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PROPORTIONAL-RESONANT CONTROLLERS AND FILTERS FOR GRID-CONNECTED VOLTAGE-SOURCE CONVERTERS

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ABSTRACT: The recently introduced proportional-resonant (PR) controllers and filters, and their suitability for current/voltage control of grid-connected converters, are described. Using the PR controllers, the converter reference tracking performance can be enhanced and previously known shortcomings associated with conventional PI controllers can be alleviated. These shortcomings include steady-state errors in single-phase systems and the need for synchronous d–q transformation in three-phase systems. Based on similar control theory, PR filters can also be used for generating the harmonic command reference precisely in an active power filter, especially for single-phase systems, where d–q transformation theory is not directly applicable. Another advantage associated with the PR controllers and filters is the possibility of implementing selective harmonic compensation without requiring excessive computational resources. Given these advantages and the belief that PR control will find wide-ranging applications in grid-interfaced converters, PR control theory is revised in detail with a number of practical cases that have been implemented previously, described clearly to give a comprehensive reference on PR control and filtering.

I. INTRODUCTION

Fault studies are important in large scale grid connected renewable energy systems and have been reported in the technical literature. However, most of these studies focused on grid connected wind power plants. In the case of grid connected photovoltaic (PV) power plants (GCPPPs), research reported thus far focused on fault ride through (FRT) capability. Specifically, a three phase current source inverter (CSI) configuration was investigated under various fault conditions, in which the output currents remain limited under all types of faults due to the implementation of a current source model for the inverter. However, this configuration may lead to instability under dynamic conditions. Three phase voltage source inverters (VSIs) are used in grid connected power conversion systems. Due to the increasing number of these systems, the control of the VSIs is required to operate and support the grid based on the grid codes (GCs) during voltage disturbances and unbalanced conditions. Among several studies for unbalanced voltage sags, a method was introduced in to mitigate the peak output currents of a 4.5 kVA PV system in nonfaulty phases. Another study in presented a proportional resonant (PR) current controller for the current limiter to ensure sinusoidal output current waveforms and avoid over current. However, in the mentioned studies, reactive power support was not considered. In a study dealing with the control of the positive and negative sequences was performed.

Two parallel controllers were implemented, one for each sequence. The study demonstrated the dynamic limitations of using this control configuration due to the delays produced in the current control loops. A study was reported in for the control of the dc side of the inverter, which shows the impact of various types of faults on the voltage and current of the PV array. Considering FRT strategies for grid connected VSIs, some research has been done on wind turbine applications and also on VSI based high voltage direct current (HVDC) systems. Some of these studies are based on passive control, e.g., crowbar and chopper resistors, where as others are based on active control schemes. Although both categories can provide FRT capability, the passive methods have the drawbacks of requiring additional components and dissipating significant power during the voltage sag processes. In the application of hybrid with the configurations of single stage conversion (single stage conversion means direct connection of the PV source with wind to the dc side of the VSI), some research were done in evaluating the FRT issues of both ac and dc sides of the inverter under unbalanced voltage conditions.

However, in the application of a two stage conversion (meaning a dc/dc conversion or preregulator unit exists between the PV source and VSI), no project so far has proposed a comprehensive strategy to protect the inverter during voltage sags while providing reactive power support to the grid. All the designs and modifications for the inverter in both the single and two stage conversions have to accommodate various types of faults and address FRT capability based on the GCs. PV inverter disconnection under grid faults occurs due to mainly

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three factors: 1) Excessive DC-link voltage 2) Excessive alternating currents and 3) Loss of grid voltage synchronization, which may conflict with the FRT capability. In this project, the control strategy introduced in for a single stage conversion is used, although the voltage sag detection and reactive power control is modified based on individual measurements of the grid voltages. The main objective of this project is to introduce new control strategies for the two stage conversion in hybrid that allow the inverter to remain connected to the grid under various types of faults while injecting reactive power to meet the required GCs. Some selected simulation results for single and two stage configurations are presented to confirm the effectiveness of the proposed control strategies.

