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Grid Integration of Utility Scale Photovoltaic (PV) Plants Under the South African Grid Code Using a Modified Generic PV Model in DigSilent

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Abstract— **The integration of large scale PV power plants into the power system grid at medium voltage (MV) level are required to operate like the conventional power plants in terms of controlling the frequency and voltage to ensure grid stability. The paper describes the procedures of Utility scale PV plant modeling and then focuses on implementing static reactive power control for the PV inverter on the already existing generic PV model in DigSilent. The model undergoes various simulation tests namely fixed reactive power, fixed power factor and voltage control. The fixed reactive power was set to 0.203 p.u, the fixed power factor was set to 0.95 and the voltage was varied at the point of connection in the continuous voltage range with a droop constant value of 8 for voltage control. The results show that the model works as required by the South African grid code.**

Keywords— Photovoltaic model; DigSilent; South African grid code; Reactive power; Voltage control.

I. INTRODUCTION

The electric power system is experiencing increasing integration of PV and wind generation and this has led to changes in power system operation procedures, planning, performance standards and grid reliability [1]. There is an increasing need to operate renewable energy generation as conventional power plants to ensure a reliable and secure integration. Renewable energy power plant capabilities imply that the plants have to be controlled and operated according to system requirements and curtail grid issues (faults and disturbances) [2]. These capabilities include the active and reactive power control of renewable energy technologies. In the last two decayed, renewable energy generation plants such as PV and wind generator were seen as either line-commutated inverters (PV) or induction generator (wind) without voltage control capability [3]. Due to increasing integration of PV and wind power system into the existing power system, there is need for the renewable energy systems to contribute to voltage and reactive power regulation in the grid. Although, synchronous generators were almost exclusively used for providing voltage regulation. Technically, the SA grid code is divided into two requirements that is the static and the dynamic requirements. Subject regarding continuous operation such as continuous voltage control, power curtailment, frequency, and power factor requirement are examined by the static requirement of the grid code while subjects regarding plant operation during fault ride through and fault recovery capabilities are examined by the dynamic part of the code [3]. During the continuous operation of PV plants, the voltage has to be regulated within a voltage range of ± 10% of its nominal value using either the control functions of voltage control, power factor control, or fixed reactive power control [4]. The PV inverters used for utility scale power plants are allowed to regulate the voltage at the point of connection (PoC) or point of common coupling (PCC) with the grid. Today, solar inverters can absorb or inject reactive power to regulate voltage if needed. The local inverter control will have similar control capabilities as the PV power plant level controls or master controls in terms of reactive power control and active power control [5], [6]. The SA grid code specifies the power factor range of 0.95 leading or lag for PV plants producing a power capacity of 20MVA and above (category C) and also a power factor range of 0.975 leading or lag for power plants producing a power capacity of l MVA-20 MVA (category B). Allowing a power factor that is not unity will allow the inverters to participate in regulating the voltage [7]. The amount of reactive power produced by a generating source must match that which is being consumed for voltage to be regulated [3]. If reactive power is either under or over supplied, the voltage on the network may rise or fall [3]. The flexible alternating current transmission systems (FACTs) compensators such as static Var compensator (SVC), static converters (STATCOMS), etc., can further enhance power factor capabilities if needed to support the reactive power capabilities of solar and wind power plants [3],[5],[8]. It should be noted that PV inverters need to be sized larger for reactive power support at full active power output which is not economical [3].

The dynamic technical requirements of the SA grid code are concerned with how the RPP operates and recover during a fault on the grid network [4], [9]. The low voltage-ride through (LVRT) and the high voltage-ride through (HVRT) are describe in the grid code to show how the RPP should stay integrated for specific durations of time before disconnecting completely.

Transmission system operators (TSO) need PV plant simulation models including their control because the grid code specifications have implications in the PV plant system control and design [10]. These plant models with their control are made in power system software's like DigSILENT Power Factory, ETAP and PSS/E [4], [5], [10]. Generation assets applying for grid connection must comply

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with the mentioned grid code technical requirements. In this article a modification is made in the PV system model in DigSILENT. The DigSILENT PV system model does not have static reactive power control during continuous operation. Power factor regulation, voltage droop control and fixed reactive power control based on the SA grid code are implemented and compared with the existing DigSILENT PV system model. The modified model was shown to work according to the SA grid code for static reactive power control. This paper is focused on the implementation of local inverter controls so that the inverter can participate in regulation the voltage during continuous operations. A master plant level control which would control all the inverters on the plant and any extra equipment like capacitors and STATCOMS is discussed but not implemented.

II. Review of South Africa Grid Code Compliance Requirements

The South African Renewable Energy Grid Code (SAREGC) provides minimum technical requirements for a RPP based on size and connection voltage level of the renewable energy plant. The introduction of the SA grid code has helped South Africa deal with the increase penetration of Independent Power Producers (IPP) generation sources by ensuring grid stability and quality of power supply [9]. For this paper, the focus will be on the technical requirements for category C power plants which range from a power capacity of 20MVA and above. These plants are connected on the medium voltage (1kV-33kV) or high voltage (33kV-220kV) [4].

