

A Voltage Regulator Based in a Voltage-Controlled DSTATCOM with Minimum Power Point Tracker

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Abstract— This paper presents a voltage regulator based in a Distribution Static Synchronous Compensator (DSTATCOM) applied to low voltage distribution grids. The DSTATCOM consists in a three-phase four-wire Voltage Source Inverter (VSI) connected to the grid through a second order low pass filter. The control structure is composed of three output voltage loops with active damping and the two dc bus loops. In addition, a new concept of Minimum Power Point Tracking (mPPT) is introduced, forcing the DSTATCOM to operate with the minimum power. In certain conditions, this means no compensation. The dynamic models of the converter are presented, as well as the control design. Simulation results show the capacity of regulation and the features of the mPPT.

I. INTRODUCTION

In low voltage distribution grids, end users have some issues concerning the voltage regulation, which may drop below the allowable levels. In this case, the power distribution company has a constrained deadline to solve these issues. The time needed to apply a definitive solution, like capacitors banks, can require more time than the deadline allows.

After the deadline, the distribution company must refund the affected users in such distribution grid, as long as the voltage problem persists [1].

In order to avoid the refunds, a mobile voltage regulator is suggested. The voltage regulator must have a fast voltage regulation, low volume and easy installation [2], [3].

To ensure the characteristics described, a DSTATCOM connected in parallel with the utility grid is proposed, as shown in Fig. 1. The DSTATCOM uses a VSI as power circuit with a high frequency output filter, Fig. 2, and a suitable control structure.

In voltage controlled DSTATCOM, the Point of Common Coupling (PCC) voltages are the output voltages of the converter and the DSTATCOM can maintain the PCC balanced, irrespective of unbalanced in the grid voltage or at the load. The utility grid is responsible of the operation and maintenance of the DSTATCOM [3].

So, the voltage regulation can be viewed as a control problem [4]. With a suitable control, the impact of sudden load changes can be rapidly mitigated, preventing a significant drop or rise of voltage rms value.

This work presents a voltage controlled DSTATCOM operating in low voltage utility grids acting as voltage regulator. The operation principles, its control structure and some simulation results are also presented to show the effectiveness of the converter. Moreover, a new concept of minimum power point tracking is explored, guaranteeing that the DSTATCOM always operates with minimal compensating power. This feature extends the lifecycle of the system by reducing the converter losses.

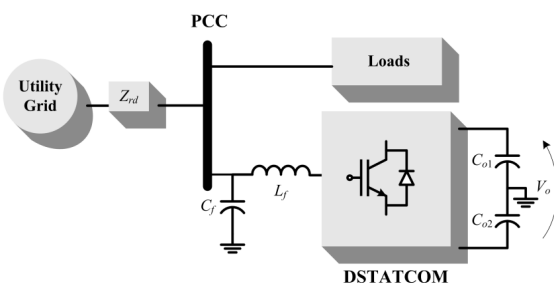


Figure 1. System under analysis

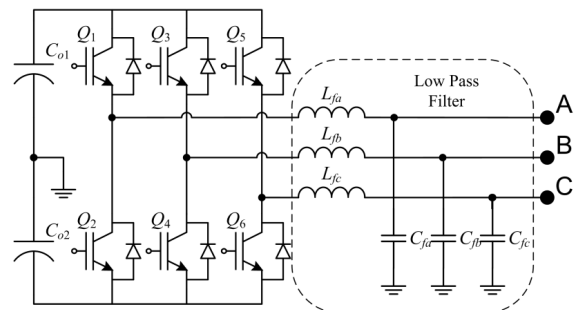


Figure 2. Employed Voltage Source Inverter

II. ANALYSIS OF THE DSTATCOM CONNECTED TO THE GRID

The converter operates controlling the AC voltage at the PCC, adjusting its phase as the load and the dc bus requires.

Analyzing the transmitted power between two bars, one can derive that the active and the reactive power are given by:

$$P_g = \frac{V_g^2}{Z} \cdot \cos(\phi) - \frac{V_g \cdot V_{PCC}}{Z} \cdot \cos(\phi) \cdot \cos(\theta) + \frac{V_g \cdot V_{PCC}}{Z} \cdot \sin(\phi) \cdot \sin(\theta) \quad (1)$$

$$Q_g = \frac{V_g^2}{Z} \cdot \sin(\phi) - \frac{V_g \cdot V_{PCC}}{Z} \cdot \sin(\phi) \cdot \cos(\theta) - \frac{V_g \cdot V_{PCC}}{Z} \cdot \cos(\phi) \cdot \sin(\theta) \quad (2)$$

where P_g and Q_g are the active and reactive powers drained from the grid, V_{PCC} is the voltage at the PCC, ϕ and Z represents the angle of the grid impedance and its module, and θ represents the angle between the grid voltage and the PCC voltage.

