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Power Quality Improvement in a Utility Grid by using Proportional Resonance Controller Based D-STATCOM

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ABSTRACT

Increasing awareness and concerns regarding unacceptable power quality are causing a growing interest in custom power devices, used to improve power quality on distribution level. One of the most interesting types of custom power devices, due to its exibility and fast control, is the shunt-connected voltage source converter (VSC), also known as the static synchronous compensator (STATCOM). A single distribution static compensator (DSTATCOM) connected at the beginning of the network working in current control mode is capable of circulating power. In this dissertation a comparative analysis has been made between the conventional proportional integral (PI) controller and proportional resonance (PR) controller. This voltage controller holds the voltage at the point of common coupling (PCC) and supplies/absorb necessary power to keep the system stability. The DSTATCOM is assumed with a battery to enable this facility. However, correcting the PCC voltage to 1 per-unit (pu) cause a large amount of reactive power to/from the utility substation. This increases the current flow in the system and increases the line loss where the R/X ratio is high. It is desired to have the least reactive power from the utility substation. A modified voltage magnitude controller can solve this problem though it changes the voltage of buses.

KEYWORDS: *D-Statcom, Frequency Compensation, Minimum Power Point Tracker, coordinated control, Distributed generation, PR controller, Voltage control.*

I. INTRODUCTION

Distribution networks in different parts of the world have gone through significant growth and improvement with the utilization of distributed generation (DGs). This is line with the policies of government of countries towards the use of renewableenergy resources technology. Previously, the distribution system has been working on a unidirectional power flow but with the connection of DGs, the system has to accept bidirectional power flows which resulted in several technical issues such as voltage levels and power flow, protection issues, equipment thermal ratings and fault current levels [1]. One of the major concerns in the integration of DGs in the distribution systems is the voltage rise issue. This further requires the DNOs to find solutions to the overvoltage problems in ensuring that the customers receive the voltage within its specified limits. Two main voltage control methods in a distribution system with DGs which have been identified are categorized as coordinated or centralized control while the other one is categorized as semi-coordinated and decentralized control. The coordinated control determines their control actions based on the information from the whole network, hence requiring data transfer and communications between the network nodes. On the other hand, the decentralizedcontrol performs its actions locally with limited number of communications. Several studies in coordinated voltage control involves the development of centralized Distribution Management System (DMS) control as well as coordination of the distribution system components such as on load tap changer OLTCs and switched capacitors. As in the case for decentralized control, several methods of control particularly at the generator itself or involving the components in the system includes the power factor control (PFC), OLTC control, active power generation curtailment, and also reactive power compensation.

To meet the voltage regulation requirement, a voltage-controlled DSTATCOM-based voltage regulator is proposed with shunt connection to PCC, as shown in Fig. [1]. The shunt connection avoids power supply interruption while the voltage regulator is installed or disconnected. The proposed DSTATCOM allows the power company to postpone investments and enhances the flexibility of grid management. Voltage-controlled DSTATCOM can maintain the PCC voltages balanced even under grid or load unbalances. The PCC voltage is directly controlled by the DSTATCOM and sudden load changes have no significant impact in the PCC voltage waveforms. Moreover, the voltage-controlled DSTATCOM decouples the grid and the loads, serving as a low impedance path for harmonic distortions due the voltage source behavior. Current harmonic distortions from the loads have small impact in the grid and vice versa. The grid current quality, therefore, is exclusively given by the grid voltage quality.

