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Photovoltaic Generators to Power Quality at Low Voltage

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Abstract:

The PV-Grid system is modeled and simulated using real PV irradiance and temperature data collected from PV panels during the day time. The I-V and P-V characteristics of the PV-array were extracted to create a realistic model of the solar panels used in this paper. The inclusion of Distributed Energy Resources (DER) into the grid is a great way to maximize and increase power generation at large. However it could also result in power quality issues due to their generation being dependent on external factors such as the weather. This paper aims to investigate power quality problems and potential solutions in low-voltage networks with high penetration of DER sources. A Distribution STATic COMpensator (D-STATCOM) is utilized as the grid-connected inverter to perform conversion of power, power management, and compensation of reactive power. The simulation results presented demonstrate the use of the D-STATCOM to both convert the real power to AC and contribute towards the management of system reactive power at up to 100% of its rating.

Index Terms:

Renewable Energy Systems, Distributed Generation, Power Quality, Photovoltaic Generators, Inverters, Low voltage, D-STATCOM, Reactive power compensation.

I. INTRODUCTION:

Grid integration of Distributed Energy Resources (DER) can cause an imbalance and power quality issues in Low Voltage (LV) distribution networks. With the increasing penetration of DER, these effects are expected to become more significant. The question of enhancing power quality in LV distribution networks with high DER penetrations needs to be addressed. The high penetration of renewable energy resources, distributed generation, distributed energy storage, electric vehicles and controllable loads, pose new challenges in the operation of distribution networks. The operations of renewable sources are dependent on atmospheric conditions, time-dependent and uncertain factors; hence the power they produce will be varied. One growing distributed generation technology is the photovoltaic generation (PV); it's a significant source of concern for distribution network service providers due to its popularity with urban and rural customers [8]. The farther the DER sources from the loads, the more the reduction in quality of generated power to be distributed. As a result, integrating distributed energy resources into the traditional power grid will incur service reliability issues, which need to be carefully addressed. In areas where PV inverters are clustered along a weak LV feeder during the day, maintaining voltage profile within the acceptable limits has the likelihood of becoming problematic. This is because of the changes in solar irradiance in the distribution area and growing penetration of PV systems. The inability of the system to maintain the voltage profile within standards may result in voltage sag or rise, causing tripping of sensitive equipment in the distribution network which could lead to damage of plants. The capability of a grid-connected PV system is noteworthy; this is a measure of the ratio of the system efficiency and the nominal efficiency of PV modules under standard test conditions. In this paper, the performance of solar PVs was examined based on variance in energy produced, the operating nature of PV inverters and the capability of the inverter to mitigate the effect of solar photovoltaic output power on the LV network through application of an inverter VAR control strategy.

A variety of control algorithms are illustrated in the literature. During the day, the PV array is energized producing real power but at night, the same inverter in the PV farm used in transforming the DC power into AC becomes an asset for reactive power source since the solar module is not active in capturing DC power. Simulation and analysis of a modeled LV network was carried out, the voltage profile at different nodes in the network was measured and analyzed. The system was divided into two stages: a) PV array coupling with the DC-DC boost stage, and b) DC-AC Conversion stage where D-STATCOM is introduced. For grid tie inverter, two control loops were integrated; that is the external control and the internal control loop. The control section focuses on decoupling active power and reactive power in the system. In the control block of the system, the inner control algorithm is used to trace active power current and reactive power separately. The purpose of the external loop algorithm is to stabilise the DC link voltage and grid-connected voltage. A variation in the grid current was monitored to control the output of the converter in the grid network. However, in the absence of the grid network, the converter operated in standalone mode feeding the connected load. The results seen from the simulation proved the efficacy of the proposed control strategy.

II. POWER QUALITY ISSUES:

The operating nature of PVs generally can be based on either the variable energy production of the PV or by the characteristics of the PV inverter connected to it. Power issues such as voltage sags, voltage rise and harmonics can occur in the system. A system with optimum power quality should have continuous and sinusoidal voltage with constant figures of amplitude and frequency. Power quality can be expressed in terms of physical characteristics and properties of electricity. It is most often described in terms of voltage, frequency and interruptions. The quality factor of a RLC load is defined as the ratio of the reactive power stored in the load inductor or capacitor to real power consumed by the resistive load. Usually a load with a quality factor of 2.5 is considered an extreme case for the islanding study.