A. *Continuous voltage regulation requirements*

The continuous operating voltage upper and lower limits at the PoC are 1.10pu (max) and 0.9pu (min) respectively [4], [11]. This is the band in which the RPP required to operate on the power network under normal conditions. The RPP reactive power capability at the PoC will be designed to supply reactive power, depending on the requirements of the service operator. At nominal voltage (1 pu), the plant shall be able to absorb and supply maximum reactive power from 20% of P_max as seen in Fig 1 [4],[6],[11]. Table 1 shows the Qmin and Qmax values for category C plants as required by the SA grid code [11]. When the voltage deviates from its nominal value 1 pu, then the RPP needs to comply with Fig 2. Fig 2 indicates that at Umax, the plant must only absorb maximum reactive power whilst at Umin the plant must be able to only supply maximum reactive power [11].

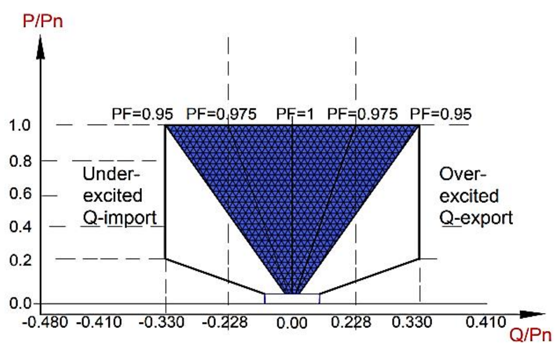

Fig. 1. Reactive power requirements for RPP of category C at nominal voltage at PoC [4]

TABLE 1. Maximum and minimum reactive power limits for category C

Voltage	Qmin	Qmax
Unominal	-0.330Pn	0.330Pn
Umax	-0.330Pn	
Umin		0.330Pn

Fig 2 shows that the reactive power control at the PoC can be tested based on different scenarios for example: when voltage is Umin (0.9pu) reactive power is exported to achieve 0.95 PF and reactive power is imported to achieve 1 PF. A voltage around 0.95 pu will export reactive power to achieve 0.95 PF and import reactive power to achieve a 0.975 PF. As long as voltage is below the nominal, reactive power is exported to achieve 0.95 PF and reactive power is imported to achieve a different PF values. When nominal voltage (1 pu) is achieved reactive power is exported to achieve 0.95 PF and reactive power is imported to achieve 0.95 PF (Fig 1). Also, when there is a high voltage above the nominal, reactive power will be imported to achieve 0.95 PF.

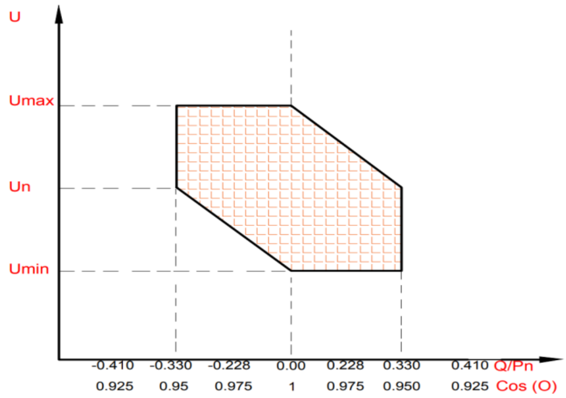

Fig.2. Requirements for voltage control range for RPP of category C [4]

A1. *Voltage and Reactive Power Control functions*

There are three types of control modes specified in the SA grid code, and they are Voltage control, Power factor control and fixed reactive power (Q) control. All the controllers are implemented in the SCADA system because it allows full visibility and controllability of the power plant. Reactive power (Q) control functionality controls the reactive power delivered at the PoC independently of change in active power or voltage within the P-Q and Q-V capabilities of the plant as illustrated in Fig 3 [4]. For Q control, "the RPP must comply with the set point issued within 30 seconds upon receipt to a measured accuracy of the higher value of ±2% of the set-point" [4]. For PF control, the reactive power is controlled proportionally to the change in active power at the PoC within the P-Q and Q-V capabilities of the plant [4].

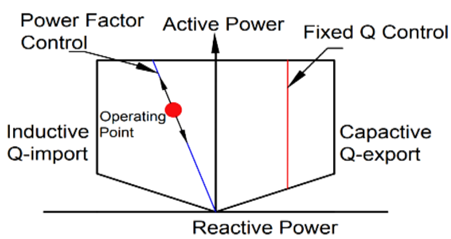

Fig. 3. Reactive power control functions for the RPP [4]

The voltage at the PoC is controlled by controlling the injection or absorption of reactive power according to the droop characteristics shown in Fig 4. The RPP shall be able to perform the control within its dynamic range and voltage limit with the droop configuration as shown in Fig 4. For voltage control, “the RPP must comply within 30 seconds of receipt of the set point to a measured accuracy of ±0.5% of nominal voltage and ±2% of the required injection or absorption of reactive power according to defined plant droop characteristic” [4].

