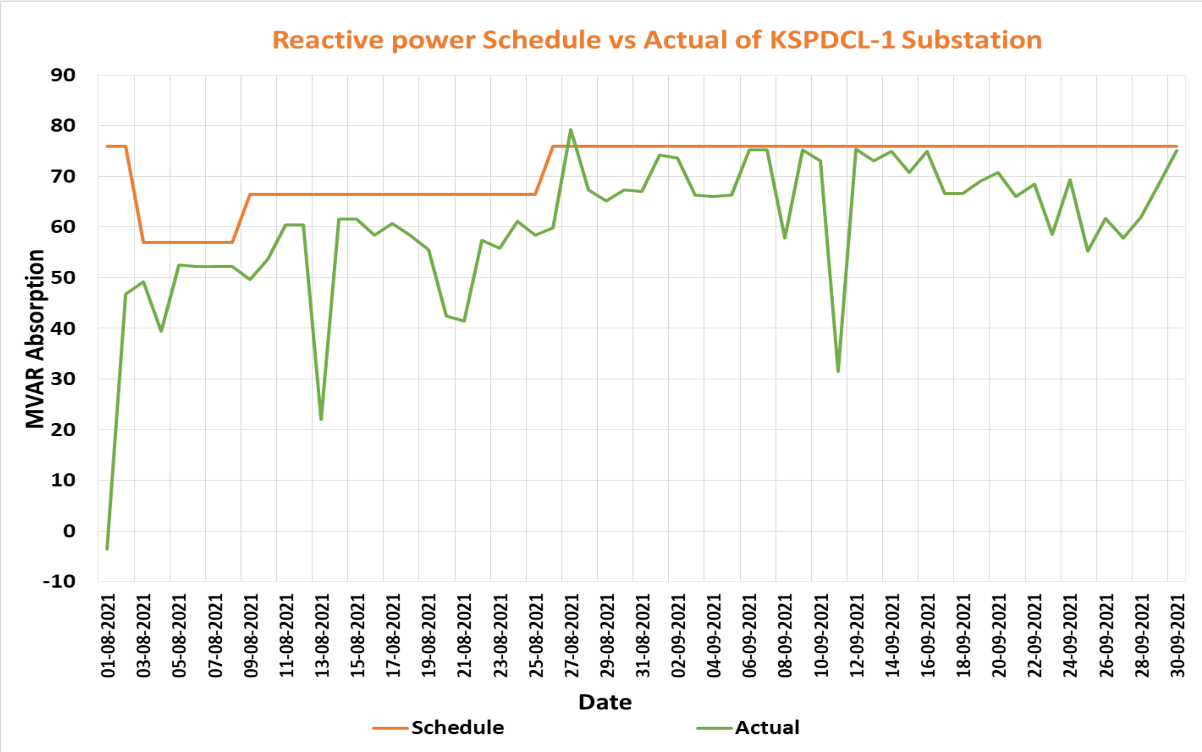

Reactive Power Schedule vs Actual of KREDL
MVAR Absorption
Date
SCADA issues partly operated
Schedule
Actual

