Design and implementation of a DC-DC converter for photovoltaic applications

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Abstract — **This paper presents the modeling, design and simulation of a DC–DC converter suitable for photovoltaic applications. A Push-Pull topology has been chosen with peak current control (CIC) technique. In a first step the Push-Pull electrical design is made for a 200W nominal power and 380VDC output voltage. Following this a Push-Pull small signal model is presented, from which they are derived all transfer function needed to implement the controllers that regulate the output current, input voltage and the interacting with the MPPT algorithm. Additionally, is presented the algorithm of maximum power point tracking (MPPT), implemented. Finally, the simulation results are presented.**

Index Terms— **Maximum power point tracking (MPPT), Peak current control, Photovoltaic systems, Push-Pull converter, Small-signal model.**

I. INTRODUCTION

Sustainable energy development makes an essential part in the present day energy systems research, with solar energy as one of the highest rising and promising impact. Thus, renewable energies such as solar, wind, hydroelectric and biomass have taken an important role to solve these energy disruptions. Photovoltaic energy is considered to be one of the most useful natural energy sources because it is free, abundant, pollution-free, and distributed throughout to the Earth. Solar cells are the main element in the PV array, since they convert solar radiation into electricity, due to the photons absorption [1].

The efficiency of photovoltaic panels can be improved by forcing the panel to operate at its maximum power point (MPP). For this reason several methods for extracting the maximum power have been proposed as Fixed Duty Cycle, Constant Voltage, Perturb and Observe (P&O), Incremental Conductance (IC), Ripple Correlation, fuzzy logic, neural network and others.

The microgrids are the beginning of the shift to a distributed generation system, where generation points are close to the consumer points and the network energy flux is bidirectional for the optimal use of renewable energy sources. In addition, the use of local energy sources to serve local loads helps to reduce energy losses in transmission and distribution, further increasing efficiency of the electric delivery system [2].

Thus, the DC-DC converters are widely used in the photovoltaic generation systems as an interface between the PV power source and the inverter that injected energy to the grid, allowing modifications in the operating point of the cells, thereby adjusting the extracted power and tracking the maximum power point [3]. The converters are essential elements in the generation stages, transport and distribution of electrical systems, since these devices allow a more flexible power swap between sources and loads. In this way, these are used as impedance adapter using the duty cycle, which can be controlled. Therefore the power electronic converters hold great importance in development of a microgrid. For example the DC-DC converters provide easier interconnection and reliability of various renewable sources to bus line of a DC microgrid [4].

On the other hand, for any system, it is essential to have a control which ensures its stability. Thus, for power electronic converters are numerous control techniques such as voltage control, average current control mode and peak current control mode (CIC), which are different in the design level complexity and the number of components required for implementation, which finally has an impact on the cost.

It should be noted that the non-linear nature of the PV module I-V curve demands some technique to track the Maximum Power Point. The MPPT technique is used in photovoltaic systems to maximize the photovoltaic array output power, independently of the load electrical characteristics and for different environmental conditions. Thereby several MPPT techniques have been developed like perturb and observe, incremental conductance, artificial neural network, fuzzy logic, etc. [5]. These methods vary in complexity, range of effectiveness, implementation hardware, cost, sensors required, convergence speed and other important aspects at the moment to choose an adequate technique [6].

This paper is organized as follows: The design and modeling of Push-Pull converter are analyzed in section II, the peak current control design and the MPPT technique are presented in section III and IV, respectively. The simulation results are given in Section V and finally the conclusions are presented.

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II. Design And Modeling Of The Dc-Dc Converter

This paper focuses on the development of control strategies to find the maximum power point (MPPT) in a photovoltaic power generation system, using DC-DC converters that can produce the bus DC voltage suitable to connect an inverter. In this paper has been chosen a push–pull DC/DC converter, this topology is a good choice for low input voltage and medium power. In other way it is necessary to provide galvanic isolation between the PV array and the external load without losing high conversion efficiency within a wide input voltage range which is characteristic for PVs. Table I presents the values of the parameters of the push-pull converter to be implemented.