As the DSTATCOM provides or consumes only reactive power, the active power of the converter is equal zero and the power balance is given by:

$$P_g + P_o = 0 \quad (3)$$

where P_o is the active power consumed by the load. Replacing (1) in (3):

$$\frac{V_g^2}{Z} \cdot \cos(\phi) - \frac{V_g \cdot V_{PCC}}{Z} \cdot \cos(\phi) \cdot \cos(\theta) + \frac{V_g \cdot V_{PCC}}{Z} \cdot \sin(\phi) \cdot \sin(\theta) + P_o = 0 \quad (4)$$

is obtained the expression that relates the angle θ with the active power of the load and the PCC amplitude. In the other hand, the reactive power balance is given by:

$$Q_{inv} = Q_o - Q_g \quad (5)$$

where Q_{inv} is the reactive power provided by the converter and Q_o the reactive power drained by the load. With the angle values for each operation point, is possible to calculate the reactive power processed by the converter.

With the angle values for each operation point, is possible to get the reactive power needed by the converter and it is expressed by:

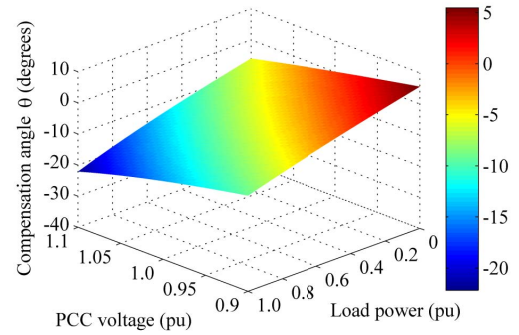


Figure 3. Compensation angle as function of PCC voltage and load power ($Z = 0.2$ pu, $\phi = 45^\circ$ and $V_g = 1$ pu).

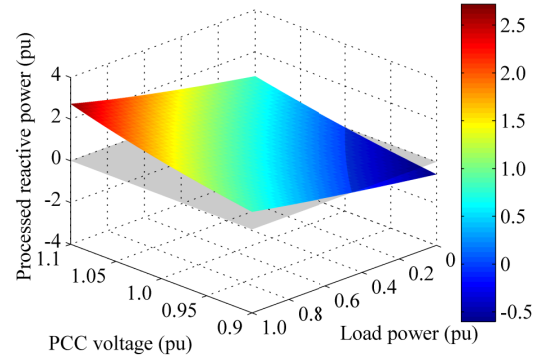


Figure 4. Processed reactive power processed as function of PCC voltage and load power ($Z = 0.2$ pu, $\phi = 45^\circ$ and $V_g = 1$ pu).

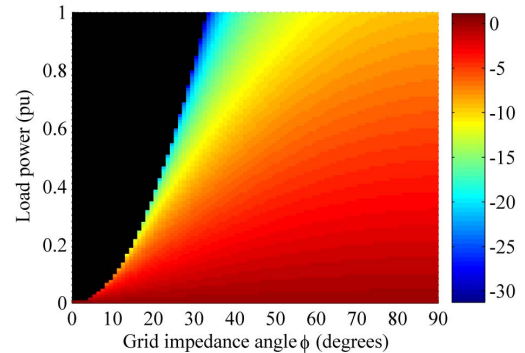


Figure 5. Compensation angle as function of grid impedance angle and load ($Z = 0.2$ pu, $V_{rd} = 1$ pu and $V_g = 1$ pu).

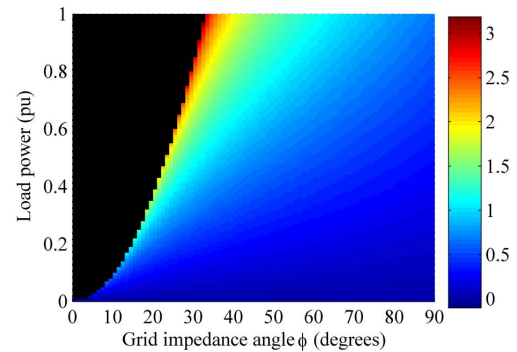


Figure 6. Processed reactive power processed as function of grid impedance angle and load power ($Z = 0.2$ pu, $V_{rd} = 1$ pu and $V_g = 1$ pu).

$$Q_{inv} = Q_o - \frac{V_g^2}{Z} \cdot \sin(\phi) + \frac{V_g \cdot V_{PAC}}{Z} \cdot \sin(\phi) \cdot \cos(\theta) + \frac{V_g \cdot V_{PAC}}{Z} \cdot \cos(\phi) \cdot \sin(\theta) \quad (6)$$

Fig. 3 presents the numerical solution of (4) and Fig. 4 the numerical solution of (6) for an inductive load with power factor equal to 0.8 (with $Z = 0.2$ pu; $\phi = 45^\circ$; $V_g = 1$ pu). The highlighted plane in Fig. 4 shows the null values for the processed reactive power.

The converter, in order to keep the PCC voltage balanced and equal to the reference, can operate over its rated power (the same power of the grid transformer, assumed to be 1 pu) in many points of operation, especially with high values of load power and PCC voltage.

Fig. 5 and Fig. 6 presents also the numerical solution of (4) and (6) for the same load and grid parameters, but now varying the grid impedance angle ϕ (with $V_{PCC} = 1$ pu).