II. PHOTOVOLTAIC INVERTER

The basic block diagram of grid connected PV power generation system is shown in Fig. 1.The PV power generation system consists of following major blocks:

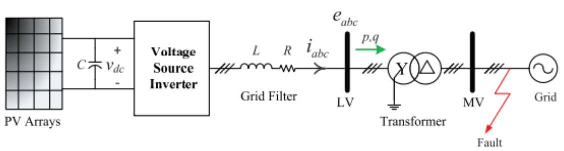

Fig 1 :Schematic of the GCPPP case study

1. PV unit : A PV unit consists of number of PV cells that converts the energy of light directly into electricity (DC) using photovoltaic effect.

2.Inverter : Inverter is used to convert DC output of PV unit to AC power.

3.Grid : The output power of inverter is given to the near by electrical grid for the power generation.

4.MPPT : In order to utilize the maximum power produced by the PV modules, the power conversion equipment has to be equipped with a maximum power point tracking

(MPPT).It is a device which tracks the voltage at where the maximum power is utilized at all times.

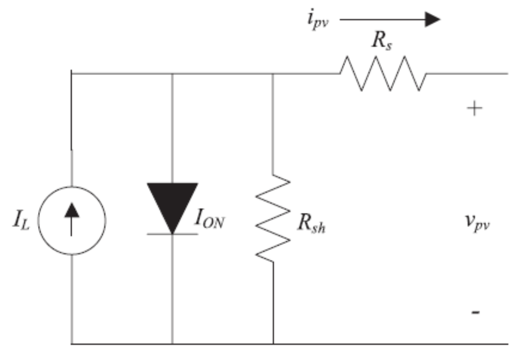

Fig..2 Equivalent Circuit Diagram of PVCell

$$i_{pv} = I_L - I_s[\exp[\alpha(v_{pv} + R_s i_{PV})] - 1] - \frac{v_{pv} + R_s i_{pv}}{R_{sh}}$$

2.1 MPPT: (Maximum Power Point Tracking)

Maximum power point tracking (MPPT) is a technique to maximize the energy obtained over all normal operating conditions. The use of MPPT can reduce the cost of energy by making the system more efficient. The problem raised by MPPT methods is to automatically find the voltage or current (V_{mp}, I_{mp}) in which a PV array works on its maximum power point under a certain irradiance and temperature. There are many techniques to realize the MPPT. However, most techniques respond to both irradiance and temperature variations but some responds to constant temperature.

2.1.1 Perturb and Observe algorithm

At present, the most popular MPPT method in the PV systems is perturb and observe. In this method, a small perturbation is injected to the system and if the output power increases, a perturbation with the same direction will be injected to the system and if the output power decreases, the next injected perturbation will be in the opposite direction.

The Perturb and observe algorithm operates by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage and comparing the PV output power with that of the previous perturbation cycle.

If the PV array operating voltage changes and power increases, the control system moves the PV array operating point in that direction, otherwise the operating point is moved in the opposite direction.

In the next perturbation cycle, the algorithm continues in the same way. The logic of algorithm is shown in flow chat ig 3. A common problem in perturb and observe algorithm is that the array terminal voltage is perturbed every MPPT cycle, therefore when the maximum power point is reached,

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the output power oscillates around the maximum power point resulting in power loss in the PV system.

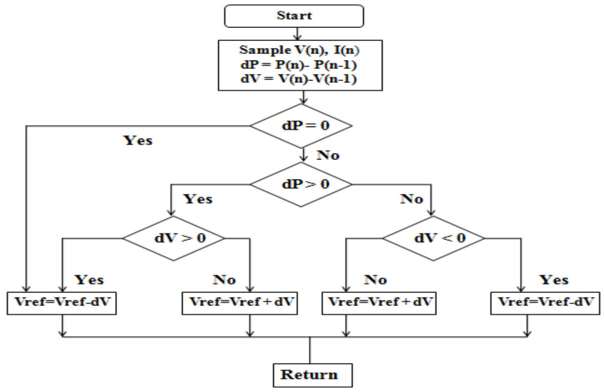


Fig 3. Perturb and Observe

III . DC-DC CONVERTER BASICS

A DC-to-DC converter is a electronic circuit or electromechanical device that converts a source of direct current(DC) from one voltage level to another.It is a type of electrica power converter.Power levels range from very low (small batteries) to very high (high-voltage power transmission).It is a gadget that acknowledges a DC info voltage and produces a DC yield voltage. Normally the yield delivered is at an alternate voltage level than the info. Also, DC-to-DC converters are utilized to give clamor confinement, force transport regulation, and so on. This is a synopsis of a portion of the prevalent DC-to-DC converter topologies.