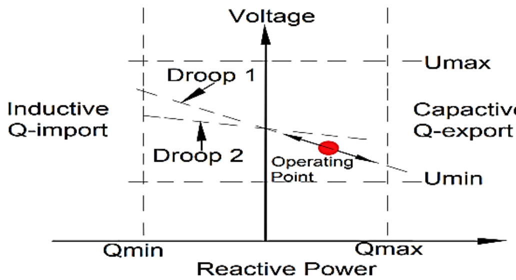

Fig. 4. Voltage control for the RPP [4]

The grid code states that “When the voltage control has reached the RPP dynamic design limits, the control function shall await possible overall control from the tap changer or other voltage control functions” [4],[8],[11]. This implies that if an inverter reaches its maximum or minimum continuous operating voltage limit, the power plant transformer On-load tap changer must operate so as to increase or reduce the nominal system voltage such that the inverters can supply or absorb additional reactive current required to meet the new reactive power set point. The biggest constrain for this requirement is when the voltage at PoC is 1p.u since this is the only voltage at which the RPP must function for the full power factor range of 0.95 import to 0.95 export.

III. DYNAMIC MODELING OF INVERTER BASED GENERATOR

In Europe, most of the power networks are now supported by renewable energy [12]. This means renewable energy that uses inverters should have functionalities similar to conventional generators to maintain stability. In the past there were no grid code requirements to specify control functions and the level of renewable energy penetration was minimum hence inverters could be modeled using a negative load model [12],[13]. The increase in penetration of renewable energy and detailed grid codes is a need for more accurate modeling of inverter based generators to understand the effects they have on the power system stability. Network planners can benefit from detailed inverter based generator models to assess voltage and frequency issues, protection system behavior, etc.

Inverter modeling differ with synchronous conventional generator modeling in terms of inertia, synchronization capability, fault current contribution etc. [12],[13].These characteristics cannot be easily emulated by inverter based generators. This means that the dynamic impact of inverter based generator will be different on the power system [12],[13]. When modeling conventional energy sources such as hydro and thermal, the dynamics of the generator has a critical impact. For inverter based generators the electrical control modeling plays a very important role. The inverter is used as an interface between the energy source and the electricity network. The dynamics of the inverter based generator are determined by the electrical control model [12],[13],[15]. Even though inverters cannot emulate conventional generators the key is to have the inverter with its electrical control functions that deal with important phenomena's that occur in the power systems such as deviation of frequency from the nominal (frequency control) due to a loss of a generating unit from the grid. Also, it is noted that a large deviation of voltage from the nominal (Low voltage ride thru)is due to a three phase fault while a small deviation of voltage from the nominal (continuous voltage control)is due to small increments of load (morning or evening peak) on the network or post fault clearing after a large deviation of voltage [12],[13],[15],[16]. Conventional synchronous generators have control functions to deal with these issues and they include speed governor control (primary active power control) and automatic generation control (AGC) (secondary active power control). Speed governor deals with deviation of frequency from the nominal, while automatic voltage regulators (AVR) deals with voltage deviation from the nominal. [13],[14],[15],[17].In this paper emphases are given to modeling of continuous voltage control of inverters.

A. *Inverter grid following control and reactive power grid support functions*

Grid following control of inverters involves the control of injected currents into the grid with a specific phase angle difference with respect to the grid voltage at the PCC [18],[19].For the accurate calculation of the inverter instantaneous reference currents which will lead to the voltage reference, the fundamental frequency phasor of the grid voltage at the PCC is required at all times. Fig 5 shows a schematic diagram of grid-following control. The grid phase angle is calculated using a phase locked loop (PLL). The reference currents $i_{q\,ref}$ and $i_{d\,ref}$ are independent currents reference for reactive power control and active power control respectively. Grid support functions of voltage droop, fixed reactive power and fixed power factor control can be used to create $i_{q\,ref}$ for reactive power control. The functions are mutually exclusive.

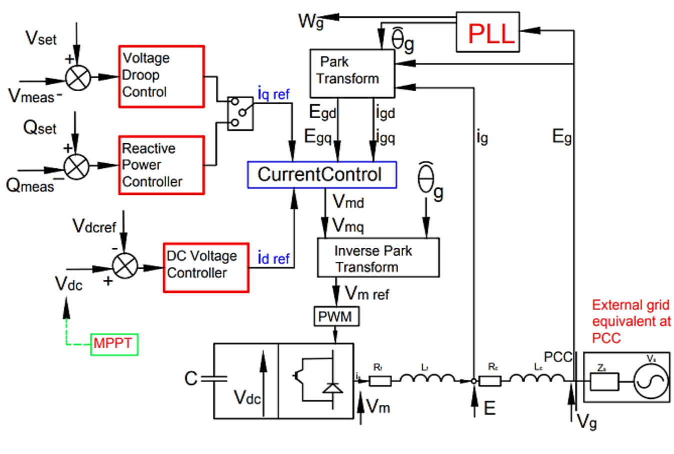

Fig. 5. Schematic of grid-following control.

A1. Voltage droop control

The voltage control function is used to regulate the voltage at the PCC. The reactive power is regulated and limited based on the upper and lower bounds of the plant reactive power limits as well as the upper and lower voltage limits as seen on Fig 4. A voltage value target is set and a specific droop settings of D to be used are specified. The corresponding reactive power is calculated based on equation (1). The reactive power changes as a function of measured voltage.

$$Q_{set} = \frac{Q_{max} \times (V_{set} - V_{meas})}{D \times (V_{nom})} \quad (1)$$

Where D (p.u) is the droop. V_{set} is the voltage target, V_{meas} is the voltage measured at PCC, Q_{max} is the plant maximum reactive power and $V_{nominal}$ is the nominal voltage at PCC [9].