The area in black shows where the combination between the load power and the grid impedance angle values produces no solution. This means that the operating points in this area are not possible to achieve. The area in black grows according the power factor of the load approaches to the unity and with the increase of the PCC voltage.

III. CONTROL STRUCTURE

The control scheme must synthesize three balanced voltages at PCC with low THD, regulate the voltage and avoid voltages unbalances in the dc bus.

To do so, the control structure has three ac voltage loops and two dc bus voltage loops, one total and one differential. Moreover, it is proposed a loop responsible for changing the PCC voltage amplitude. Fig. 7 shows the complete control diagram. The design of the controllers was made based in the parameters of the Table I.

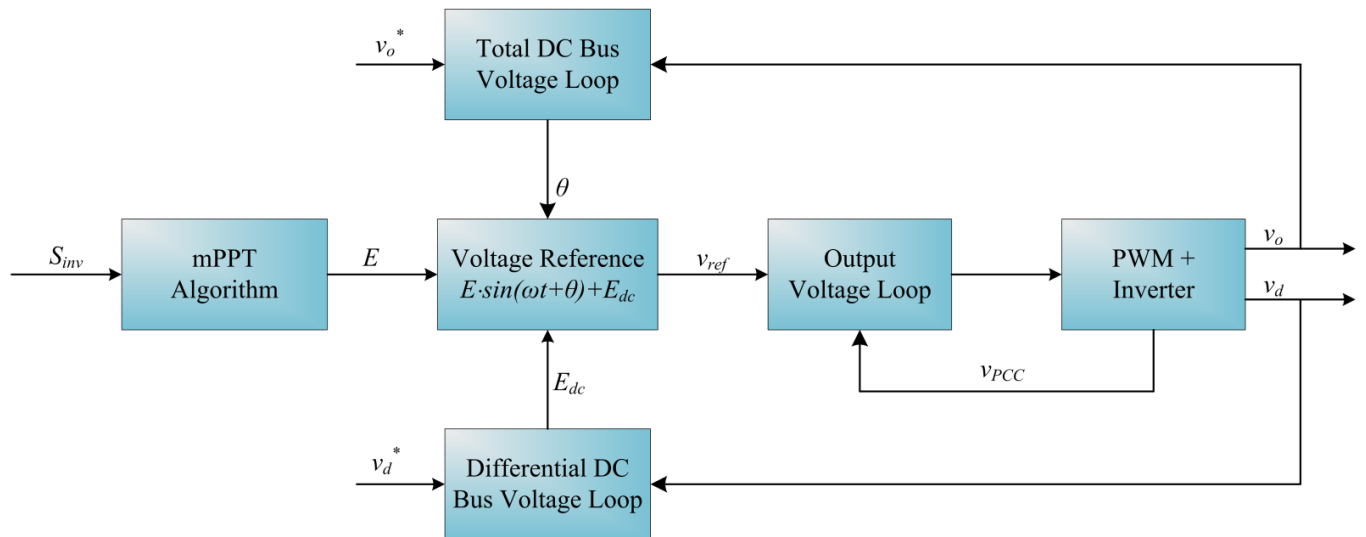


Figure 7. Proposed control structure including the mPPT algorithm.

TABLE I. DSTATCOM PARAMETERS

Nominal Power	S_o	30 kVA
Nominal dc bus voltage	V_o	800 V
Grid voltage	V_g	220 V
Grid frequency	f_g	60 Hz
Switching frequency	f_s	20 kHz
dc bus capacitance	C_{ocq}	3500 μ F
Output filter inductance	L_f	560 μ H
Output filter capacitance	C_f	47 μ F
Grid resistance	R_r	0.685 Ω
Grid inductance	L_r	1.82 mH

The PCC voltage amplitude loop decides to increase or decrease the PCC voltage amplitude based in the variation of the converter processed reactive power, represented by the mPPT algorithm block.

The total dc bus voltage loop regulates the total voltage, v_o , through the change in the angle θ . The dynamic model for the total bus voltage loop is [4]:

$$\frac{v_o(s)}{\theta(s)} = -\frac{3 \cdot V_g \cdot V_{PCC}}{s \cdot \omega \cdot L_r \cdot C_{ocq} \cdot V_o} \quad (8)$$

The total dc bus voltage controller C_{v_o} is a PI plus a high frequency pole. The crossover frequency is 52.1 Hz with phase margin of 77.7° . Fig. 8 shows the total dc bus voltage loop G_{v_o} , the total dc bus voltage controller and the compensated total dc bus voltage loop $G_{v_{ocom}}$.

The differential dc bus voltage loop adds a little dc component, E_{dc} , keeping the difference between the voltages across the capacitors, v_d , near to zero. The derived model for the differential loop is:

$$\frac{v_d(s)}{v_{PCC}(s)} = \frac{3}{s \cdot R_r \cdot C_o} \quad (9)$$

The differential dc bus voltage controller C_{v_d} is also a PI

plus a high frequency pole. The crossover frequency is 1.2 Hz with phase margin of 76.5°. Fig. 9 shows the differential dc bus voltage loop G_{vd} , the differential dc bus voltage controller and the compensated differential dc bus voltage loop G_{vdcom} .