3.1 Boost Converter

The schematic in Fig.3.6 shows the basic boost converter. This circuit is used when a higher output voltage than input is required.

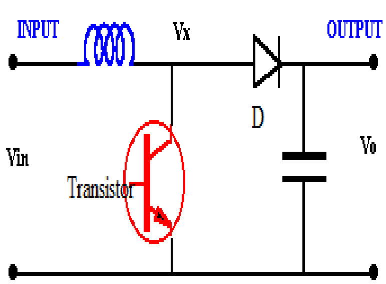
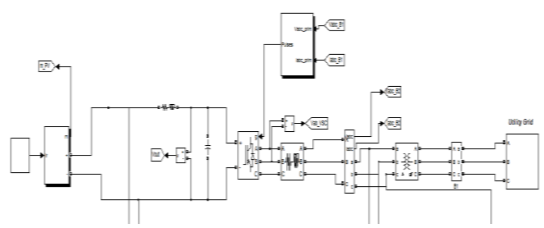


Fig.4 Boost Converter Circuit

While the transistor is ON $V_x = V_{in}$, and the OFF state the inductor current flows through the diode giving $V_x = V_o$. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in Fig.4 and the average must be zero for the average current to remain in steady state

IV. OPERATION&CONTROL OF PROPOSED MODEL

In this section, a 1-MVA single-stage GCPPP with WIND system is considered. It is modelled using MATLAB/Simulink and the system main specifications are summarized in Table 1 and Fig.5 shows the model of the schematic diagram of a single stage HYBRID conversion.By concerning the FRT capability, the inverter disconnection factors are illustrated according to the GCs it is explained in chapter



5.

Fig 5 model of proposed system

4.1 Grid Voltage Synchronization

In grid connected inverters, one important issue is the voltage phase angle detection. This is usually performed by phaselocked-loop (PLL) technique based on a synchronous reference frame PLL (SRF-PLL), known as conventional PLL. The conventional PLL configuration does not perform well under unbalanced voltage sags and consequently may lead to the inverter being disconnected from the grid. Several methods were proposed to extract the voltage phases accurately under unbalanced voltage conditions. In this project, the method based on moving average filters (MAFs) introduced in is applied, which was also used in showing very satisfactory performance. In this method, the positive sequence of the voltage is extracted from the grid by means of an ideal low-pass filter. Then, the angle of the positive sequence is detected.

4.2 Excessive AC Current

Commercial grid-connected inverters have a maximum ac current value specified. If any of the

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currents exceed such value, the inverter is disconnected from the grid. Under a grid voltage sag, the d-component of the current (in the SRF) increases because the controller wants to maintain the active power injected into the grid and grid voltages are temporarily reduced. In addition to the increase of the d current component, the inverter has to inject reactive current during the fault to meet the FRT requirements. The amount of reactive current is assigned according to the droop control given in eqn(5.1). Since the d and q current components increase, this may lead the over-current protection to disconnect the inverter from the grid. In this case study, according to the specifications of the PV modules and their numbers of being connected in series and parallel given in Table .1, the maximum power injected under standard test conditions (STC) is 1.006 MW. This power gives a rated rms current value of 1399.5 A (a peak value of 1979 A) at the low-voltage (LV) side of the transformer considering 100% efficiency for the hybrid. According to the the inverter datasheets, the maximum acceptable output current at the LV side of the transformer is 1532 A (a peak value of 2167 A). In the case of a fault, e.g., a single-line-to-ground (SLG) voltage sag at the MV side of the transformer as the one presented in the waveforms of Fig.7 the output currents exceed the limits. This will lead to inverter disconnection, although it is not applied in this simulation. Unbalanced and distorted currents are produced because the instantaneous output power and the dc-link voltage have low-frequency ripples, and therefore, the active current reference contains low-frequency ripples as well. The final reference for the d current component (i_{dref}) should be limited considering the need of reactive current injection as shown in Fig.6