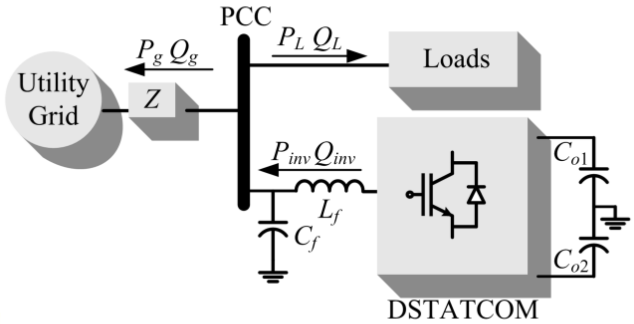

Fig. 1. Low voltage distribution grid under analysis with the voltage regulator

Voltage-controlled DSTATCOMwill preserve the PCC voltages balanced even below grid or load unbalances. The PCC voltage is directly controlled by the DSTATCOM and abrupt load variations don't have vital impact in the PCC voltage waveforms. Additionally, the voltage controlled. DSTATCOM decouples the grid and the loads, serving as a low impedance path for harmonic distortions due the voltage source actions. Current harmonic distortions from the loads have little impact in the grid and vice versa. The grid current quality, therefore, is solely given by the grid voltage quality. According to, angular position reference is needed for the voltage controlled DSTATCOM to work properly. Before the DSTATCOM starts its operation, synchronization circuits generate the angular position to the voltage regulator. Once the operation begins, the voltage-controlled voltage regulator replaces the PCC voltage and the gridvoltage frequency and angle are no longer available. PCC voltage frequency and angle are then determined by the voltage regulator. For a real application, due to the distance between the transformer and the PCC, only the PCC voltage should be measured to compose the voltage reference of the DSTATCOM.

In past years, the PCC voltage amplitude (VPCC) for responsive remuneration strategies was normally received as the ostensible network voltage, i.e. 1.00 p.u. In any case, Brazilian lattice code decides a most extreme (1.05 p.u.) and a base (0.92 p.u.) voltage amplitude for low voltage appropriation matrices. The PCC amplitude can be seen as a level of opportunity and the prepared power can be decreased with a reasonable control circle. In this exertion, proposesanother technique to decide the reasonable PCC terminal voltage for decrease of the DSTATCOM control rating. The strategy is figured by the coveted source current, intending to accomplish the solidarity control factor at the lattice. In any case, this strategy requires data about the source current, network opposition and reactance. In [9] the creators propose another strategy to decide appropriate VPCC utilizing the positive grouping segments of the heap current to figure the PCC voltage. In the two cases, extra data is required, expanding the procedure multifaceted nature, number of sensors and the cost of the arrangement. To keep up the simple establishment highlight and sensible costs, it is advantageous to set the PCC voltage, in which the prepared power is insignificant, without checking any heap or lattice data and utilizing just inside signs of the DSTATCOM, for example, the PCC voltages and DSTATCOM yield streams.

This paper introduces a voltagecontrolled DSTATCOM-based voltage controller for low voltage appropriation lattices, utilizing a three-stage four-wire VSI with a LC low-pass yield channel, as appeared in Operation standards of the voltage-controlled DSTATCOM and the control procedure are displayed. Also, two circles are incorporated to the proposed control technique: the idea of least power point following (MPPT) and the recurrence circle. The MPPT maintains a strategic distance from superfluous receptive remuneration, expanding the pay capacity. The recurrence circle beats the functional trouble of synchronization by redressing the recurrence of the voltage reference.

II. MINIMUM POWER POINT TRACKER

The voltage amplitude to be regulated at PCC changes the power flow between the grid, load and DSTATCOM, as demonstrated in Section II. Suitable VPCC makes the processed apparent power be minimal. When the VPCC is between the desired voltage limits, the MPPT minimizes the converter apparent power and no reactive power at the grid frequency is processed. Apparent power minimization means current minimization, which lower the losses and extends the equipment life cycle. For the MPPT analysis, apparent power is chosen to be minimized instead of reactive power due to: (i) active power in DSTATCOMs is a small fraction of the apparent power; (ii) the harmonic currents from the grid and load are also processed; (iii) the converter power rating and the losses are given by the apparent power; and (iv) apparent power is easier to calculate in comparison to extracting the reactive power at the grid frequency from distorted current waveforms.

A. A.The P&O-based MPPT Algorithm

The reduction of voltage regulator apparent power can be performed by tracking algorithms. An example of tracking algorithm is the Maximum Power Point Tracker (MPPT), which is widely used in PV systems.