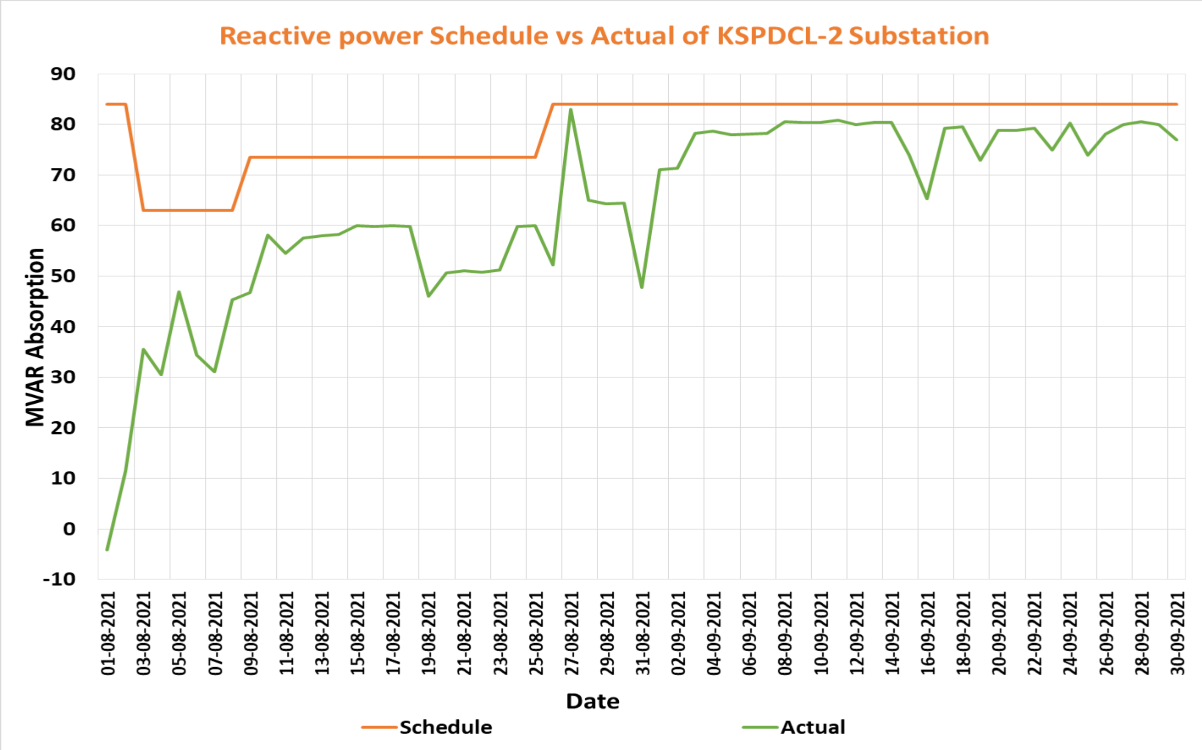

Reactive Power Schedule vs Actual of Parampujya
MVAR Absorption
Date
No specific reason quoted
Schedule
Actual