TABLE I. Parameters of the Push-Pull Converter

Push-Pull Converter	
Parameter	**Value**
Panel voltage variation, Vs	23 V – 36.5 V
Switching frequency, fs	20 kHz
Duty cycle variation	0.26 – 0.413
Current panel in the MPP, Ipv	7.5 A
Injected power by panel, P_{pv}	200 W
Output Voltage ,Vo	380 V
Transformer turns ratio	20
Output Current, Io	0.526 A
Input Capacitor, Cin	8 mF
Inductance, Lx	22 mH
Output Capacitor, Co	4700 µF

The main disadvantage of a push-pull converter is the electrical stress that must be withstand by the power transistors, but this is not a drawback in low input voltage applications.

The DC-DC converters are nonlinear circuits, for this reason they must be linearized around an operating point in order to apply linear control techniques. The model developed in this paper is based on the PWM switch model because this is a simple and versatile method to be used in comparison with the other ones and explains the small signal behavior of converters in continuous and discontinuous conduction mode. In addition it is possible to provide results close enough to reality [7] [8].

The equivalent circuit of the push–pull converter at the operating point is shown by Fig. 1.

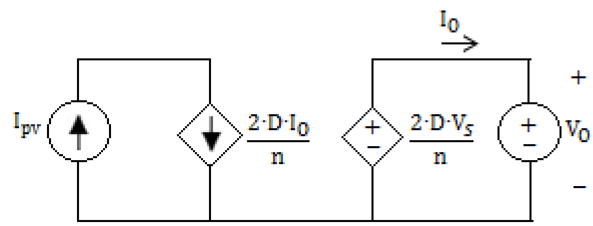

Figure 1. Equivalent circuit of the push–pull at the operating point.

From Fig. 1 the following relationship can be established:

$$Vo = \frac{2 \cdot D \cdot Vs}{n} \quad (1)$$

The transformation ratio is defined as $n = N_p/N_s$. Therefore, after the linearization around the operation point, the small signal model of the Push-Pull is shown in Fig. 2. Should be noted that the quantities written in lowercase with the symbol "^" mean small-signal terms and the uppercase quantities are operation point values.

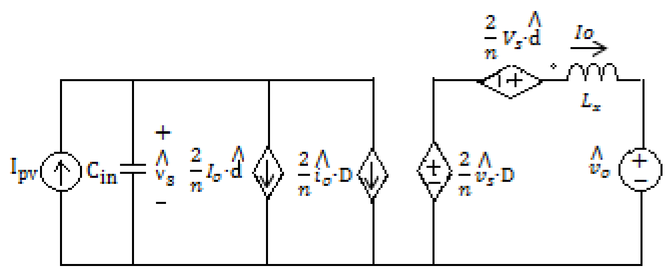

Figure 2. Small signal model of the push–pull converter.

III. Push Pull Control

The technique selected is the peak current control mode, because is a simple technique with fast disturbances correct, increase the converter bandwidth and it works as overcurrent protection. Also, this control method provides greater stability and control the system using two feedback loops (Feedback and Feed Forward). Although the modulator modeling is more complex, it is possible to achieve greater accuracy of system behavior because of the sampling effect [9]. Fig. 3 shows the voltage control loop and the current for the Push-Pull converter.

From the figure, the current loop is defined as:

$$Ti(s) = G_{i_o-d}(s) \cdot F_M \cdot k \cdot Ri \cdot He(s) \quad (2)$$

For the current loop, Ri is the current sensing gain ($\mathrm{Ri} = 0.02\,\mathrm{V/A}$), k is inverse of the turns ratio, $He(s)$ is the sampling gain and F_M is the gain of the PWM modulator.

