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Design and Analytics of Dynamic Reactive Power Controller for 6 MW Solar Power plant

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Abstract

Conventional electrical power systems are designed for unidirectional power flow from the utility to the consumer. Alternate energy sources such as solar and wind energy systems have led to distributed generation unlike the centralized generation of power. Integration of solar plants with the grid, leads to bidirectional flow of power, which disturbs the voltage level at the point of common coupling. Reactive power management is an essential part of how voltage levels are controlled in the electric power system. However, the reactive power requirements of the power system vary with respect to time as load levels and generation patterns change with respect to time leading to the requirement of dynamic compensation of reactive power. The objective of the project is to compensate the net reactive power requirement of a 6 MW solar photovoltaic plant by generating the reactive power from the inverter. Usually the source of the reactive power consumption in PV plant arises from the inverter transformer, power transformer and auxiliary electrical equipment installed in the PV power plant. By supplying the reactive power requirement of the photovoltaic plant from the inverter, net reactive energy import and export at the point of common coupling is close to zero. This achieves unity power factor at the point of integration of the plant with the grid. This is achieved by changing the reactive power dynamically at the inverter terminals, which in turn will reduce the reactive power at the grid as zero. A PID controller is used to make the PCC reactive power to zero by dynamically changing the reactive power generation from the inverter. A MATLAB Simulink model of solar plant is developed and reactive power at the point of common coupling is reduced close to zero dynamically.

Keywords: Solar powerplant; Grid integration; Reactive power controller

Introduction

Renewable energy sources pave the way for future electricity requirements due to the depletion in conventional energy sources such as coal and fossil fuels. They present the alternate way by providing clean and green energy to the environment. Renewable energy is a challenging aspect for now and future of the world's increasing energy demand. Among those alternative sources of energy, Photovoltaic (PV) energy and wind power are the most extensively available sources. Its advantages include abundance, pollution free nature, recyclable and distribution throughout the earth. Furthermore, being a semiconductor device solar energy is free of moving parts which results little operation and maintenance costs. Applications with photovoltaic energy and wind energy have been increasing significantly due to the rapid growth of power electronics.

Conventional power systems are designed for centralized power generation with unidirectional power flow from utility to grid. Introduction of renewable energy sources in the grid paves the way for distributed generation and introduces bidirectional power flow in the grid. To connect a photovoltaic plant to the utility grid, power electronic converters carry out a prominent role, from tracking the maximum power point of the PV array on the DC side of the plant to injecting a sinusoidal current to the grid at unity power factor and even power conditioning. At the point of integration, power factor, reactive power and voltage levels are the important parameters which have to be monitored. Reactive power is one of the important parameter that has to be controlled in order to maintain unity power factor at the point of common coupling.

The reactive power requirement of the solar power plant arises from the inductive elements such as power transformer, inverter transformer and other auxiliary equipment's. In order to maintain acceptable voltage level in the line, reactive power compensation is required. Reactive power is either imported or exported to the grid based on the performance of the plant. When the plant is inductive, reactive power is imported from the grid. When the plant is capacitive, reactive power is exported to the grid. Unity power factor has to be maintained at the point of interconnection of the plant with the grid. However the reactive power requirements of the equipment's vary based on the voltage drop at that instant. Hence the reactive power controller should be capable of adjusting its output dynamically with the load changes in the grid.

Materials and Methods

This paper presents a Dynamic Reactive Power Controller (DRPC) for a 6 MW solar plant capable of reducing the net reactive energy import/export of the plant close to zero thereby achieving Unity Power Factor (UPF) at the point of common coupling. The work involves the data analysis of the controller at the site and developing a MATLAB simulink model for the plant and the controller. Figure 1 presents the block diagram of the plant model.

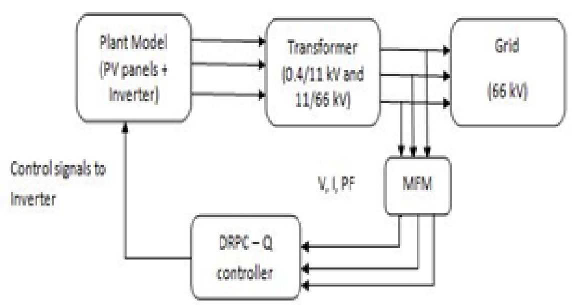

Figure 1: Block diagram of the plant model.