Lastly, the ac voltage loop guarantees the synthesis of the voltage reference, v_{ref} , into the PCC with low harmonic distortion and steady state error. This loop contains an active damping controller to improve the system stability [5], [6]. The dynamic model for the ac voltage loop is given by:

$$\frac{v_{PCC}(s)}{d(s)} = \frac{s \cdot V_o \cdot L_r + V_o \cdot R_r}{s^3 \cdot L_f \cdot L_r \cdot C_f + s^2 \cdot R_r \cdot L_f \cdot C_f + s \cdot L_f + L_r + R_r} \quad (7)$$

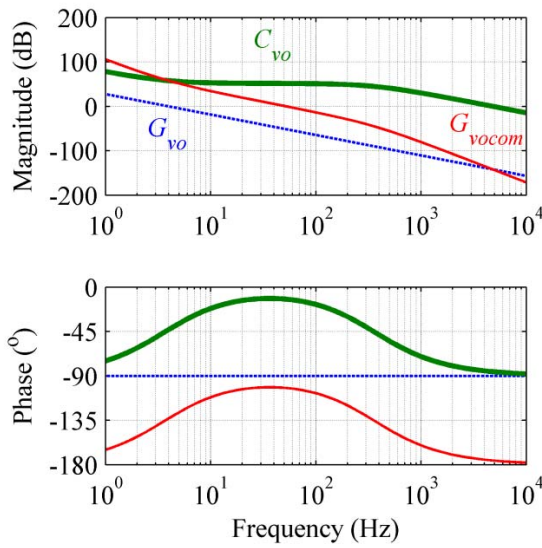


Figure 8. Closed loop diagram for the total dc bus controller

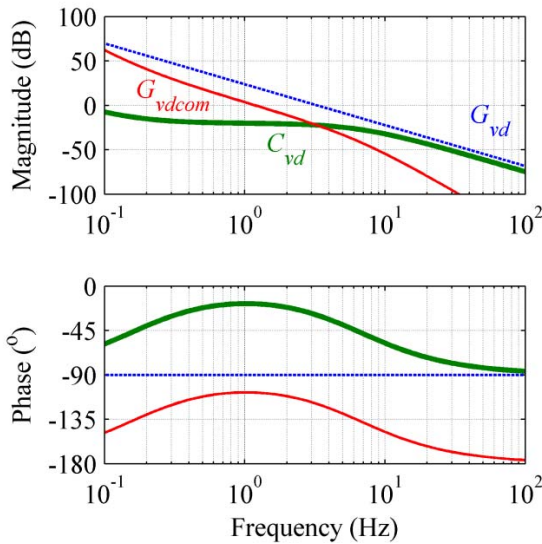


Figure 9. Closed loop diagram for the diferential dc bus controller

The active damping controller C_{ad} is a double stage lead controller tuned on the resonance peak of (7) and the output voltage controller C_{vac} is a PID. The crossover frequency of the output voltage loop is 5.3 kHz with the phase margin of 81.8°. The bode diagram of the output voltage open loop G_{vac} , the active damping controller and the damped output voltage loop G_{dam} are presented in Fig. 10. Fig. 11 shows the damped output voltage loop, the output voltage controller and the compensated output voltage loop G_{vaccom} .

IV. MINIMUM POWER POINT TRACKER

The output voltage amplitude at PCC for reactive compensation methods is usually adopted as the grid nominal voltage [2] [7]. However, local standards determinate a maximum and a minimum voltage value for low voltage