A2. Fixed reactive power control

This control function is independent of change in active power or voltage at the PCC. The reactive power is set to a constant value within the reactive power limits and compared with the measured reactive power at PCC. Equation (2) illustrates this

$$Q_{set} = Q_{meas} \quad (2)$$

A3. Fixed power factor control

For fixed power factor the reactive power is set by measuring the active power at PCC to meet a specified power factor value. The following equations are used for this control.

$$P = S \times \cos(\emptyset) \quad (3)$$

$$Q = S \times \sin(\emptyset) \quad (4)$$

Where P is the measured active power Q is reactive power S is apparent power.

$$PF = \cos(\emptyset) \quad (5)$$

Where PF is power factor. Equation (4) can be written using equation (5) as

$$Q = \frac{P \times \sin(\emptyset)}{\cos(\emptyset)} \quad (6)$$

Using the math identity of equation (7), equation (4),(5)and (6) can be simplified to equation (8).

$$1 = cos^2(\emptyset) + sin^2(\emptyset) \quad (7)$$

$$Q_{set} = \frac{P \times (\sqrt{1 - PF^2})}{PF} \quad (8)$$

B. RMS and EMT Models

There are two types of models used in commercial power systems simulation software packages for power systems analysis (network planning, stability, protection coordination, faults) [12],[20]. These model types are the Root mean square (RMS) model and Electromagnetic transient models (EMT). The selection of the model type of simulation is strictly dependent on the specific power system phenomena to be studied [12],[20]. The inverter model functions to be modeled for an inverter based generator should be based on the relevant phenomenon to be investigated not the model types [12],[20].The type of dynamic study and the network conditions to be investigated determine the selection of the model type.

B1. Electromagnetic transient models

EMT programs model power system equipment to simulate high-frequency transients in power systems [12],[20]. This means they can be used to study the impact of power electronic equipment including high-frequency interactions of the controllers on system behavior [12],[15],[20]. The programs use small integration time steps of approximately 50us or less for their simulation [12],[14]. This is done so as to cover the appropriate bandwidth. Due to the small integration time steps EMT simulations are slow compared to RMS simulation. In order to reduce the computational burden when running large systems in EMT simulation it is recommended to focus only on were the high frequency event is occurring and let the other area of the networks to be studied in RMS [12],[20]. EMT programs solve the differential equations of the power system electrical network. This means that they can be used to illustrate the non-linear response of electrical devices, the effects of higher frequency transients, harmonics, unbalanced networks (negative and zero sequence components of transients) and detailed power electronic components including the interactions of the controllers of inverter based generators with other power electronic such as SVC in the power systems [12]. EMT models are usually used in scenarios were RMS programs are not accurate enough. These scenarios include: weak power systems were the short circuit ratio at PCC is below 3 [12] under these conditions the interactions of the controllers has a big effect on the power system [12],[14],[20]. EMT simulations are solved in the time domain i.e the solved problems produce solutions of a time series of voltage, currents etc which can be graphed. Frequency domain solutions can also be achieved, these can be beneficial for filter design [12],[20]. Power systems simulation software's like Digsilent, PSS, ETAP etc used for grid integration run EMT and RMS programs by allowing graphic user interface (GUI).This means that the user can construct the electrical network and power electronic devices with the controllers using building blocks that interact together e.g in Digsilent this can be the user defined models designed in Digsilent simulation language (DSL) interacting with the external modeled network. Detailed modeling of EMT models including the type of inverter models (discrete switch, average switch and simple source models), controller models (generic control models, detailed control models and exact control models), can be used depending on the level of modeling accuracy required and the type of power system study being performed [12],[13],[20].

B2. Root mean square models

RMS model types were mainly used to study electromechanical oscillations of power systems consisting of large synchronous generators and dynamic motors [12],[14],[20]. They are used under the assumptions of a balanced network i.e positive sequence fault component. The differential equations which arise from the power system elements are not solved completely as compared to EMT models. RMS programs use a numerical integration time-step

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in the range of 1-10 milliseconds, this means that there faster when simulating compared to EMT programs [12],[20]. RMS models focus on the operation of the power systems at the nominal frequency [12]. For systems operating several Hz above or below the nominal frequency or the analysis of harmonics it is recommended to use EMT programs. Due to the ability of RMS models solving the differential equations of the network quickly there more used than EMT on studying network transient stability [12]. The inverter models are simplified (averaged models or simple source) ignoring high switching changes of the power electronic and interactions of the controllers [12], [20]. The inverter model outputs are based only on the fundamental frequency hence high level detail of the inverter model for stability analysis is not necessary [12]. The operating range of the inverter models (normal and abnormal conditions) is limited due to modeling limits of RMS programs. RMS type models are not recommended on weak grids were weak grids are defined as a network having a short circuit ratio (SCR) at the PCC below three [12], [20]. As mentioned these grids are affected highly by controller actions hence EMT type models are recommended. RMS models are mostly recommended for electromechanical phenomena's, transient stability study (ability of the network to remain synchronies after a severe disturbance) and small signal stability (ability of the network to remain synchronies after a small disturbance)issues in the power system these include deviation of frequency and voltage in the network. Even though the study of these issues can also be achieved by EMT models, RMS models can achieve acceptable accurate results at a faster simulating time [12],[20].