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The concept of reactive power, need for reactive power compensation and the mechanism for dynamic reactive power compensation are presented by Gole et al. [1]. Reactive power performance requirements for wind and solar plants are discussed by Hong et al. [2] with the recommended improvements in providing voltage support to the grid. Various control techniques are available. Control of DFIG is compared between PI and direct power control Liu et al. [3]; concluding DPC is more robust and simpler. A current control algorithm using D-Q synchronous reference frame transformation method is presented by El-Aamri et al. [4]. It uses PI control methods to obtain zero error as the current components considered are steady state values. Decoupled active and reactive power control is achieved with cascaded modular multi-level converters for large scale grid connected photovoltaic system [5]. A new topology Dejia et al. [6] using a single stage single phase grid connected PV inverter with high efficiency is proposed for residential applications. A current controlled space vector pulse width modulated inverter in rotating synchronous coordinate d-q with the proposed MPPT algorithm and feed-forward compensation is discussed [7-10].

In this paper, the current from the inverter is converted into dq reference frame before implementing the current controller loop. An outer DC bus voltage controller loop decides the active power level while the dynamic reactive power controller decides the reactive power level injected to the grid.

Layout of the Solar Power Plant

Specifications of solar panel and inverter

The plant model includes photovoltaic panels, combiner box, inverters, inverter transformer, power transformer, auxiliary equipment's, etc. The solar panel specification is shown in Table 1. The photovoltaic module used is JA-Solar 315 W–JAP6 72-315/4BB.

Table 1: Solar panel specifications.

Parameter	Value
Rated maximum power at STC	315 W
Open circuit voltage (Voc)	45.95 V
Maximum power voltage (Vmp)	37.19 V
Short circuit current (Isc)	8.98 A
Maximum power current (Imp)	8.47 A
Module efficiency (%)	16.25%
Power tolerance (W)	-0-+5 W
Temperature coefficient of Isc (αIsc)	+0.058%/°C
Temperature coefficient of Voc (βVoc)	-0.330%/°C
Temperature coefficient of Pmax (γPmp)	-0.410%/°C
STC Irradiance	1000 W/m2
STC Cell temperature	25°C
STC Air mass	1.5

Table 2 presents the DC input specifications and Table 3 presents the AC output specifications of the inverter used. The inverter is E-1.4 MVA photovoltaic inverter. The photovoltaic inverter is capable of supplying the reactive power required by the plant. Table 4 presents the PQ table of the inverter.

Table 2: Inverter dc input specifications.

Parameter	Value
Recommended rated power	1400-1800 kWp
Maximum direct current at 50°C	2100 A
DC Voltage range	570-1050 V
DC MPPT Voltage range	570-920 V
No. of DC inputs	12
Start of production	0.5 % of Pn approx

Table 3: Inverter Ac output specifications.

Parameter	Value
Apparent power	1400 kVA
AC Active power at PF=1 at 50°C	1375 kW
Nominal AC voltage	400 V rms
Voltage allowance range	-1.5
Output frequency	50 / 60 Hz
THD of AC current	<3 % at Pn
Max. AC current per phase at 50°C	2020 A rms
Max. AC current per phase at 25°C	2165 A rms

Table 4: PQ table of the inverter.

P-Q Table			
Temperature	**PF**	**Active Power**	**Reactive Power**
50°C	1	1375 kW	0 kVAr
	0.95	1330 kW	437 kVAr
	0.9	1250 kW	600 kVAr
40°C	1	1400 kW	0 kVAr
25°C	1	1500 kW	0 kVAr

Design specification

The design steps for determining the number of solar panels to be used are as follows.

1. Vmin_MPP is calculated as 35.16 V by using the ratings from the datasheet.

Vmin_MPP=Vmp–(Temp coeff of Vmpp*Temp range) (1)

Where Vmin_MPP is the Minimum MPPT voltage and Vmp is the Maximum power voltage

2. Assuming a voltage drop of 3%, Vmin_MPP=0.97*35.16=34.1052 V.

3. Maximum operating dc voltage is calculated as 49.25 V using the ratings from the datasheet.

Vdc_max=Voc–(Temp coeff of Voc*Temp range) (2)

Where Vdc max is the maximum DC voltage and Voc is the open circuit voltage.