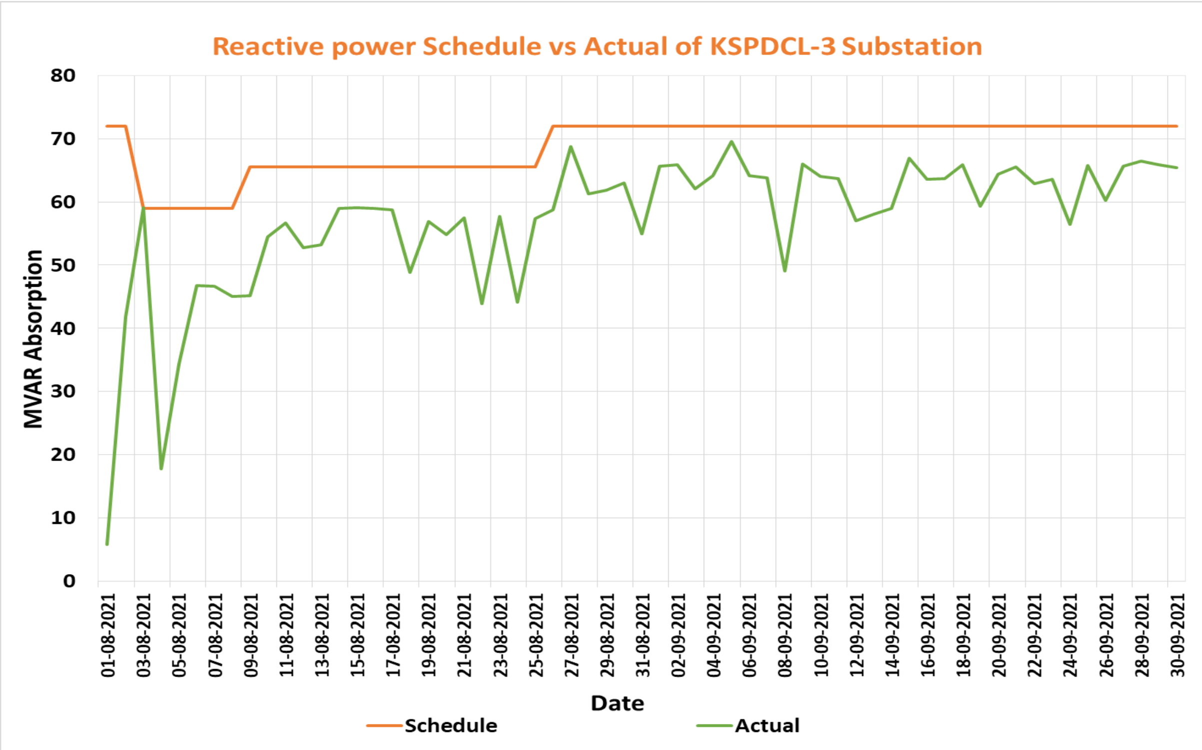

Reactive Power Schedule vs Actual of SB Energy
MVAR Absorption
Date
Schedule
Actual
Increase in actual absorption after team visit to Pavagada on 26.08.2021

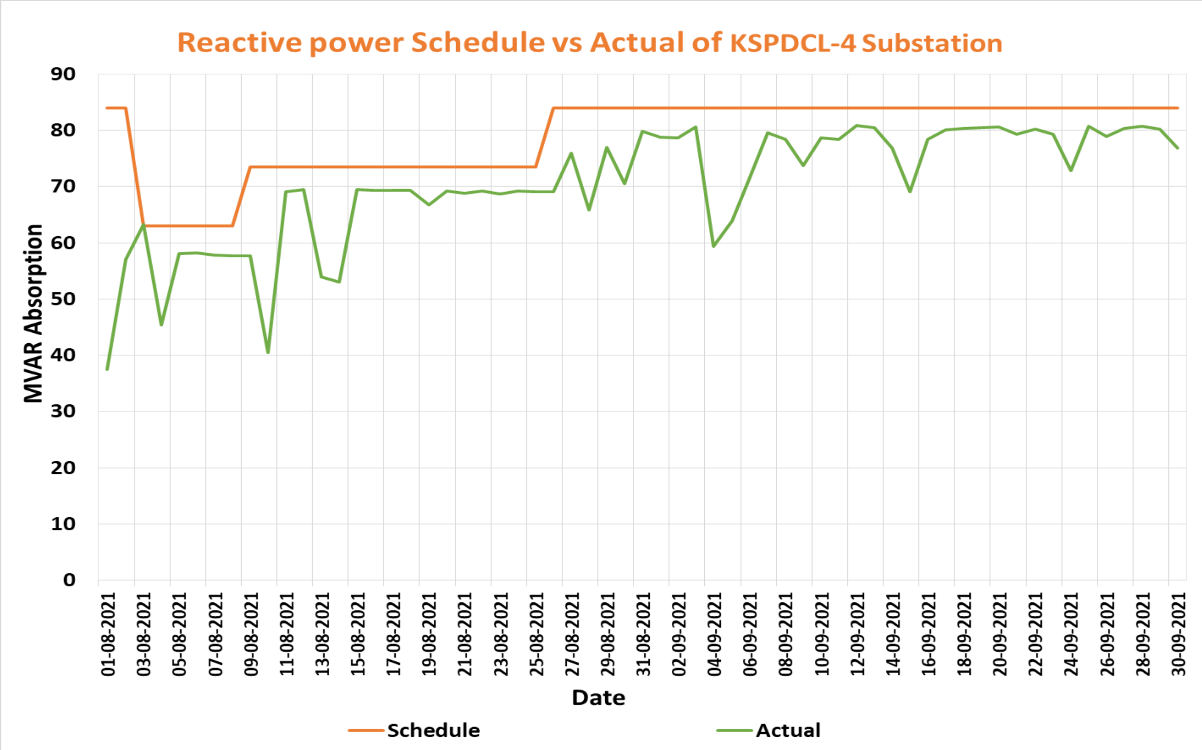

Reactive Power Schedule vs Actual of TATA Renewable Solar
MVAR Absorption
Date
Schedule
Actual
Perfectly followed the schedule