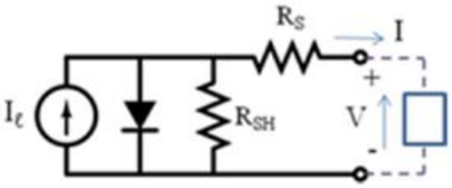


Fig. 1. PV cell (Single diode model)

III. PV-GRID DESIGN ANALYSIS:

This section briefly discusses the main units in the design.

A. Modelling the Photovoltaic (PV) Array:

The Solar PV array, which produces DC power, is the DER. Maximum Power Point Tracking (MPPT) subsystem is employed to extract the maximum power from the PV plant. The PV array is modelled using several individual PV cells which are connected both in series and in parallel to generate voltages and power which are equivalent to those of the PV plant. As explained in, several factors determine the efficiency of the PV module. Different electrical component are used to model the characteristic of the PV module

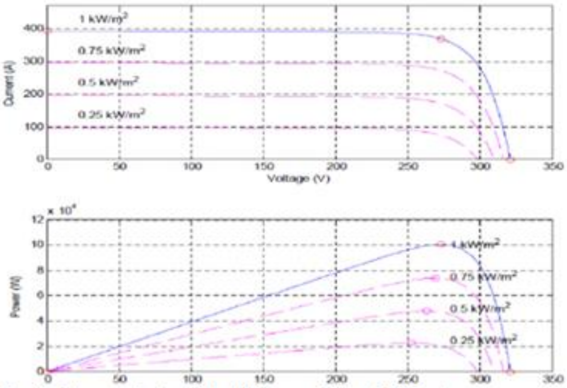


Fig. 2. Characteristics of the PV array: I-V and P-V values

B. Modelling the DC-DC boost converter:

The DC-DC converter receives the voltage from the PV array and works on it to boost the voltage before it is converted to AC voltage. At the DC-DC converter stage, it is key for a steady state operation to check that the inverter is not working at over voltage conditions.

Generally, there are two conventional topologies in grid-connected PV applications; that is (a) conventional two-stage design and (b) single-stage configuration. Grid connected PV systems are generally designed using the two-stage setup as shown in Fig.3 (a) below. The first stag is used to boost the PV array voltage and track the maximum power using Maximum Power Point Tracking (MPPT) control technique [22-23], while the second stage is used to convert the DC power into AC power using either a half-bridge or full bridge inverter topology. Typically, the first stage comprises of a boost or buck-boost type of dc–dc converter topology. The conventional two-stage design was selected in this paper because it offers an additional degree of freedom in the operation of the system when compared with the one-stage configuration. Therefore, by including a DC-DC converter between the PV module and the inverter, which is connected to the utility as shown in Fig.3 above, different control objectives can be pursued concurrently within the PV-Grid setup. The DC-DC converter produces a chopped output voltage to control the average DC voltage at its output with the aim continuously matching the characteristic of the PV system to the equivalent impedance presented by the dc bus of the voltage sourced inverter (VSI) [13].

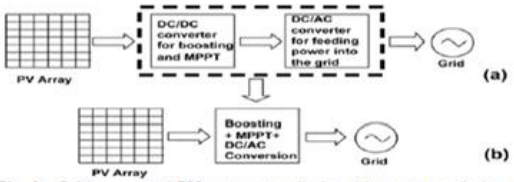


Fig. 3. Grid connected PV system topologies: (a) two-stage design and (b) single-stage configuration

The steady state voltage and current at the output of the boost converter can be derived using the following formulae [9].

Where:
ηb = Efficiency of the boost converter
D = Dc-dc converter duty ratio
IA = PV array output current
VA = PV array output voltage
ID = Dc bus current (inverter side)
VD = Dc bus voltage (inverter side)

C. Modelling the DC-AC Inverter:

The boosted DC power is to be converted to alternating current and fed into the grid for AC loads. Generally the DC-AC inverter is implemented in various forms; half bridge and full (H) bridge are the two common inverter types and the choice of inverter is dependent on the application. The full bridge topology is capable of delivering high current at low voltage. PV-Inverter interfacing with the grid involves two major tasks. First, the PV array is operated at the maximum power point (MPP) and the second task is to inject sinusoidal current into the grid. Voltage Source Inverters (VSIs) or converters (VSC) are widely used for inverting DC to AC power.