4. No voltage drop in maximum operating circuit voltage as it is open circuit.

5. Minimum allowable DC voltage at Inverter is 570 V. Allowing a safety margin of 10%, Min DC voltage is taken as 0.90*570=513 V.

6. Maximum allowable DC voltage at Inverter is 1050 V. Allowing safety margin of 5%, Max DC voltage is taken as 0.95*1050=997.5 V.

7. Minimum number of modules in a string is calculated as 15 using the formula given below.

Min. of no. modules in a string=Vmin_dcinv/Vmin_MPP (3)

Where Vmin_dcinv is the minimum DC inverter voltage and Vmin_MPP is the minimum MPPT voltage.

8. Maximum number of modules in a string is calculated as 20 using the formula given below.

Max no. Of modules in a string=Vmax_dcinv/Vdc_max (4)

Where Vmax_dcinv is the maximum DC inverter voltage and Vdc_max is the maximum DC voltage.

Table 5 summarizes the values obtained after the calculation. Based on the calculation, 20 modules are connected in a string. Two parallel strings are connected by a Y-connector and 12 such connections are given to the combiner box. Outputs of 8 combiner boxes are given to an inverter of 1 MW. Six Inverters connecting a total of 23040 solar panels give an output of 6 MW.

Table 5: Calculated values.

Parameter	Value
Vmin_MPP	35.16 V
Vmin_MPP with voltage drop	34.1052 V
Vdc_max	49.25 V
Minimum operating DC voltage at inverter	513 V
Maximum operating DC voltage at inverter	997.5 V
Min no. of modules	15
Max no. of modules	20

Data Analysis

The data analysis of the 6 MW solar power plant installed at the site with dynamic reactive power controller gives the performance of the plant. Table 6 shows the SCADA data at an instant and the reactive power requirement and the active power loss associated with it.

Table 6: Sample scada data at an instant.

Parameter	SCADA Data
Date and time	01/12/2017 12:18 hours
MFM Apparent power	5777.7329 kVA
MFM Reactive power	821.9554 kVAr
MFM Active power	5718.967283 kW
MFM Power factor	0.9889
Reactive power requirement of the plant	751.34 kVAr
Active Power lost	205.5 kW

The data analysis for the month of december is presented as graphs. Figure 2 shows that reactive energy imported is fluctuating in nature.

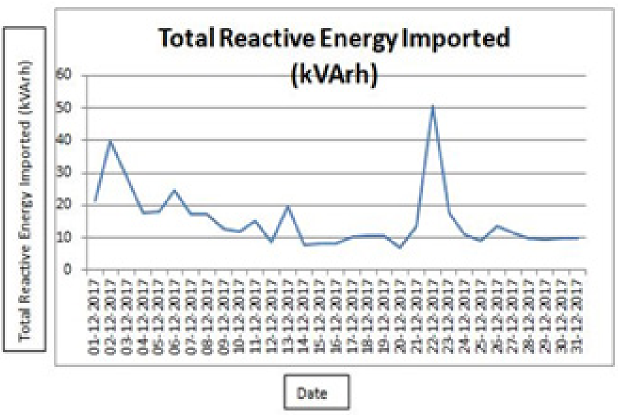

Figure 2: Reactive power import for December 2017.

The import of the reactive energy from the grid results in being penalized by the grid operator.

Reactive energy export for the month of December is presented in Figure 3. It shows lesser fluctuations.

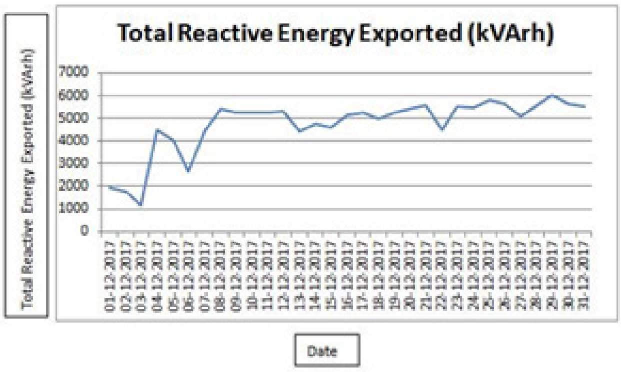

Figure 3: Reactive power export for December 2017.