Among several MPPT algorithms, the Perturb & Observe (P&O) method was chosen to compose the MPPT algorithm due to its simplicity, low computational effort and a small number of sensors, although it has slow transient response and operates around a Maximum Power Point (MPP) [15]–[18], which can be a local or a global MPP [19]-[20].

Two parameters must be set to the P&O algorithm: perturbation amplitude and sample time. The perturbation amplitude defines the convergence time to reach the MPP and the amplitude of the oscillations in steady state [16]. The sample period must be greater than the response time of the system to avoid instabilities [15].

One interesting feature of the P&O method is its independency of PV arrays parameters [16], [17]. This feature makes the P&O not restricted to PV systems.

The P&O-based MPPT algorithm presents the same features of the P&O algorithm applied to MPPT, but is designed to achieve the Minimum Power Point (MPP) instead of MPP [14].

The MPPT can be derived analyzing Fig. 2(a). The marker 1 represents an increase of V_{PCC} and the marker 4 represents a decrease of V_{PCC} which leads to reduction of the S_{inv}. In these cases, the next perturbation will conserve the perturbation signal (positive for marker 1 and negative for marker 4) and the MPPT will converge to the MPP. On the other hand, the marker 2 represents a decrease of V_{PCC} and the marker 3

represents an increase of V_{PCC} diverging from MPP. Therefore, the direction of the next perturbation must be positive for marker 2 and negative for marker 3.

The MPPT algorithm is summarized in Table I. Comparing the perturbation logic of the P&O MPPT with the conventional P&O MPPT algorithm, one can conclude that the P&O-based

MPPT can be obtained by simply changing the perturbation signal of the conventional P&O MPPT.

The processed power at the MPP was intentionally considered as S_{min}, the minimal power to be processed. DSTATCOM losses and harmonic distortions contributions to the apparent power cannot be minimized to zero.

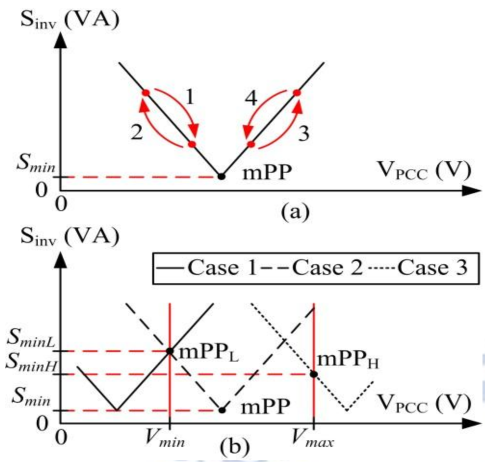

Fig. 2. (a) P&O-based mPPT derivation (b) Example of the mPPT algorithm with voltage constraints

Table I - Summary of the features of the mPPT algorithm.

Apparent Power	Voltage Amplitude	Marker	mPTT Action
increasing	increasing	3	decrease
	decreasing	2	increase
decreasing	increasing	1	increase
	decreasing	4	decrease

B. B.The Amplitude Loop

The amplitude loop is composed of the P&O-based mPPT algorithm and has voltage constraints to meet, which are imposed by the Brazilian grid code [13]. The voltage constraints are not considered in [14] and directly affect the apparent processed power.

There are three different cases when voltage constraints are present as depicted in Fig. 2 (b). In case 1, S_{min} requires a V_{PCC} below the minimum allowable PCC voltage (V_{min}). The MPPT goes toward the MPP, but V_{PCC} cannot be lower than V_{min}. V_{PCC} is kept at V_{min} and the voltage regulator supplies reactive power to maintain the V_{PCC} regulated. Therefore, the mPP in case 1 will be at MPP_L and the processed power is represented by S_{minL}. The Case 3 shows a similar outcome to case 1 with V_{PCC} kept at the maximum allowable PCC voltage (Vmax). The converter operates at MPP_H and process reactive power equal to S_{minH}.

In case 2, the MPP occurs with V_{PCC} between V_{max} and V_{min}. The MPPT tracks the MPP and the converter process S_{min}, the active power to compensate the losses and the harmonic distortion from the grid and load.