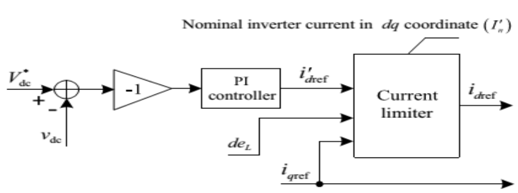


Fig.6 Control Diagram of the Current Limiter 4.3 Excessive DC-Link Voltage

If the active current reference is limited, i.e. $i_{dref} < i_{dref'}$, the generated power from the PVs is more than the injected power into the electrical grid. As a consequence, some energy is initially accumulated into the dc-link capacitor, increasing the dc bus voltage as shown in output waveform of Fig.7.4(c). In a single-stage hybrid, as the dc-link voltage increases, the operating point on the I−V curve of PV array moves toward the open-circuit voltage point (V_{OC}), which leads the PV current to decrease, as shown in Fig.6.3. The power generated by the PV panels is reduced because the operating point is taken away from the maximum power point (MPP) and therefore, less active current is injected into the ac side. This happens until the hybrid reaches a new steady state where the dc-link voltage stops increasing. Thus, single-stage hybrid system is a self-protected because the generated power is reduced when the dc-link voltage increases under ac faults.

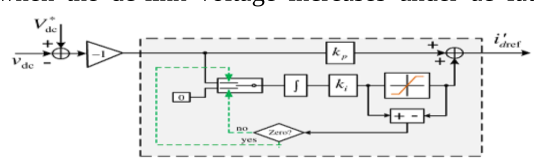


Fig.7 PI Controller with Anti-Wind-up Technique

V. SIMULATION RESULTS

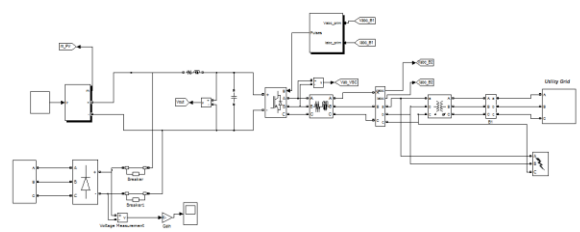
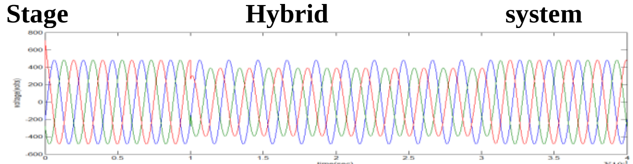


Fig.7 Simulated Circuit Diagram of a Single-Stage Hybrid system



(a)

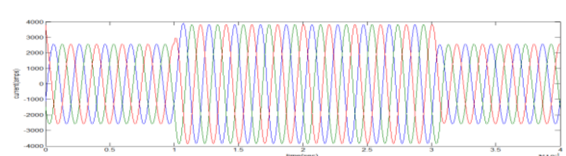


Fig.8 Output Waveforms of a (a) Grid Voltages (b) Grid Currents at the LV side under 60% SLG Voltage Sag produced at MV side of the Transformer