Active power import and export are presented in Figure 4 and Figure 5. Active and reactive power waveforms are similar as reactive power depends on the active power.

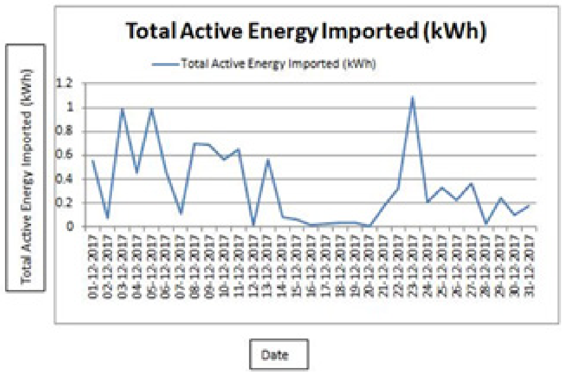

Figure 4: Active power export for December 2017.

Simulation Results and Discussion

The modeling in MATLAB Simulink is carried out in three modules as stated below.

- Power flow between two nodes
- Transformer model
- Control modeling

Power flow between two nodes

Power transmission in a line depends on voltage magnitude and angle between the sender and receiver end. Active and reactive power flow between two nodes or buses is governed by the following equations.

$P=(V1)(V2)\sin\theta/X$ (Watts)

$Q=((V1)(V2)\cos\theta-(V2^2))/X$ (Var)

Where V1=Voltage at sending end, V2=Voltage at receiving end, X=Reactance/impedance between the sending and the receiving end, θ=load angle (difference between the angles of sending and receiving end voltages), P=Active power and Q=Reactive power.

From equation 5, it is seen that active power P depends on the load angle (θ) between the voltages at the sending and receiving end and from equation 6, it is seen that reactive power Q depends on the magnitude of voltage at the receiving end. Here the voltage magnitude and angle can be controlled only at the inverter terminal. The reactive power is generated at the inverter terminal to supply the reactive power requirement of the plant. In order to achieve decoupled control between P and Q values, abc-dq transformation is required. The transformation involves abc- αβ transformation followed by αβ-dq transformation. Following matrices establish the relationship between these transformations.

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

In the above matrices f represents voltage or current.

Transformer modeling

There are two step-up transformers in the plant of 3.35 MVA and 8 MVA rating to increase the generation voltage to 66 kV. Table 7 presents the nameplate details of the transformers available from the single line diagram.

Table 7: Transformer ratings.

Parameter	Transformer 1	Transformer 2
Power	3.35 MVA	8 MVA
No. of windings	4 winding	2 winding
Voltage rating	0.4-0.4-0.4/11 kV	11/66 kV
Impedance	6.25%	8.35%
Configuration	Dy11y11y11	Dyn11

Table 8: Transformer parameter.

Parameters	Transformer 1	Transformer 2
R1 (pu)	0.002	0.002
R2 (pu)	0.032	0.042
L1 (pu)	0.002	0.002
L2 (pu)	0.032	0.042
Rm (pu)	500	500
Lm (pu)	500	500
Rated current LV and HV	4713 A, 171.4 A	416.9 A, 69.48 A

Table 8 presents the equivalent circuit parameters obtained from the short circuit and open circuit tests of the transformer. These values are verified by calculating the base and actual values and mentioned in per unit values.

Control modeling

The photovoltaic system of the plant consists of a lookup table which has the IV curve data as the set points and breakpoints. The output from the photovoltaic system is converted into AC by giving it to an inverter. A filter, two transformers and a voltage source which acts as a grid forms the rest of the circuit. The idea behind the control of the firing pulses given to the inverter is generating a voltage reference from the grid voltage and the inverter current. It involves current regulators for Id and Iq.

The active and reactive power control is achieved by generating the reference points for the current controller. The active power reference is controlled by the Iq controller whose reference is given from the DC bus voltage controller. The reactive power reference is controlled by the Id controller whose reference is the output of the Dynamic Reactive Power Controller (DRPC). It is a PI controller which takes the value of reactive power from the grid and adjusts it close to zero (reference value) by giving the reference to the current controller.