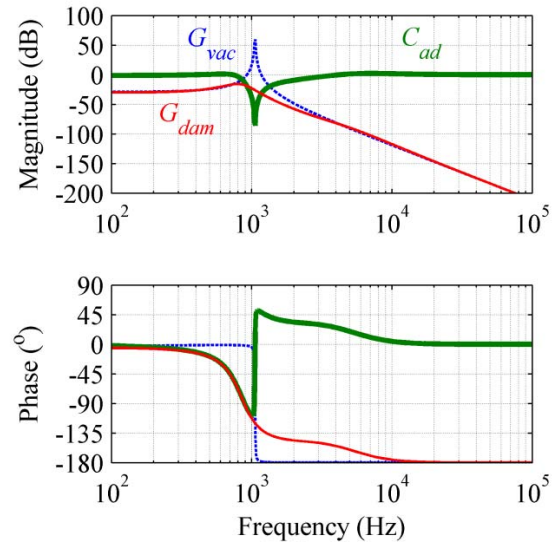


Figure 10. Closed loop diagram for the active dampening controller

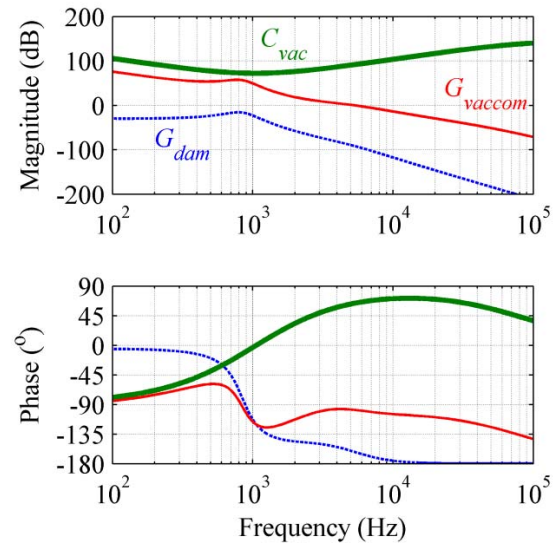


Figure 11. Closed loop diagram for the output voltage controller

distribution grids [1].

A voltage reduction at PCC implies in reduction of the processed reactive power, as shown in Fig. 4. Thus, there will always be an operation point, even on the maximum or minimum allowed voltage, that the converter processed power will be the minimum.

The converter, operating as mentioned, will have a smaller current effort and, consequently, fewer losses on semiconductors. This also provides a longer life cycle for the equipment.

In DSTATCOMs, the active power is a small amount comparing to the reactive power. So, the converter apparent power is chosen to be minimized.

Besides, the distribution grid has the voltage between the limits on most part of time. With an external loop it is possible to minimize the converter processed power, setting convenient voltage amplitude.

A. The P&O method

Similar algorithms that perform this task are those implemented in PV systems, tracking the maximum power point (MPPT). MPPT methods vary with the complexity, required sensors, convergence speed, cost, efficiency, and so on [8], [9].

The chosen method was Perturb & Observe (P&O). This method is widely utilized due to its low computational effort, the accuracy and the reduced numbers of sensors. However, it has a slow transient response and is considered slow [9], [10], [11].

In MPPT, if the power variation is positive, the next perturbation is in the same way. Otherwise, the next perturbation is in the opposite way. The process periodically repeats, with a known sample time, until the maximum power point (MPP) is achieved. Then, the system oscillates around the MPP [8].

Although it has an easy implementation, the P&O algorithm has some deficiency [10]: the system cannot operate at the maximum power point due the oscillations around the MPP and may fail to track the MPP due to sudden changes on sunshine, for example.

There are two main parameters to be defined in P&O technique [12]. The first parameter is the sample time, which must be chosen to be higher than the response time of the system. The second is the perturbation size, determining the convergence time and the oscillation amplitude.

B. mPPT Algorithm

The minimization strategy is based on P&O method, but achieves the minimum power (mPP) point instead.

Fig. 12 shows an example of minimization. When the converter is operating on the left side of mPP and the voltage amplitude is increased (marker 1), the apparent power is reduced. The next perturbation will be in the same way because the converter is converging to mPP. However, if the

voltage is decreased, the apparent power is increased and the next perturbation will be in the opposite way (marker 2).

The same analysis is applied to the right side of mPP, which a voltage increase deviates the converter from the

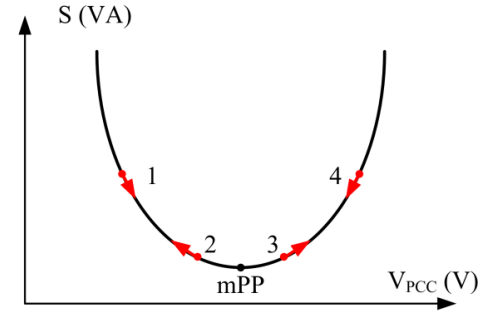


Figure 12. Example of minimization

TABLE II. SUMMARY OF MPPT

Apparent Power	Voltage Amplitude	Operation Point	Action
increasing	increasing	3	decrease
	decreasing	2	increase
decreasing	increasing	1	increase
	decreasing	4	decrease

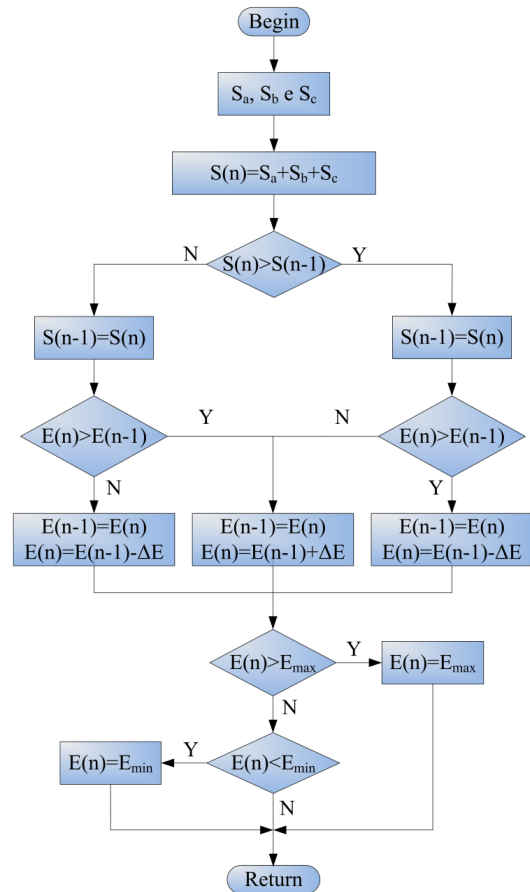


Figure 13. Complete mPPT flowchart

mPP (marker 3) and a voltage decrease leads to the mPP (marker 4).