III. CONTROL STRATEGY

The control strategy aims to synthesize three balanced voltage waveforms at PCC with adequate amplitude, low THD and also regulate the voltage of the dc bus capacitors. Therefore, the control strategy has three output voltage loops, one total and one differential dc bus voltage loop. The aforementioned controllers were designed with the parameters presented and evaluated for a range of the grid impedance (0.1 to 10 of $R_g$and L_g) through frequency response analysis. In this range the designed controllers work properly. Additionally, this paper includes two loops: a loop responsible for the PCC voltage amplitude and another one responsible for mitigating the grid frequency effect on the voltage regulator. Fig. 3 shows the complete control block diagram with the amplitude and frequency loops.

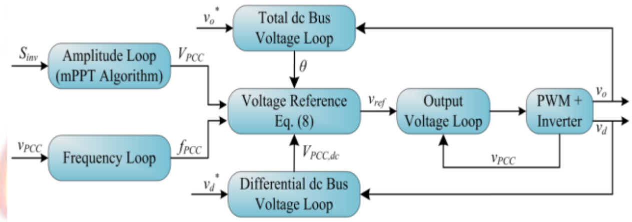

Fig:3. Proposed control strategy including amplitude and frequency loops.

A. Output Voltage Loop

The inputs of the output voltage loop are three voltage references (v_{ref}). The voltage references are composed of the dc bus controllers' output, the MPPT and the frequency loop, as depicted in Fig. 3. To achieve adequate synthesis of the voltage references, the output voltage loop must have fast dynamic response. The output controller is a PID controller. The simplified output voltage loop block diagram can be seen in Fig. 4. The output voltage loop has active damping controllers to enhance the stability of the voltage regulator against grid impedance variations.

B. Grid Frequency Variation and the Total dc Bus Controller

The DSTATCOM operation causes power losses in the power converter as a result of semiconductor switching is shown in fig 4. The losses diminish the total dc bus voltage (v_o). As the displacement angle θ determines the active power flow at the PCC. Therefore, the total dc bus loop compares $v_o$to the reference v_o* and, through a PI plus pole controller, set a suitable θ to drain active power from the grid and reestablish the power balance between the grid, the loads and the DSTATCOM. The DSTATCOM is composed of three-phase four-wire VSI and the voltage balance at the split capacitors is required. The difference between the split capacitor voltages (v_d) is compared to the reference (v_d*) and a PI plus pole contributes to the reference generator with a small dc component ($V_{PCC,dc}$). This dc component charges one capacitor more than the other and the voltage balance can be achieved.

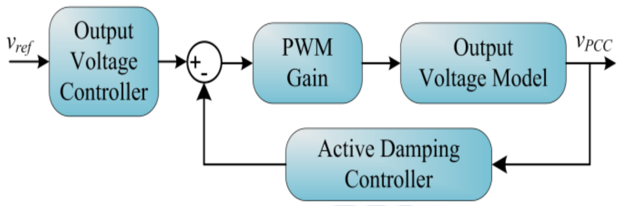

Fig:4. Output voltage loop block diagram

IV. SIMULATION RESULTS

The block diagram for existing network is shown below in figure .5 and corresponding output waveforms shown figure 9, to 18.

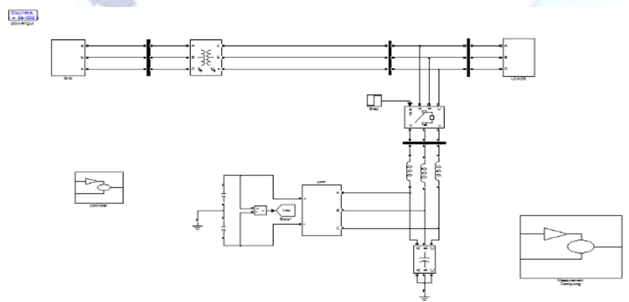

Fig:5. Simulation diagram of grid frequency variation impact

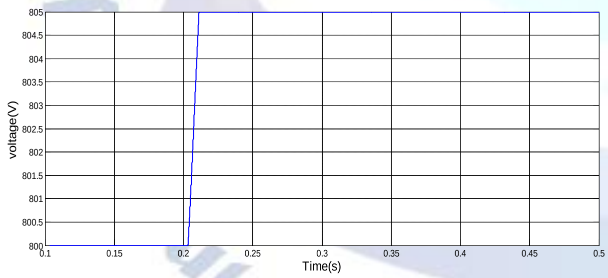

Fig:(a)