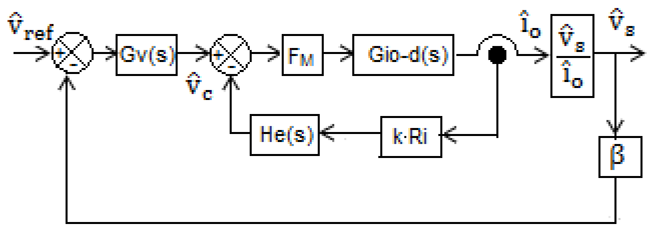

Figure 3. Control loops of current and voltage for the Push-Pull converter.

From the small signal model of the Push-Pull converter is derived the transfer function $G_{i_o-d}(s)$, which relates the duty cycle to the output current. The transfer function is expressed as:

$$G_{i_o-d}(s) = \frac{\frac{2}{n}\left(k_{pv}\cdot V_s - s\cdot C_{in}\cdot V_s + \frac{2}{n}\cdot D\cdot I_o\right)}{-\frac{4}{n^2}\cdot D^2 + s\cdot k_{pv}\cdot L_x - s^2\cdot L_x\cdot C_{in}} \quad (3)$$

After obtaining the transfer functions, it is necessary to find the sampling gain *He(s)*, which is very important in the inner loop current analysis for stability reasons. Because it adds to the current loop two complex conjugate non-minimum phase zeros at half the switching frequency [10]. Then:

$$He(s) = \frac{s\cdot T_s}{e^{sT_s}-1} \approx 1 + \frac{s}{\omega_z\cdot Q_z} + \frac{s^2}{{\omega_z}^2} \quad (4)$$

Where

$$\omega_z = \frac{\pi}{T_s} = 62832$$
$$Q_z = -\frac{2}{\pi} = -0.6366 \quad (5)$$

Therefore,

$$He(s) = 2.533\cdot 10^{-10}\cdot s^2 - 25\cdot 10^{-6}\cdot s + 1 \quad (6)$$

The following step is to determine the gain of the PWM modulator, F_M is defined as:

$$F_M = \frac{1}{m_c\cdot S_n\cdot T_s} \quad (7)$$

There, *Sn* is the slope of the sensed ramp and m_c is a factor which evaluates the degree of stabilization by the external ramp. In order to determine the value of *mc* that makes the current loop stable, it is necessary to perform a sweep of Ti(s) in function of such parameter. Thus, for mc= 7, the phase margin is 69.1°and bandwidth of 2.32 kHz.

Also, for the voltage control loop $Tv(s) = G_{v_s-v_c}(s)\cdot\beta\cdot Gv(s)$, Gv(s) is the voltage controller, β is the voltage sensor gain, in this case β =0.05, and $G_{v_s-v_c}(s)$ is the transfer function from the control voltage to the input voltage of the push–pull converter.

Thus, the voltage controller sets the reference signal for the current control loop to regulate the push–pull input voltage; this was implemented using a PI controller. The expression of the controller results to be:

$$Gv(s) = \frac{8.558s + 611.3}{s} \quad (8)$$

With the proposed controller, a phase margin of 88.8 ° and a bandwidth of 300 Hz are achieved. This crossover frequency for the voltage loop was selected so that this value to be much smaller than the crossover frequency of the current loop, but not too small to slow down the control action, because the voltage loop should be much faster than the operating frequency of the MPPT in order to prevent interactions between them.

IV. MPPT TECHNIQUE

The MPPT technique selected was "Perturb and Observe (P&O). Fig. 4 shows the flowchart of this algorithm.