Reactive Power Schedule vs Actual of Azure
MVAR Absorption
Date
Schedule
Actual


Reactive power Schedule vs Actual of KSPDCL-1 Substation
MVAR Absorption
Date
Schedule
Actual


Reactive power Schedule vs Actual of KSPDCL-2 Substation
MVAR Absorption
Date
Schedule
Actual


Reactive power Schedule vs Actual of KSPDCL-3 Substation
MVAR Absorption
Date
Schedule
Actual


Reactive power Schedule vs Actual of KSPDCL-4 Substation
MVAR Absorption
90
80
70
60
50
40
30
20
10
0
01-08-2021
03-08-2021
05-08-2021
07-08-2021
09-08-2021
11-08-2021
13-08-2021
15-08-2021
17-08-2021
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18-09-2021
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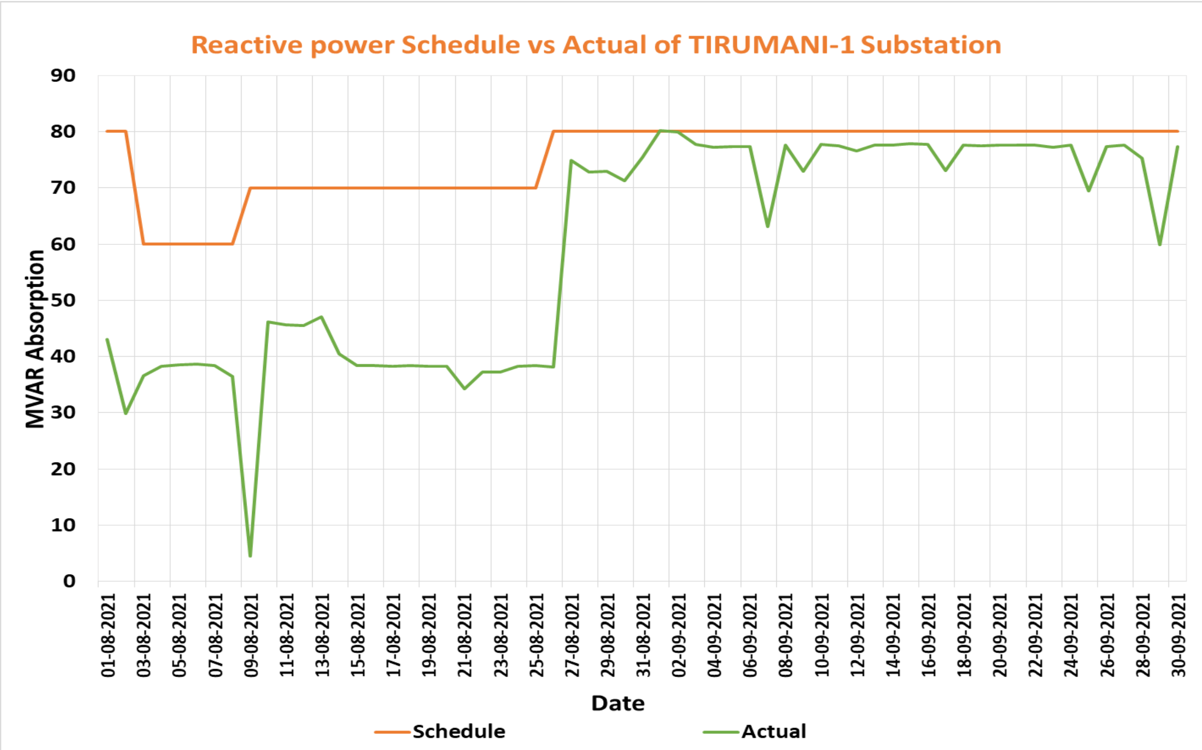
30-09-2021
Date
Schedule
Actual