VSI is designed using super-fast high-power semiconductors called Insulated-Gate Bipolar Transistors IGBTs. The IGBTs are used due to their higher power handling capacity when compared to other devices such as MOSFETs. Furthermore, the output voltage control of the VSI can be achieved through pulse width modulation (PWM). The VSI is connected to the utility grid through low pass filter; the LC filter further explained in [14] is introduced into the design to reduce the distress on distribution system from high-frequency switching harmonics generated by PWM control block.

In addition to VSI topology, an important aspect of D-STA TCOM is the reference current generation algorithm explained in [18]. The H-bridge VSC (Voltage Source Converter) is connected to the grid through an inductor. On DC side, an energy storage capacitor is connected to the D-STATCOM to hold the DC voltage.

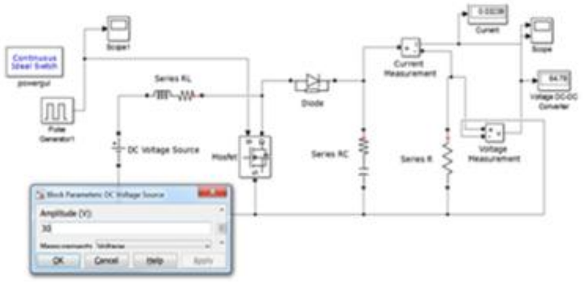


Fig. 4. DC-DC boost converter

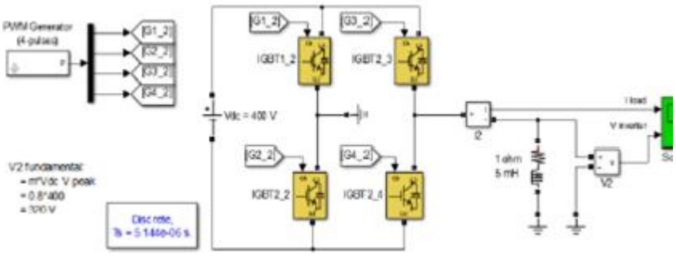
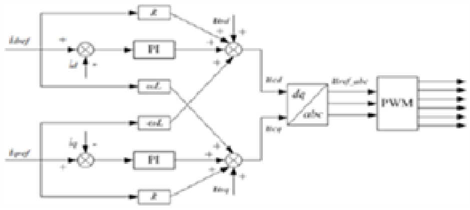


Fig. 5. DC-AC H-Bridge inverter

MODELLING THE D-STATCOM CONTROL BLOCK:

This section focuses on the control schematics used in decoupling active and reactive power as well as regulation of the DC link and grid-side voltages. Compared to a current source inverter (CSI), the VSI prevents over-voltage of the DC link capacitor with less power loss [16]. There are two control loops in the system that was used in this study. The external control loop regulates the grid-connected voltage and the DC link voltage. The internal control loop is responsible for regulating the active and reactive power through the corresponding current control parameters of id and iq respectively. The D-STATCOM controller is made up of several sub-blocks. Voltage and current regulators are utilised in the control system. The in phase current (id) along with the voltage regulates the active power flow. The id_ref value is generated by the DC voltage regulator, which is also used to keep the DC link voltage constant at its nominal value using limiters and the Phase Integral (PI) controller as shown in Fig.7 below.

During the daytime the DC link capacitor is usually charged via the photovoltaic array but at night time or in conditions of low power generation, the DC voltage. controller works to maintain the DC bus voltage constant. At such instance, Proportional Integral (PI) regulator will draw active power from grid to support the voltage regulation at DC bus and supply the associated power loss in the inverter. Once the Voltages and the currents are measured, the d-axis and q-axis components of the voltages and currents are computed by performing abc-dq coordinate transformation in the synchronous reference frame. This synchronous reference is determined by performing sin(ωt) and cos(ωt) calculations. The angle, ωt is provided by the phase locked loop (PLL). The two PI controllers in the current-regulator control the d-axis and q-axis currents and evaluate the ucd and ucq output voltages needed to generate the PWM signals. These PWM signals are used to drive the inverter.