When performing grid integration studies it is important to select the appropriate model type (RMS or EMT) depending on the study being carried out [12]. The modeling of the inverter interface and the controls are different depending on what model type selected. Advancements have been made in models of wind models for commercial simulation packages to study large renewable integration studies [15]. There are a few models available to the public for PV models to do grid studies on commercial simulation packages (Digsilent). Western Electricity Coordinating Council (WECC) have developed generic RMS PV models for the public to use which have been validated with actual PV plants with good accuracy [21],[22]. The WECC RMS PV model was recently developed for Digsilent software this model does not consider the energy source and DC voltage control modeling [23]. Generic models can be modified by the user in terms of model parameter changes to approximate what is required. EMT models are often developed by the manufacture of the product and are not accessible to the public [12]. The EMT models specifically resemble the actual physical inverter with its controls to be implemented for a PV plant hence confidentiality is of most important [12],[20]. The challenge is users who require EMT models need to sign strict non-disclosure agreements. Digsilent software has a built in template of a PV model but it lacks continuous voltage control which is required by the grid code. To the authors knowledge they haven't been a PV model in Digsilent software with continuous voltage control functions (fixed reactive power, fixed power factor and voltage droop control) considering also the modeling of the energy source with the DC voltage control being used for South Africa grid code compliancy. WECC RMS PV models ignore the energy source and DC control modeling [22]. Ref [24] implemented similar control functions but were based for the Germany grid code. RMS models should be developed for dynamic studies without increasing the computation burden so as to suit large scale grid integration studies whilst also being accurate enough to capture the necessary phenomena being studied [12].

C1. Model verification

The service operator (SO) require accurate dynamic simulation models from renewable power plant (RPP) developers to assess reliability, security and system stability. The dynamic simulation models must operate under RMS and EMT simulation to replicate the performance of the RPP facility or individual units under analysis [4],[9]. The dynamic models must represent the RPP performance and must include all the protection and control functions of the plant [4]. For detailed RPP design, the network service provider provides "the PoC, including the nominal voltages, expected fault levels, the busbar layout of the PCC substations, the portion of the network service provider's grid that will allow accurate and sufficient studies to design the RPP to meet the Grid Code" [4]. The test model and dynamic model data will be tested for grid compliance and network stability studies [4], [5]. After commissioning the RPP electrical dynamic simulation model is validated by comparing the model results with commissioning test data and measurements. The model parameters e.g controller gains are tuned until the model accurately resembles measured data [12].Fig 6 shows the summary of the grid integration process. It should be noted that the paper focuses of local controls of a PV inverter. Plant level control is usually used for large plants (20MVA) so as to coordinate the multiple inverters involved and to further refine reactive power control by including other reactive power sources like SVC. Different plant level AC collection designs are well explained in ref [25],[26],[27],[28]. Aggregated models of PV plants were multiple inverters are reduced to a single PV generator help to reduce computation burdens when simulating whilst also preserving PV plant dynamic responses. They simplify the load flow calculation process [12].The aggregated models are compared with detailed PV plants to validated the modeling [29]. Detailed models are suitable for the study or performance of an individual inverter within a plant during network faults [29].

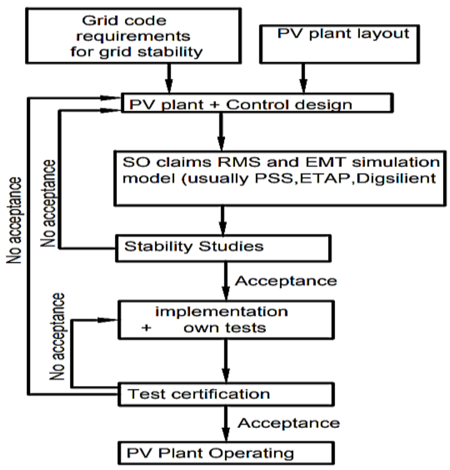

Fig. 6. Grid integration procedures

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IV. Modelling and Simulation

Fig 1 can also represent the inverter capability curve. The shaded area reflects the reactive power capability [30]. The PV inverter should be able to provide reactive power within the area defined by the reactive power range from -0.330 to 0.330 Q/Pn [30].Fig 7 shows the PV model frame with all its controls in DigSilent. This model uses static generator to represent the PV inverter model. The model has been modified to include static reactive power control to operate in the continuous voltage range. It is well known that the already existing generic model template in the library does not have a static voltage regulation [24], [31], [32]. Due to the nature of the grid phenomena being studied, an RMS model is used. It is also assumed that the external grid network at PCC is strong. The RMS stability model of the static generator is modeled as a current source this means the inputs id_ref p.u, iq_ref p.u, cosref (dq reference angle) and sinref (dq reference angle) control signals are inputs to the static generator [33]. For RMS studies the inner current control of Fig 5 can be ignored and the output reference currents are converted to three phase abc reference system using PLL angle and then injected directly into the grid whilst modeling the inverter as a current source. This is the simplest method that can be used whilst obtaining acceptable results. This is generally used in the feasibility stage of a project. The switching PWM (pulse width modulation) logic is also ignored [12], [20], [21].