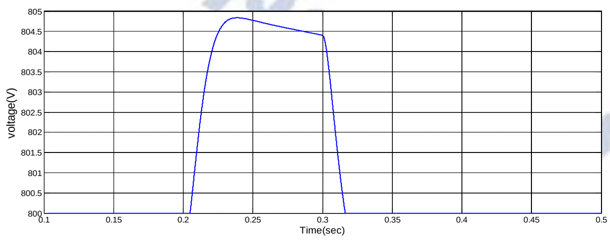

Fig:(b)

Fig:6. Total dc bus voltage during the grid frequency variation: (a) without and (b) with the frequency compensation

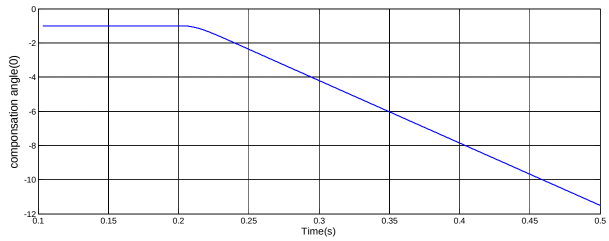

Fig:(a)

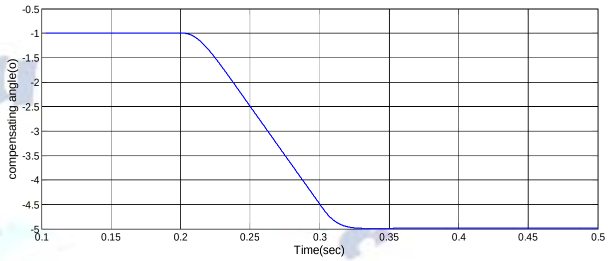

Fig:(b)

Fig:7. Compensation angle during the grid frequency variation: (a) without and (b) with the frequency compensation