Reactive power Schedule vs Actual of TIRUMANI-1 Substation
MVAR Absorption
90
80
70
60
50
40
30
20
10
0
01-08-2021
03-08-2021
05-08-2021
07-08-2021
09-08-2021
11-08-2021
13-08-2021
15-08-2021
17-08-2021
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18-09-2021
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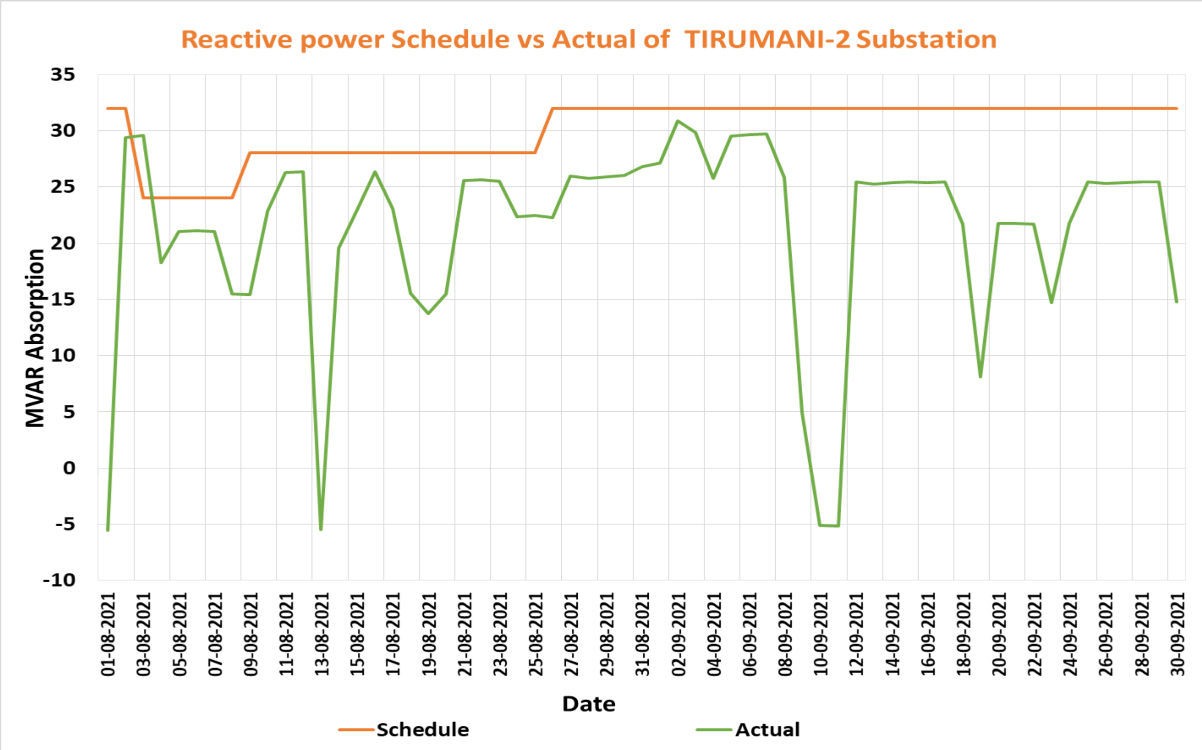