6. Diagram of active and reactive current control [21]

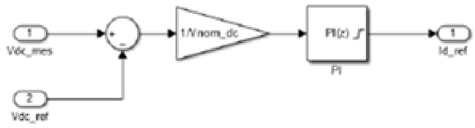


Fig. 7. The DC voltage regulator block

The main purpose of the inverter is to convert the solar power, which is DC, into AC power that can supplied to the Grid. However, due to the intermittent nature of solar power, the inverter is not always used to its full capacity even during the day time. This spare capacity could potentially be used to provide ancillary service to the Grid in the form of reactive power. This can be achieved by monitoring id_ref and adjusting the value of iq_ref in such a way as to use the grid-tie inverter to its full capacity at all times.

According to [13], iq_ref can also be regulated with a view of stabilising the common coupling point voltage via the AC regulator and to reduce the harmonic distortion of the output current.

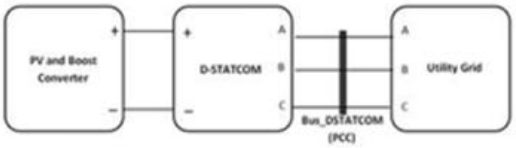


Fig. 8. Grid-connected PV array with D-STATCOM. Bus_DSTATCOM in the diagram is the point of common coupling.

Fig.8 shows the block diagram of the system under study. The PV array and the boost converter are modelled in Block A. The general characteristic of the PV array has been discussed above. The PV array module in this design is rated at 10 kW and operates at an irradiance of 1000 W/m2. The 265V DC generated by the PV array is boosted to 500V DC using a 5 kHz DC-DC converter. The DC-DC converter utilises the incremental conductance MPPT which automatically varies the duty cycle in order to produce the required voltage to extract maximum power [19]. The D-STATCOM, Block B, converts the boosted DC power to AC power and manages the reactive power generation. The inverted real power and generated reactive power in the D-STATCOM is then fed into the Grid. The uniqueness of the D-STATCOM compared to other devices that manage reactive power (such as shunt capacitors, reactors and synchronous compensators), is in its ability to handle system unbalance, minimise harmonics as well as to control the DC voltage across the DC link Capacitor. Transmission of reactive power is done via the leakage reactance of the coupling transformer when regulating the voltage at bus B1 of the grid by the D-STATCOM controller, in order to generate or absorb reactive power. A secondary voltage in phase with the primary voltage is generated by the voltage-sourced PWM inverter. When the secondary voltage value is less than the bus voltage, the D-STATCOM will behave like an inductor and absorb reactive power. On the other hand, once the secondary voltage is greater than the bus voltage, the D-STATCOM behaves like a capacitor to generate and inject reactive power into the network.

VII. RESULTS AND DISCUSSION:

Real time temperature and irradiance data was recorded for one day from the Solar panels installed on the rooftop of our laboratory. This data was then fed to the PV array model to run a realistic simulation. The profile of this data is shown in Fig.9.

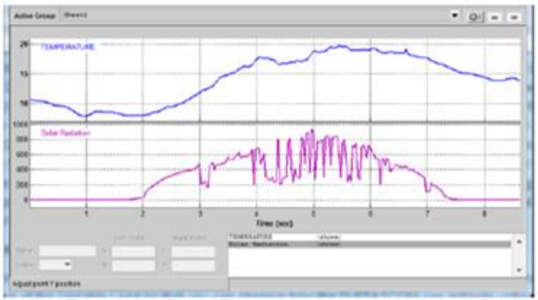


Fig. 9. Raw Solar Panel Data - temperature in degree Celsius and irradiance in W/m2

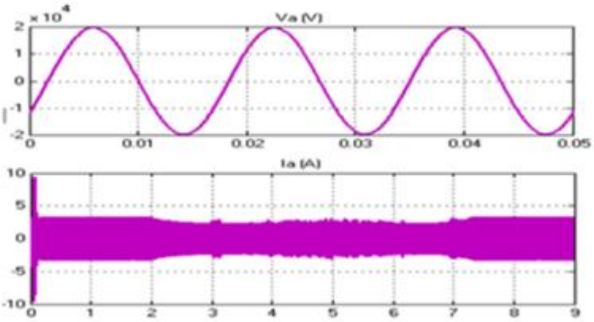


Fig. 10. Phase A voltage and current.