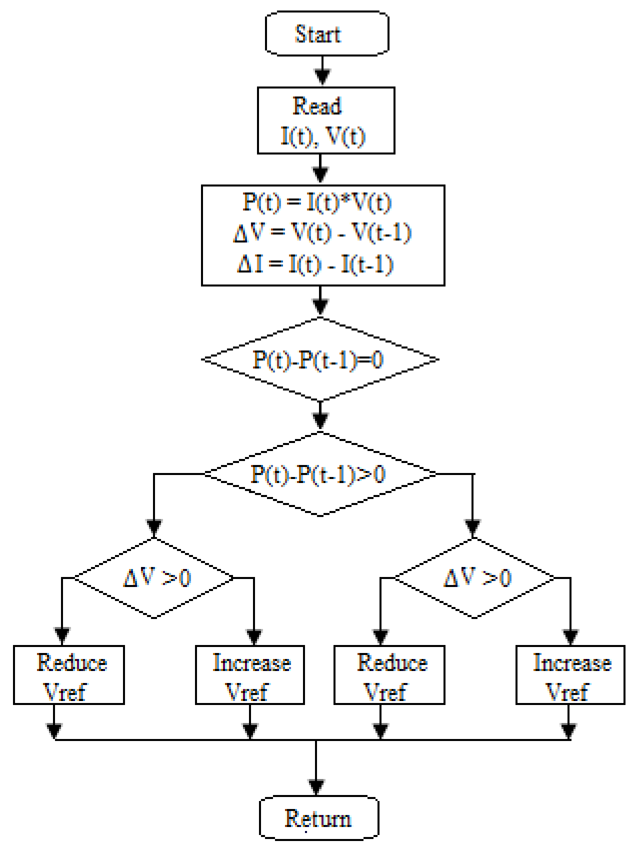

Figure 4. Flowchart of P&O algorithm.

This technique was chosen because it is widely used for its simplicity of operation and the few variables to be measured for effective results in tracking the maximum power. P&O method operates periodically incrementing or decrementing the array terminal voltage, through the converter duty cycle and then comparing the power obtained in the current cycle with the power of the previous perturbation cycle. Therefore, if the actual measured power is greater than the previous cycle, the disturbance will continue in the same direction in the next cycle. That is, if the array terminal voltage varies and power increases, the control system moves the operating point of the PV array in that direction; otherwise change the operating point in the opposite direction.

V. Simulation Results

After designing the peak current control and the MPPT algorithm, the control loops were simulated through PSIM software. The integrated circuit UC3825 was selected to implement the current control because this is a stable high speed PWM controller and is optimized for high frequency switched mode power supply applications.

Thus, to obtain the PWM signal, it is necessary the sensed current and the external stabilization ramp. So, these signals are shown in Fig. 5.

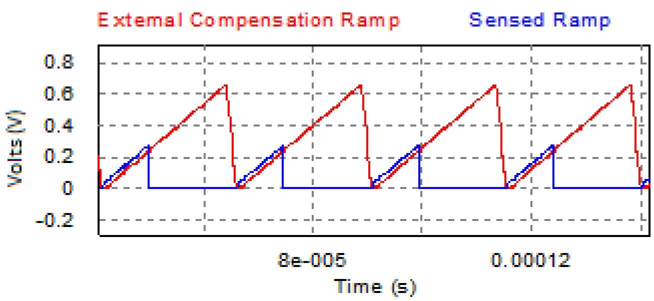

Figure 5. Sensed ramp Sn and external compensation ramp Se.

The sum of the sensed ramp and external compensation ramp is shown in Fig. 6. Additionally, the PWM signal generated is shown in Fig. 7. It should be noted that the PWM modulator output takes a high level when the sensed ramp (Sn) is activated.

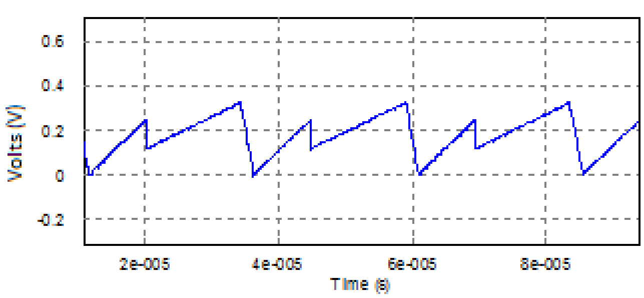

Figure 6. Sum of the sensed ramp and external compensation ramp (Sn+Se).