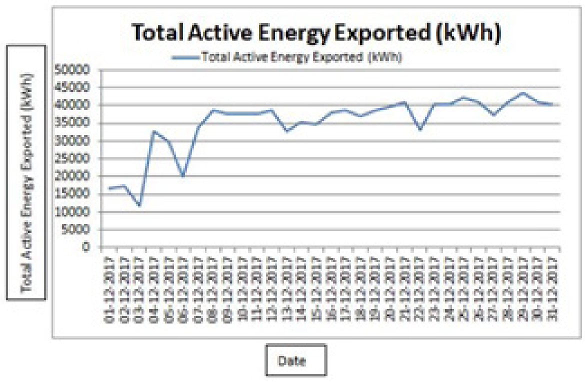

Figure 5: Active power export for December 2017.

The plant model is initially tested for constant and varying active power of 1 MW with one inverter. In order to obtain 2 MW as output power, two inverters are connected in parallel. The active power is then increased to 6 MW and tested for both constant and varying power. The simulation results of varying 6 MW plant is presented in the following figures.

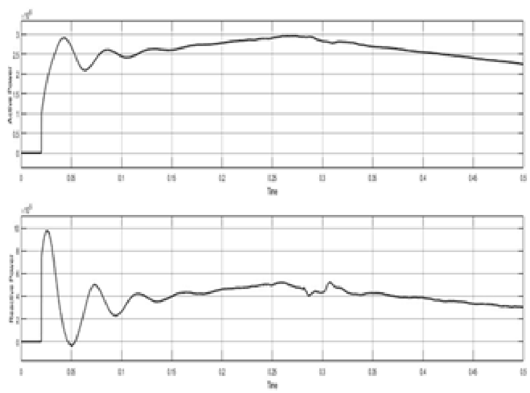

Figure 6: Active and reactive power waveforms observed at inverter terminals.

Figure 6 shows the active and reactive power waveforms obtained at the inverter terminals. It is seen that reactive power is generated. Two such inverters are connected in parallel generating close to 0.8 MVAr at the input of 3.35 MVA transformers. The reduced reactive power waveform in Figure 7 denotes the reactive power consumption of the transformer. Figure 8 shows the active and reactive power waveforms at the grid, where the reactive power is observed to be close to zero.

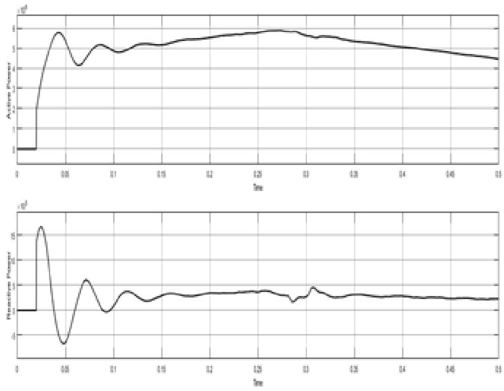

Figure 7: Active and Reactive power waveforms observed after the 3.35 MVA transformers.

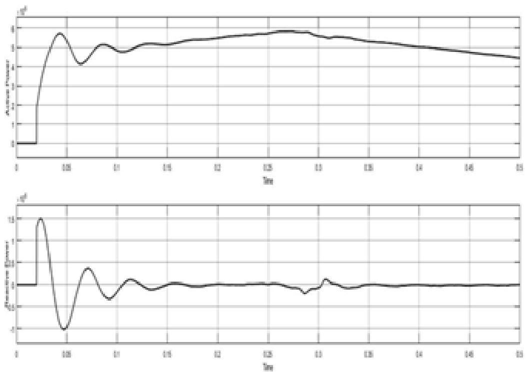

Figure 8: Active and reactive power waveforms observed at the grid.

Active power at the point of common coupling varies with the reference values with maximum power obtained as 5.985 MW and reactive power close to 20 kVAr. Figure 9 and Figure 10 show the

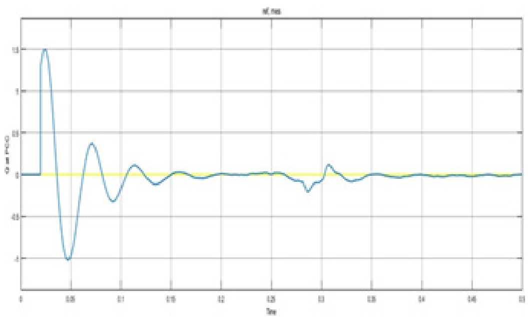

Figure 9: Reference and measured reactive power waveform.

reference and measured reactive power and power factor waveforms. The apparent power and the power factor observed at the PCC after the 8 MVA transformers are shown in Figure 11. It can be observed that power factor is maintained close to unity.