Fig 8 shows the PV model connected to an external grid with an external voltage source. The voltage source was used to easily test the voltage control by incrementing the voltage within the continuous range at the PCC. The controls of this voltage source were designed in DSL (DigSilent Simulation Language). A two winding transformer was used to step up the low voltage from 0.34kV to11kV. The inverter (static generator) was selected to have an apparent power of 0.53 MVA and the PV array was modified to produce 0.5 MWp of solar power. The inverter size of 0.53 MVA gives enough reactive power range [-0.94PF to 0.94PF] for the inverter to operate for all control actions.

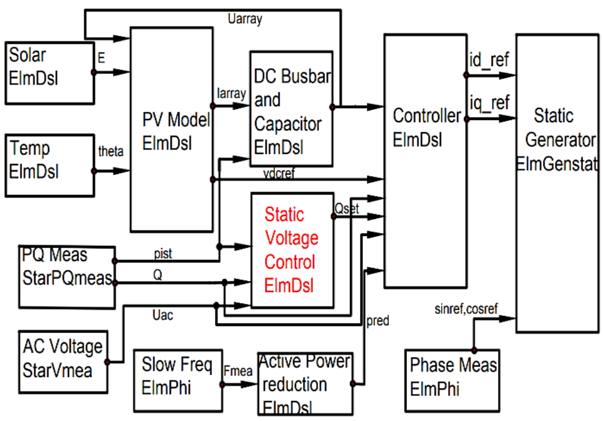

Fig .7. Local inverter control frame of the modified PV model

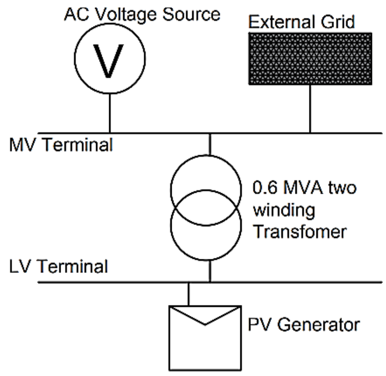

Fig. 8. The PV model connected to the external grid and voltage source

A. *Proposed Modification of the generic PV model*

Fig 9 shows the principle used to model the static reactive power control. The techniques and ideas were obtained from [23],[24],[34],[35],[36],[37],[38]. The reactive power strategy is designed to operate in three different modes depending on the system operator. The three modes are voltage control mode, constant power factor mode and fixed reactive power (Q control) mode. The input signals to the controls are reactive power (Q_{set}= Fixed Q) for fixed Q , voltage V_{meas} at PCC and V_{set} for voltage control and active power (P_{meas}) at the PCC and PF_{set} for fixed power factor control. Q_{set},V_{set} and PF_{set} are initialized though a load flow simulation were the values are manual set. The controller measures the input values, and according to the selected mode of operation, a Q_{set} output value is produced according to equations (1),(2) and (8). The Q_{set} is then compared with the measured value of reactive power at the PCC (Q_{meas}) as shown in Fig 9, and the difference is passed through a PI controller which track the Q_{set} value as close as possible (closed loop method). The PI controller uses upper and lower reactive power limits produced by the block called reactive power limits. The PI parameters were based on try and error method were the initial range of the parameters were obtained from other models e.g wind model in DigSilent template library. The limits are based on Fig 1. The output signal of the PI controller iq_ref is a reactive current component which then goes to the static generator modeled as a current source. The voltage grid phase angle is measured by the PLL (Phase Meas ElmPhi) (Fig 7).

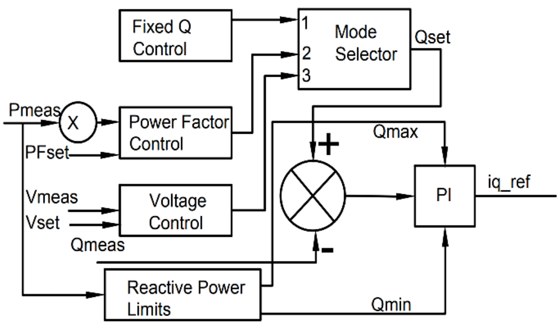

Fig. 9. Common model of power factor control, voltage control and fixed reactive power

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B. *Simulation results*

To test the generic model and the controls, two control scenarios were implemented and simulated. The first scenario was based on setting a parameter event of a decrease of solar irradiance (E) (Fig7) which resulted in a decrease of active power produced. Fig 10 shows the results of the injected active power and the effect of decrease in irradiance. This scenario was used to test for the constant power factor and fixed reactive power control techniques. A fixed reactive power of 0.102 Mvar (0.203 p.u base of 0.5 MW) was set. This value is within the inverter reactive power capabilities. The decrease of active power occurred at 5s. Fig 11 shows the response of the fixed reactive power control. Fig 11 shows that the control is independent of the reduction of the active power as it remained fixed at the set point of 0.203 p.u. The generic model does not have any static reactive power control as seen in Fig 11. A slight overshoot can be seen for the modified model due to the PI controller parameters. For the power factor control, a power factor of 0.95 was set. This allowed the inverter to participate in reactive power regulation if active power changes. All simulation values were set in per unit using a base of 0.5 MW. Fig 12 shows the comparison of the modified model and the existing generic model for fixed power factor control. As expected the generic model does not have static reactive power control so the reactive power was not regulated when active power was reduced at time 5s.