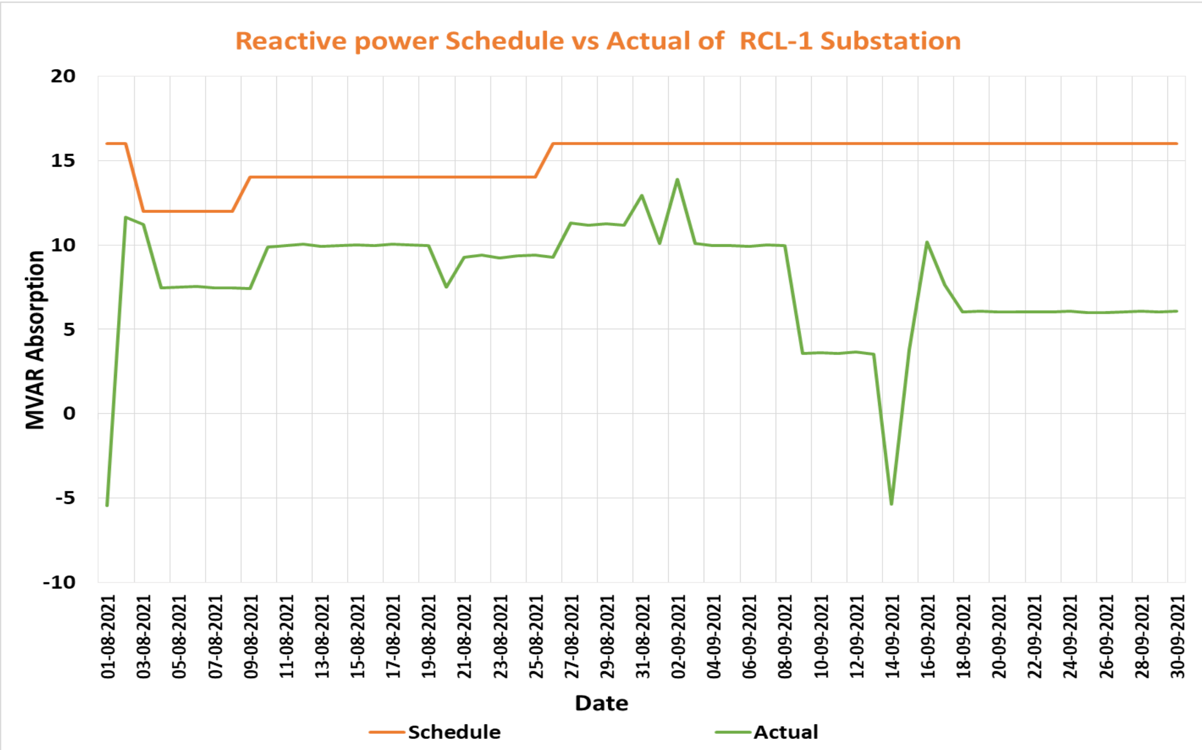
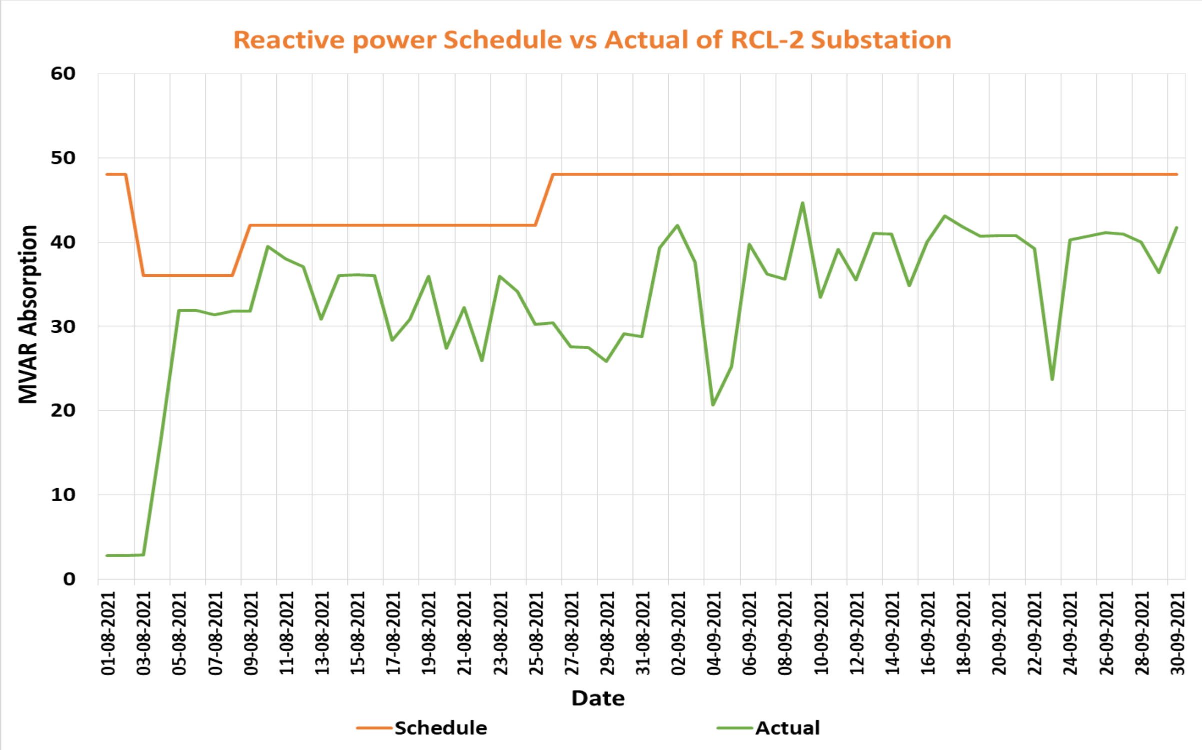
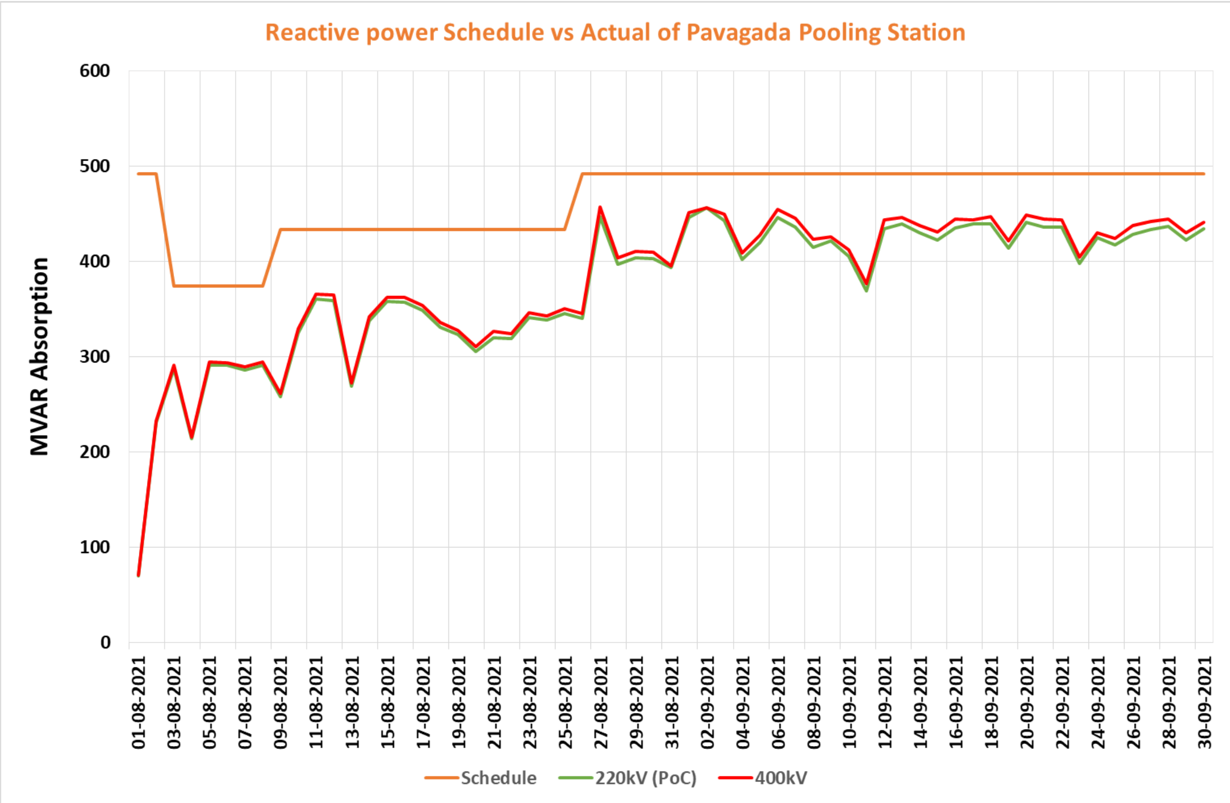
Date
Schedule
Actual