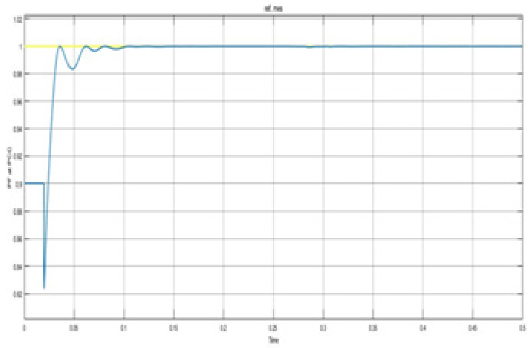

Figure 10: Reference and measured reactive power waveform.

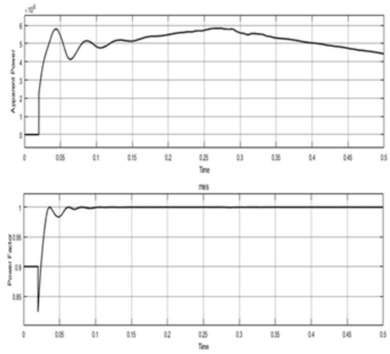

Figure 11: Apparent power and power factor observed on the grid side.

Conclusion

In this paper, a multi-input Inverter for a hybrid wind–solar power system has been designed and its performance has been evaluated through MATLAB/simulink. Initially the multi-input Inverter is analyzed using dc sources in open loop and closed loop. In closed loop control, a PI controller is used to control the dc bus voltage. The output parameters are compared. The control signal is given such that only PV source is available, only wind source is available and both the sources are available for different intervals of time. The simulation result shows that the inverter is found to supply a load of 1 kW continuously in different modes of operation.

This paper presents the data analysis of the dynamic reactive power controller at the site and the model of the plant in MATLAB simulink along with a dynamic reactive power controller. From the analysis of the SCADA data it is found that the active power loss associated with the reactive power import and export at the grid is high. The SCADA data at a particular instant shows that for an apparent power of 5777.7329 kVA at the grid, the active power lost is 205.5 kW. The reactive power requirement of the plant at that instant is 751.34 kVAR. The operating power factor is 0.9889 at the point of common coupling.

A plant model of the solar plant with dynamic reactive power controller is developed in MATLAB simulink to study the performance of the plant. The performance of the plant is evaluated for different values of active power. The analysis is done for a constant active power and varying active power for a 1 MW system, followed by a varying active power of 2 MW systems. Finally the plant model is altered to get an active power of 6 MW system using two inverters of 3 MW rating each. In all the cases, the reactive power is maintained as zero (with negligible reactive power) at the grid with the help of a PI controller which acts as the dynamic reactive power controller. The values obtained are tabulated in Table 9.

Table 9: Active and reactive power observed for different power levels.

Case	Power level	P at PCC	Q at PCC	S at PCC	PF at PCC
Constant P	1 MW	0.95 MW	2 kVAR	0.956 MVA	0.9999994
Varying P (max)	1 MW	0.94 MW	2 kVAR	0.939 MVA	0.9999895
Varying P (max)	1 MW	0.978 MW	2 kVAR	0.9775 MVA	0.9999948
Constant P	2 MW	1.925 MW	5 kVAR	1.93 MVA	0.9999992
Varying P (max)	6 MW	5.985 MW	20 kVAR	5.986 MVA	0.9999972

This is achieved by varying the reactive power generation at the inverter terminals based on the output of the DRPC dynamically. Active power lost can be reduced by reducing the reactive power close to zero.

Future work

The present plant model can be made to depend on the irradiation and temperature in order to test the controller for actual site data. The MPPT algorithm can also be implemented to track maximum power. The dynamic controller implemented for reactive power can be extended to control of power factor. In this case, the control signal to the current controller is generated from the controller and the P-Q look up table of the inverter.

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