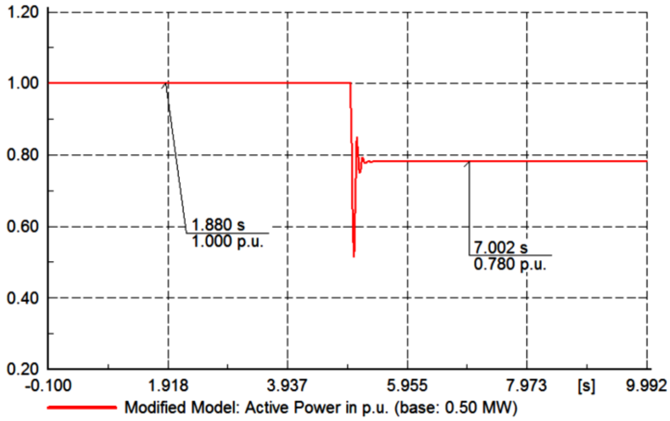

Fig.10. Active power produced by the PV inverter

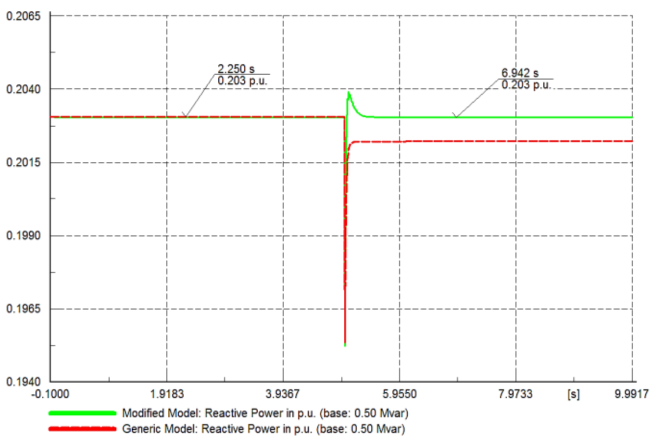

Fig.11. Fixed reactive power control of PV inverter

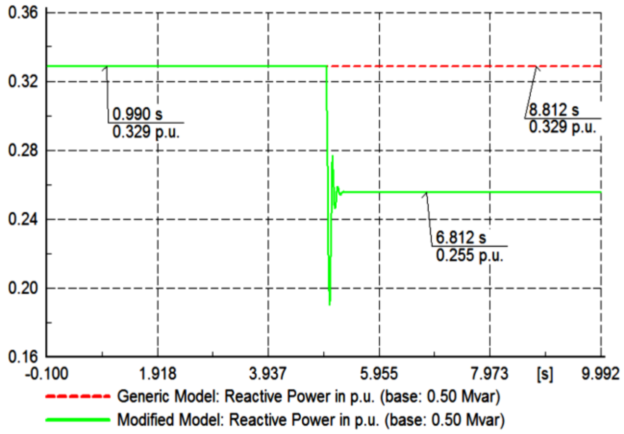

Fig. 12. Reactive power regulation using power factor control

A power factor of 0.95 shows that the inverter operate at its limit of reactive power regulation. It is observed that the modified model also reduced its reactive power proportionally to the decreases in active power after 5s which resulted in a constant power factor as shown in Fig 13. The power factor control of the generic model dropped to 0.921 which would not comply with the SA grid code as it is outside the allowed range.

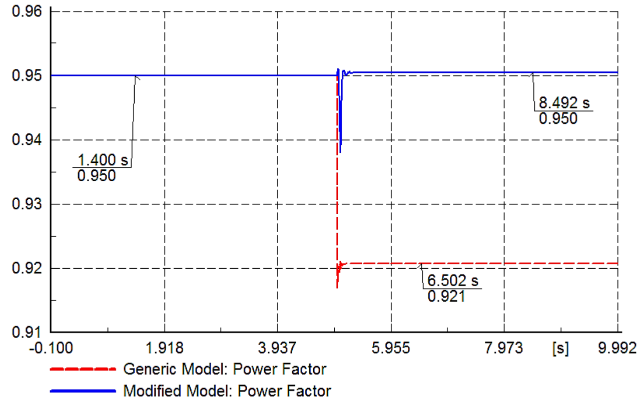

Fig .13. Power factor before and after a decreases in active power

For scenario 2, the external grid of Fig 8 was set to out of operation and the voltage source was used as an external grid. The controls for the voltage source were designed in DSL so as to simulate a disturbance at the PoC to test the voltage control mode. This mode of control was tested based on an increases in voltage and a decreases in voltage at the PoC. Fig 14 shows how the voltage level was increased. The response of the controller is shown in Fig 15. In Fig 15 the upper and lower limits are shown to illustrate that a further increase in voltage would result in going beyond the reactive power limits. The SA grid code states that when this happens other reactive power control devices like the on load tap changer transformers should take over to regulate the voltage. The controller can be seen to work as required by the SA grid code as shown in Fig 4. When the voltage increases the inverter or plant should absorb reactive power from the grid so as to regulate the voltage. When the voltage is at its nominal of 1 p,u no participation is required of reactive power hence a very minimal level can be seen of 0.001 p.u is observed.