Reactive power Schedule vs Actual of TIRUMANI-2 Substation
MVAR Absorption
Date
Schedule
Actual

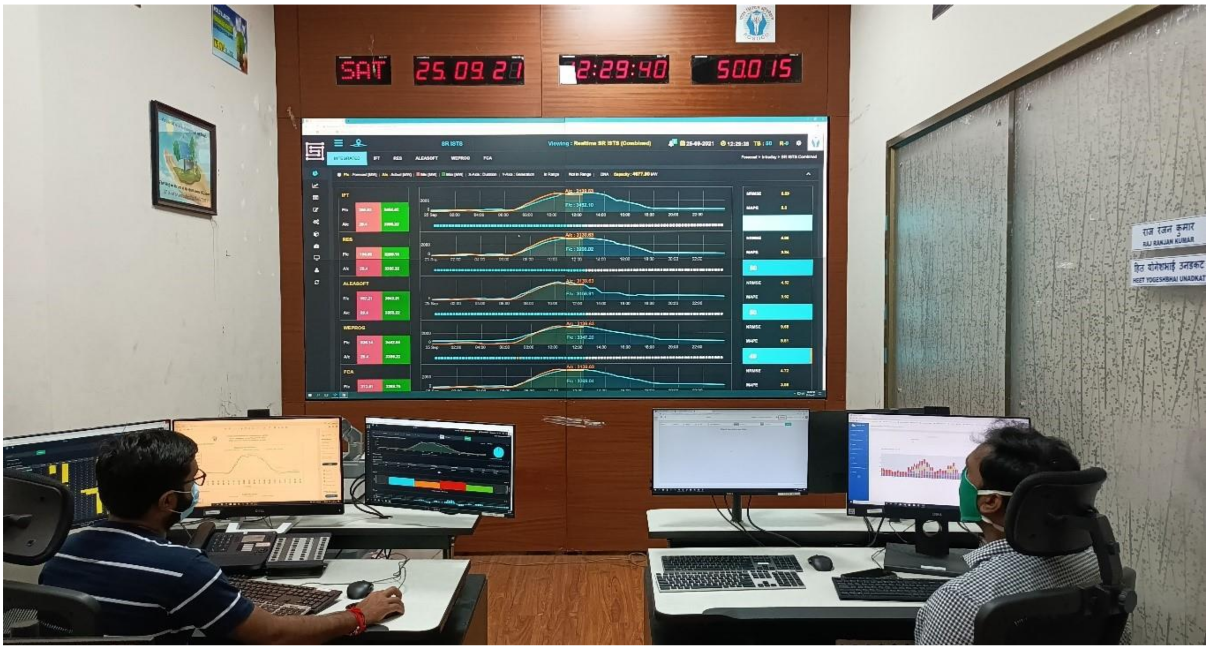

Reactive power Schedule vs Actual of RCL-1 Substation
MVAR Absorption
Date
Schedule
Actual



Reactive power Schedule vs Actual of RCL-2 Substation
MVAR Absorption
Date
Schedule
Actual



Reactive power Schedule vs Actual of Pavagada Pooling Station
MVAR Absorption
Schedule
220kV (PoC)
400kV



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