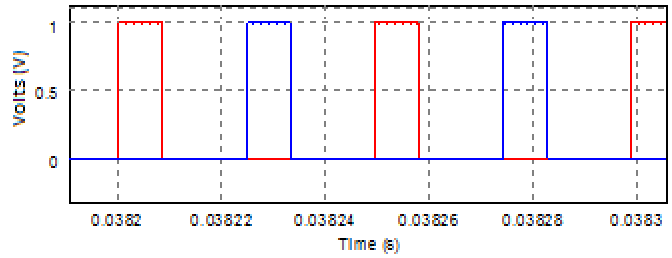

Figure 7. PWM signal.

The MPPT results are shown in Fig. 8 can observe the changes of voltage and current according different irradiance conditions.

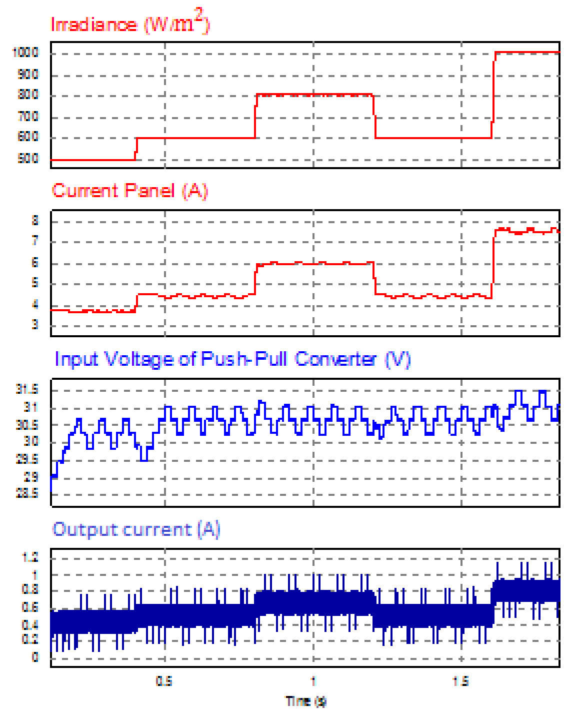

Figure 8. Main waveforms of voltage and current of the push–pull according to changes of irradiance.

In this figure it can be seen that regardless the irradiance changes, the converter input voltage remains almost constant and the output current varies according to the power from the panels, ensuring correct performance of the P&O algorithm used to maximize the power of the PV system.

The sampling frequency was adjusted at 50Hz in order to avoid interference with the voltage controller frequency; this value was selected after performing different tests and analyzes results of simulation. Importantly, this sampling frequency achieves a quicker response time to changes in irradiance.

VI. CONCLUSIONS

It was designed and simulated a dc-dc converter able to steps up the voltage to 380VDC with a nominal power of 200W. Using the PWM switch model, a small signal model was obtained making possible to determine the different transfer functions, in order to simulate the CIC control. In addition a P&0 algorithm was development causing the PV array output voltage to fluctuate around the MPP voltage as shown in final results.

Different parameters were taken into account, including cost, efficiency, size, isolation y design complex. Also the electrical variables as input voltage, output voltage and nominal power were the main reason to choose the appropriate topology. In this way a Push.-Pull converter was chosen to work in continuous mode, achieving a high output voltage from low input voltage at low-medium power range with input isolation.

The peak current control technique is an optimal choice because it provides overcurrent protection cycle to cycle. Thus, if the magnetic components are saturated or if a short circuit is generated, the control provides a quick response to protect the semiconductor devices.

Finally, the efficiency of a photovoltaic system is closely related with tracking the maximum power point. But the constant changes in environmental conditions (temperature and irradiance) make it difficult to keep the photovoltaic modules working in the MPP. Thus there are many maximum power point tracking techniques each one with inner parameters; therefore it is not possible to make a comparison between different algorithms widely equal. For this research was chosen the Perturb and Observe technique as it is a low cost method, ease of implement and efficient results were obtained with the rate of convergence.

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