It is clear from Fig.10 that even though the current produced from the PV array fluctuates with time to follow the changes in irradiance, the output AC voltage is maintained at a constant value by the inverter. The voltage waveform produced by the inverter as shown in Fig.10 is also of high quality.

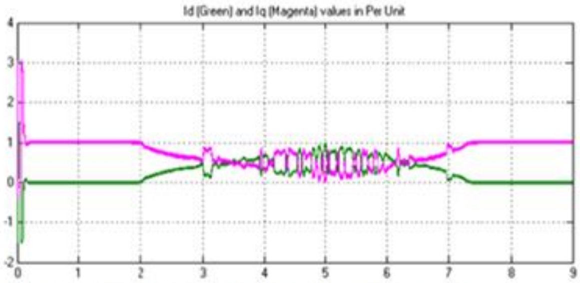


Fig. 11. (Above). The *id* (green) and *iq* (Magenta) in per unit

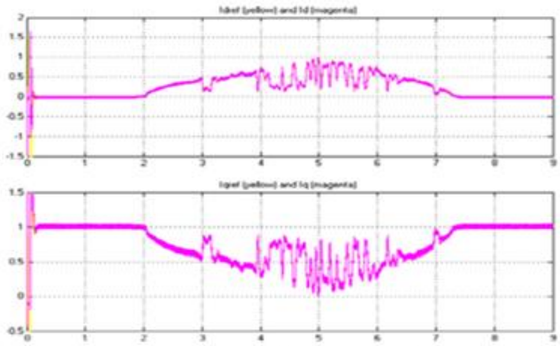


Fig. 12. The quadrature axis current *id, iq* and the quadrature axis reference current *id_ref, iq_ref* in per unit.

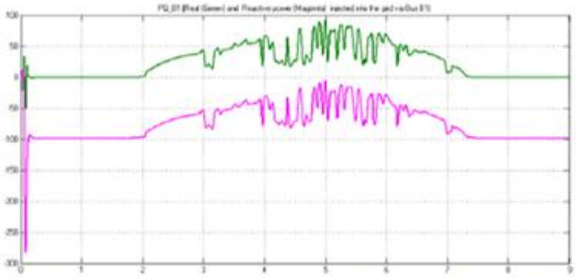


Fig. 13. The active and reactive power injected by the D-STATCOM into the network (P – kW (Green), Q – kVar (Magenta) at Bus_Dstatcom

The relative changes in the values of the direct and quadrature current as shown in Fig.11 and Fig.12 confirm the ability of the D-STATCOM to continuously adjust the reactive element as the real part, which is determined by the level of irradiance at any given time, changes with time. This observation is clearly supported by the results in Fig.13 which shows the variation of real and reactive power. The trend faithfully follows the result shown in Fig.11. For instance at the start (night time), the real power produced by the inverter is zero as there is no availability of solar energy. At that time, the reactive power produced by the inverter is equivalent to the maximum rating of the inverter MVA. However, as the solar radiation strength (that is the real power output from the inverter) fluctuates during the day, the reactive power generated by the inverter also varies – always maintaining optimum use of the inverter. Of course how much reactive power is required at any given time will depend on the ancillary service demanded by the grid and should this demand be less than what can optimally be produced by the inverter the reference current would be adjusted to meet this requirement.

VIII. CONCLUSION:

This paper has addressed the power quality issues in a Grid connected PV system by using D-STATCOM to mitigate some of the issues. The integration of DER sources (Solar PV in this case) into the distribution network and the impact of the changes in solar energy were investigated to determine the capability of the inverter to support the Grid's requirement of reactive power while operating at its optimum level of performance. It has been shown that the inverter could indeed be designed to operate as a D-STATCOM while performing its normal function of converting the solar DC power into AC for the Grid. There by providing an important ancillary service of providing reactive power to the Grid and playing a crucial role stabilising system voltages.

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