Table II summarizes the minimum power point tracker (mPPT) actions and Fig. 13 presents its flowchart.

V. SIMULATION RESULTS

The DSTATCOM was simulated with a 0.8 pu inductive load with the configuration of Fig. 1. The waveform of voltage at PCC is shown in Fig. 14 with and without (black line) compensation and Fig.15 presents the waveform of converter output current.

Without compensation, the PCC voltage has an rms voltage value of 0.86 pu, below than allowable limits of the standard [1]. The converter processes 28.1 kVA (0.937 pu) to keep the voltage at the chosen value (0.97 pu). Setting the PCC voltage to 1 pu makes converter processes 38 kVA (1.267 pu).

To verify the dynamic response of the voltage regulator, the load was suddenly changed to 0.5 pu at the time 0.2 s,

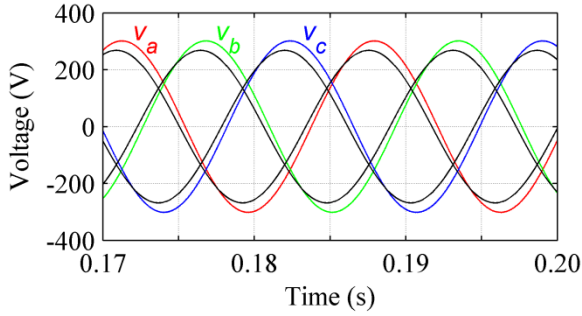


Figure 14. PCC voltage with and without compensation

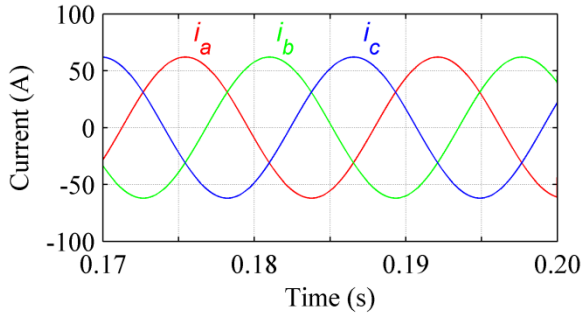


Figure 15. Converter output current

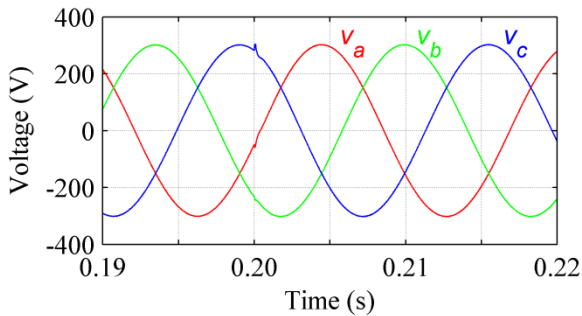


Figure 16. PCC voltage under a sudden load change

simulating the disconnection of a load at one consumer. The waveform at PCC is shown in Fig. 16. The effect of the load change is nearly imperceptible, representing a no change in the rms voltage value.

A. mPPT

The behavior of the voltage amplitude loop is depicted in Fig. 17. The initial value for the voltage amplitude is 0.97 pu and decreases to the minimum allowable value (set to 0.94 pu), according to the reduction of the apparent power, shown in Fig. 18.

The load was maintained as 0.8 pu inductive load and the voltage step was chosen as 0.44 V (0.002 pu). The processed power decreases from 28 kVA (0.936 pu) to 19 kVA (0.633 pu), reducing the power around 32 %. Setting the PCC voltage to 1 pu makes converter processes 38 kVA (1.127 pu). This means a reduction of 50 % compared to the usually adopted PCC voltage.

When the distribution grid operates at light load (assumed as 0.25 pu), the equilibrium is achieved with the PCC voltage around 210 V (0.954 pu), as seen in Fig. 19. The processed power converges to zero according to Fig. 20. Setting the PCC voltage to 1 pu makes the converter to processes 10.65 kVA (0.355 pu). With the mPPT algorithm, the converter processes less than 500 VA, a reduction of 95 %.