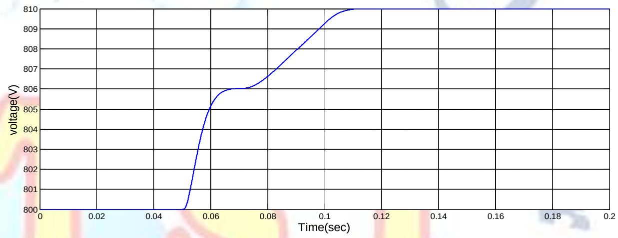

Fig:8 Dc bus voltages during the DSTATCOM initialization

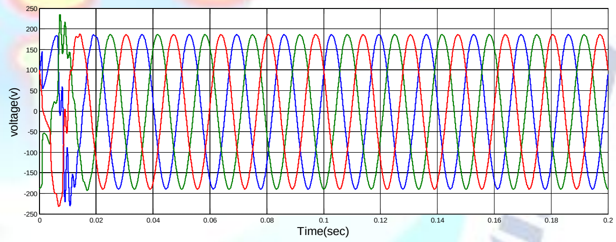

Fig:9. PCC voltages without compensation for linear loads

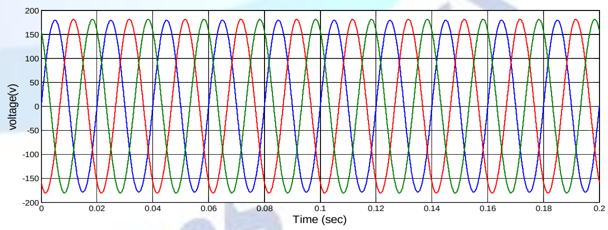

Fig:10. PCC voltages with compensation for linear loads

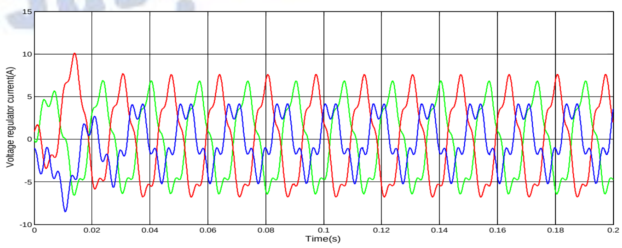

Fig:11. Voltage regulator currents for linear loads

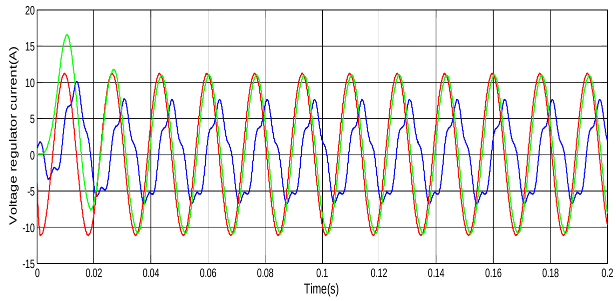

Fig:12. Grid, load and voltage regulator currents for linear loads

At the time *t*0 the auxiliary contactor (AC) closes and inserts the pre-charge resistors (PCR) in series with the DSTATCOM while the PWM is maintained disabled. The dc bus charges through the switch's diodes, as shown in Fig.8. Meanwhile, the PLL circuit synchronizes the voltage references with the PCC voltages.The PCC voltage amplitude without compensation is 180 V according to Fig.9. One can see that the PCC voltages contain some harmonic distortion inherent to low voltage distribution grids. The compensated PCC voltage was arbitrarily chosen as 188 V. The PCC voltages are regulated with low THD (0.2%), as shown in Fig.10. The compensation currents have different rms values for each phase, highlighting the natural unbalance of the low voltage grids. The harmonic distortion present in the grid voltage is compensated by the regulator. Fig.11 presents the compensation current waveforms. The quality of the *b*-phase grid current (i_{gb}) for linear loads is shown in Fig.12. The voltage regulator supplies the load with low THD voltages, as seen by the load current (i_{Lb}). The harmonic content in $i_{gb}$is given by the grid voltage distortions.