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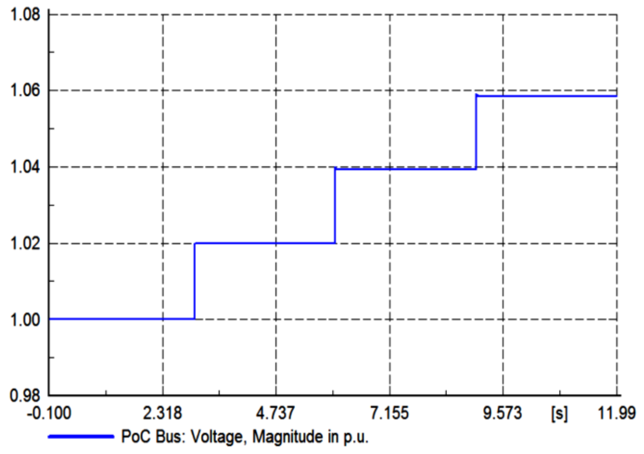

Fig .14. An increases in voltage at PoC

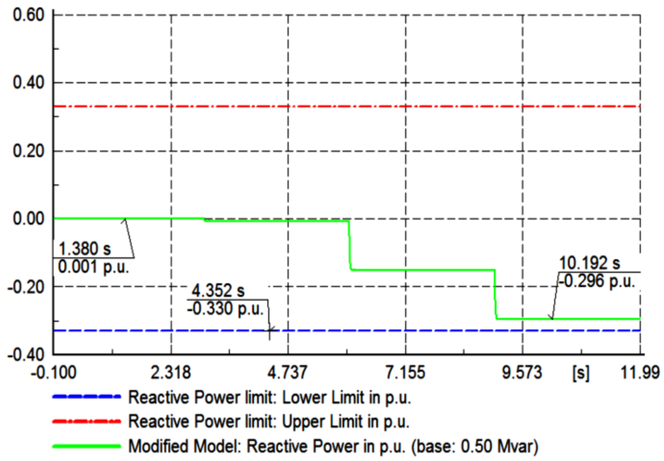

Fig.15. Voltage control response when voltage increase at PoC

Fig 16 shows the decreases in voltage at PoC while the response of the controller is shown in Fig 17. In this case the inverter supplies reactive power to the grid when the voltage decreases so as to regulate the voltage.

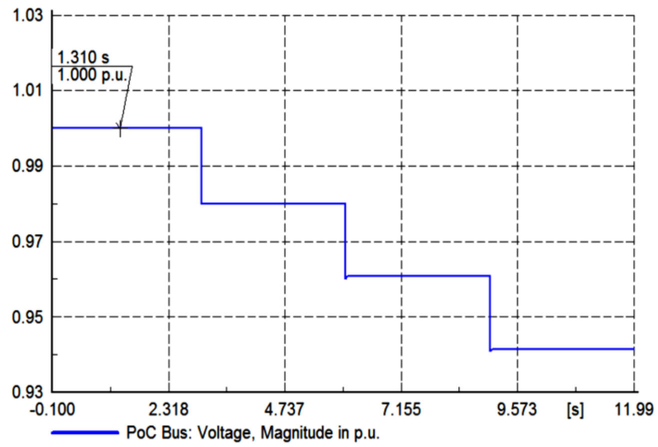

Fig.16. A decrease in voltage at PoC

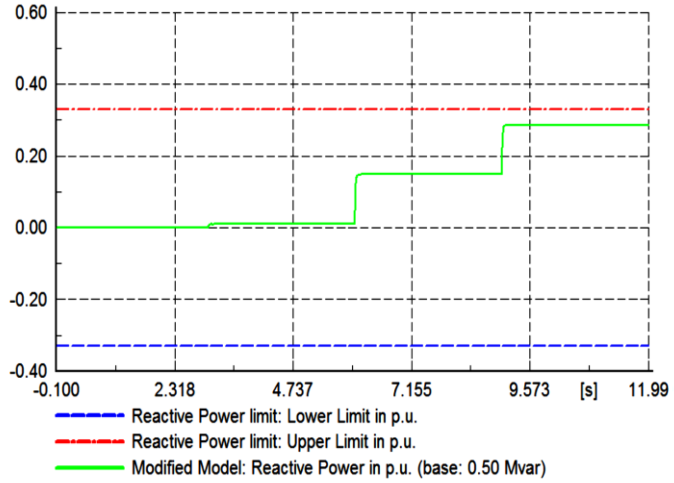

Fig.17. Voltage control response to a decrease in voltage at PoC

V. Conclusion

The local inverter controls have been shown to work according to the SA grid code. It should be noted that the model only went up to a power output of 0.5MW and followed the SA grid code category C of 20MVA and above. The model only serve as a reference of how a PV plant of category C should operate according to the SA grid code. The proposed controls (voltage control, fixed reactive power and power factor control) show sufficient behavior when voltage and active power changes at the PoC. The generic model in DigSilent library has an already built LVRT and power frequency response according to the Germany grid code. Further work is recommended to model the power frequency curtailment and the LVRT according to the SA grid code. The type of grid issue being studied plays a huge role on the selection of the model type. After the selection of the model type it is up to the user to know the level of detail required for a specific grid issue.

There are still many issues to be tested and improvements in order for the model to address other grid code compliances which include power quality studies and protection requirements. The controls investigated in this paper will allow more accurate PV plant modeling which would intern assist in better grid integration studies.

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