B. Unbalanced load

Unbalanced loads are very common in low voltage distribution grids. To emulate that, phase A was connected to a 0.8 pu inductive load, phase B to a 0.6 pu inductive load and phase C to a 0.7 pu inductive load. The PCC voltage was

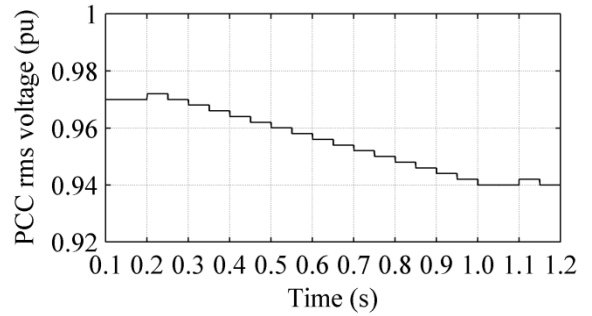


Figure 17. PCC rms voltage with the mPPT enabled

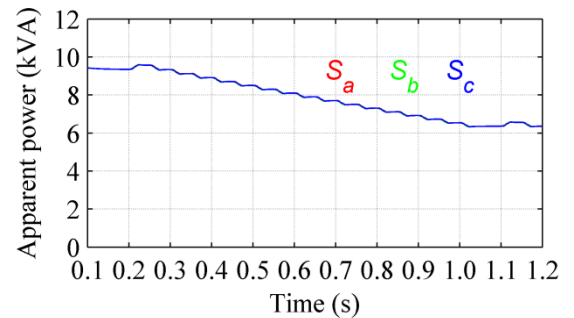


Figure 18. Processed apparent power with the mPPT algorithm enabled

set to 0.97 pu. The PCC voltages are shown in Fig. 21, with DSTATCOM compensation and without it (black line).

In this case, each phase of the converter processes different apparent power, as shown in Fig. 22. Moreover, the converter absorbs 692 W in phase A, 78 W in phase C and provides 780 W in phase B.

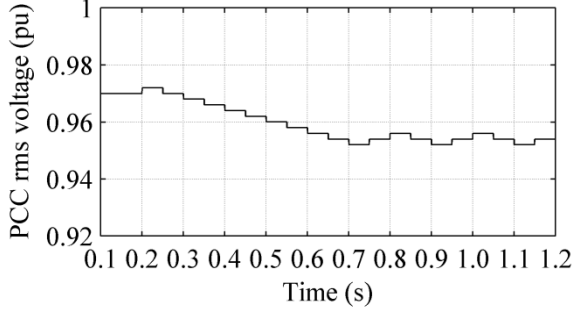


Figure 19. PCC rms voltage with the mPPT enabled and light load

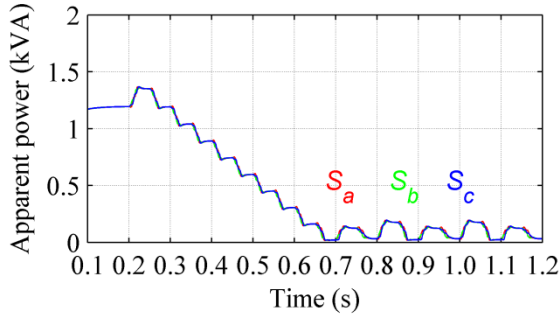


Figure 20. Processed apparent power with the mPPT algorithm enabled and light load

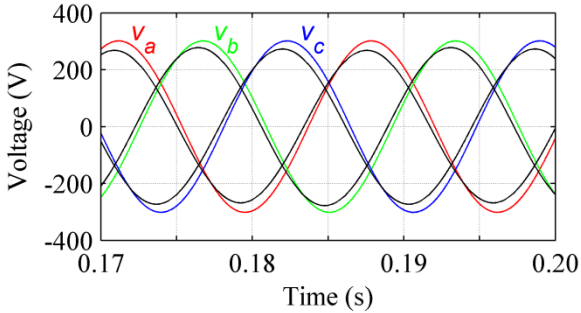


Figure 21. PCC voltage with and without compensation with load unbalance

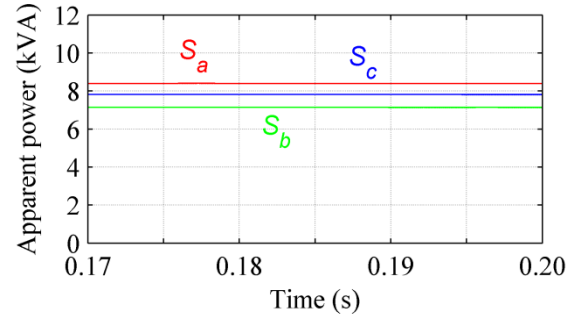


Figure 22. Processed apparent power with load unbalance

C. Nonlinear loads

The converter was also simulated with nonlinear loads. Adding 0.2 pu of a single phase rectifier with capacitive filter in each phase to 0.7 pu inductive load, Fig. 23 presents the PCC voltage waveforms and Fig. 24 the converter current. The PCC voltage THD is 0.32% and the converter output