5.1 Add current limiter

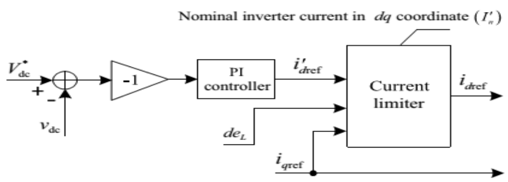
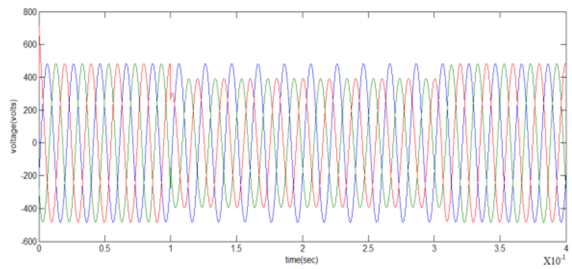
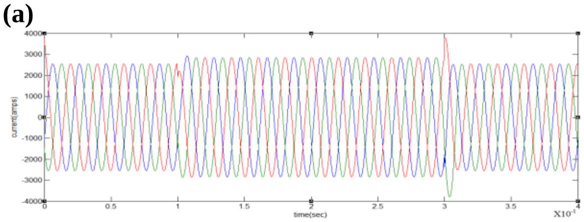


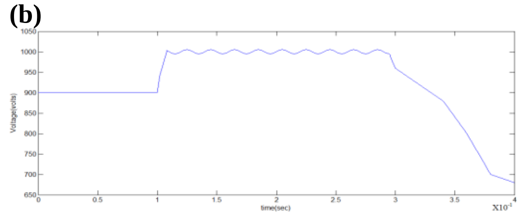
Fig 9 Control Diagram of the Current Limiter



(a)



(b)



(c)

Fig 10 Adding the Current Limiter to the VSI to Control (a) Grid Voltages ,(b) (c) Grid Currents DC-Link Voltage under an SLG Voltage Sag produced at MV side of the Transformer.

5.2 PI Controller with Anti-Wind up technique:

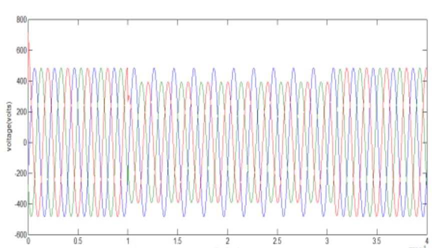


Fig.11 Application of an Anti-Wind up Technique to the PI Controller of a Grid Voltages under 60% SLG Voltage Sag produced at MV side of the Transformer

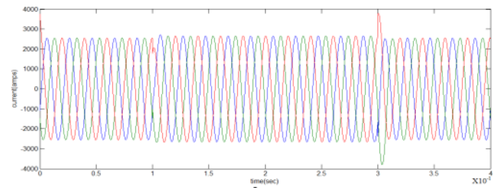


Fig.12 Application of an Anti-Wind up Technique to the PI Controller of a Grid Currents under 60% SLG Voltage Sag produced at MV side of the Transformer

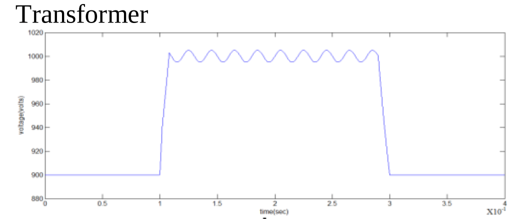


Fig.13 Application of an Anti-Wind up Technique to the PI Controller of a DC- Link voltage under 60% SLG Voltage Sag produced at MV side of the Transformer

VI . CONCLUSION

In this paper, single- and three-phase PR control schemes have been reviewed and their implementation options and suitability for current/voltage control of grid-interfaced converters evaluated. Advantages of the PR controllers include the possibility of tuning their individual resonant peaks to the grid frequency for precise fundamental reference tracking and to some low-order harmonic frequencies for selective harmonic compensation, and the possibility of implementing harmonic reference generator in the stationary frame needed for active filters. Implementation wise, the PR technique requires lesser computational overhead and does not require an explicit grid voltage feedforward control path, while still achieving the same performance as a synchronous PI controller. For three-phase systems, the PR technique also has the unique feature of compensating for both positive- and negativesequence components simultaneously, unlike synchronous PI where separate frame transformations are needed. Given these advantages, it is in the view of the authors that PR controllers can certainly replace their PI counterparts. This view has been supported by some recent developments summarised in the paper for a comprehensive review on PR control.

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