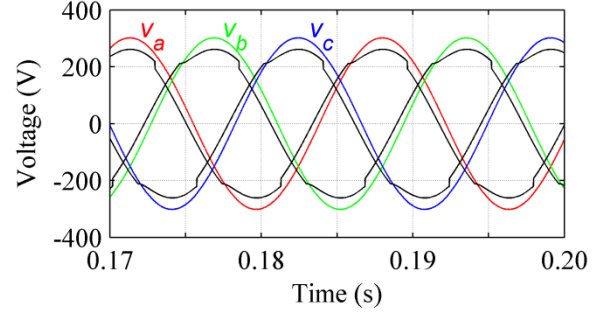


Figure 23. PCC voltage with and without compensation with nonlinear load

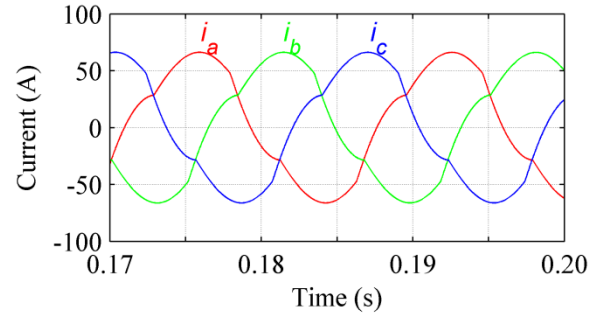


Figure 24. Converter output current with nonlinear load

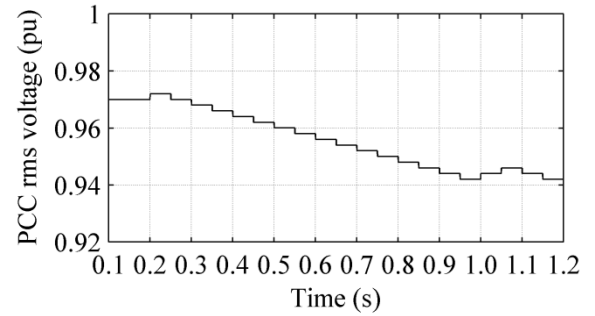


Figure 25. PCC rms voltage with the mPPT enabled, light load and nonlinear load

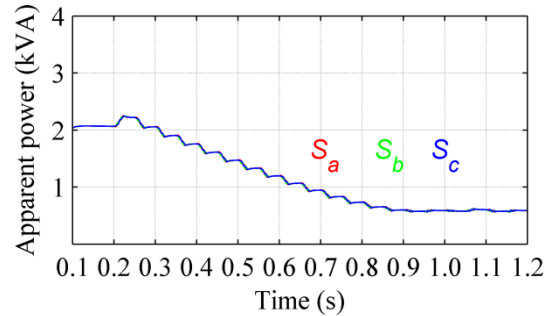


Figure 26. Processed apparent power with the mPPT algorithm enabled, light load and nonlinear load

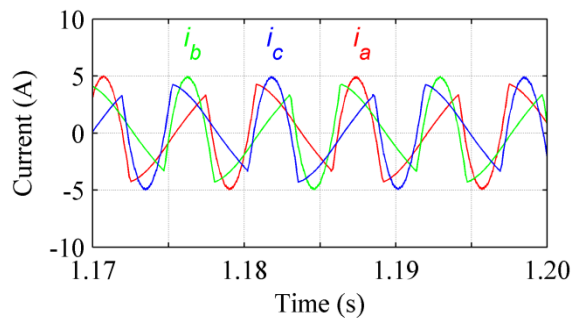


Figure 27. Converter output current with light load and nonlinear load

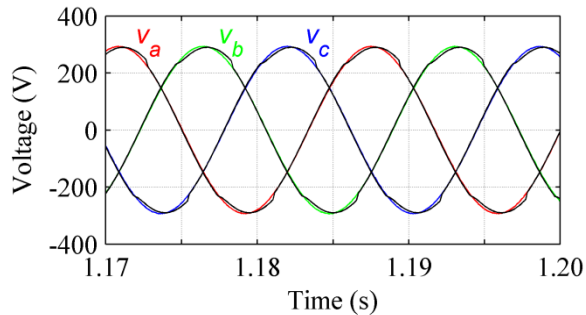


Figure 28. PCC voltage with and without compensation with light load and nonlinear load

current THD is 12.4%. Without compensation the PCC voltage THD is 5%.

Changing the linear load to 0.25 pu, the nonlinear load to 0.1 pu and enabling the mPPT algorithm, Fig. 25 shows the voltage at the PCC and Fig. 26 shows the processed apparent power.

One can see that in this situation the converter does not achieve apparent power near to zero, because the converter now acts as an active parallel filter (APF). Fig. 27 shows the converter output current, which is composed majorly by current harmonic content of the load. The PCC voltage waveform remains regulated with low THD, as shown by Fig. 28.

VI. CONCLUSION

This paper presented a three phase DSTATCOM as a voltage regulator and its control structure, including the output voltages loops, total and differential dc bus voltage loops and the output values and reaches zero power when the PCC voltage amplitude loop.

The simulation results demonstrate the voltage regulation capability, supplying three balanced voltages at PCC, even under load changes and nonlinear loads.

The proposed output voltage loop was able to reduce the converter processed apparent power about 32 % and even more with light load (95 %).

The mPPT algorithm tracked the minimum power point within the allowable voltage compensation is not necessary. Was also seen that at lights loads the DSTATCOM operates as an active parallel filter.

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