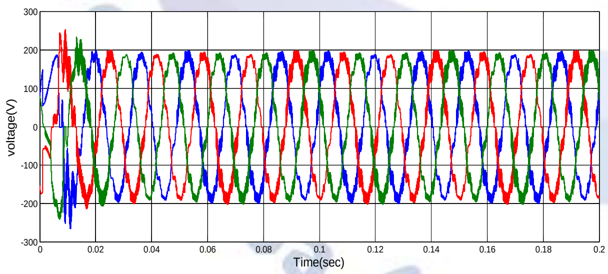

Fig:13. PCC voltages without compensation for nonlinear loads

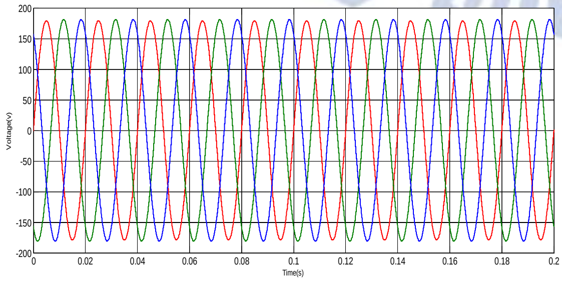

Fig:14. PCC voltages with compensation for nonlinear loads

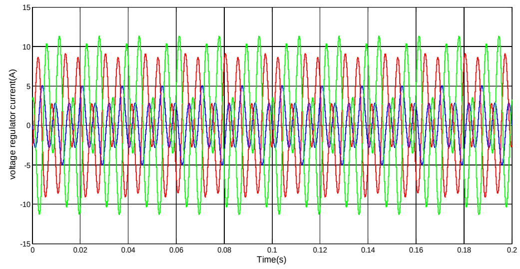

Fig:15. Voltage regulator currents for nonlinear loads

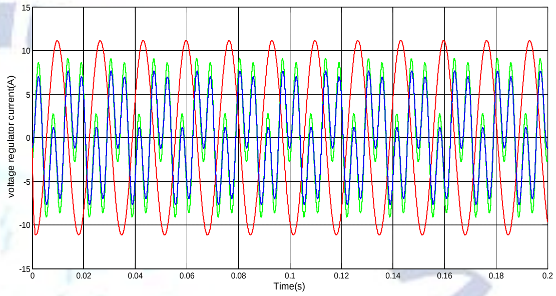

Fig:16. Grid, load and voltage regulator currents for nonlinear loads

The considered nonlinear loads are three 2 kVA single-phase rectifiers with a capacitive filter, one in each phase added to 5.2 kW three-phase resistive loads. The PCC voltage amplitude without compensation is 190 V with 6.4% THD, as shown in Fig.13. The compensated PCC voltage is depicted in Fig.14having three regulated and sinusoidal waveforms with 0.6% THD. The compensation currents contain the fundamental frequency for the reactive compensation and all the harmonic distortion from the nonlinear loads, as seen in Fig.15. The *b*-phase grid current (i_{gb}) waveform for nonlinear load is shown in Fig. 15. The voltage regulator absorbs the harmonic content from the load current (i_{Lb}) leaving i_{gb}free of load harmonic distortions. Comparing $i_{gb}$from Fig. 15 and Fig.16, one can notice the grid current waveforms present similar distortions from the grid voltage.

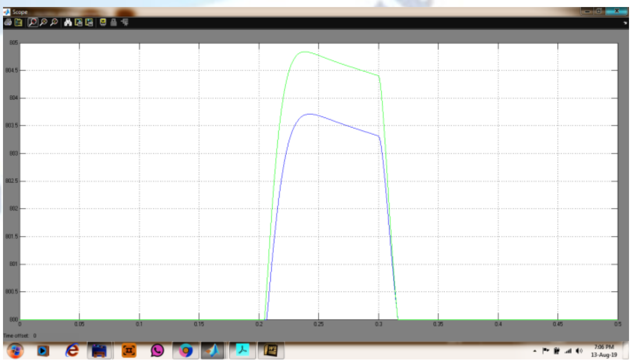

Fig:17 Total dc bus voltage during the grid frequency variation with the frequency compensation(proposed and extension system).

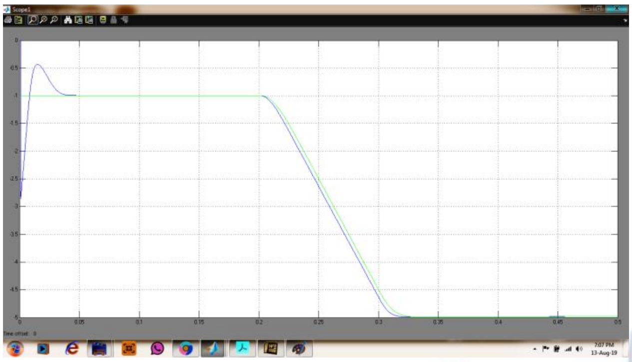

Fig:18 Compensation angle during the grid frequency variation with the frequency compensation(proposed and extension system).

The effect of the grid frequency step on the total dc bus voltage can be seen in Fig. 17. The dc bus voltage has low steady state error (around 5 V) because of a large total dc bus voltage controller bandwidth. With the f_{ref}update, Fig.17, the total voltage returns to nominal voltage. After the frequency step, the total voltage controller has a slope output. Without f_{ref}update, Fig.18 the compensation angle decreases indefinitely, whereas with the frequency loop the compensation angle is constant, as shown in Fig. 18. However, the compensation angle does not return to the previous value. Errors between $f_{ref}$and $f_{PCC}$are accumulated in the compensation angle and the controller output may reach its limits. If imminent, a protective routine is activated, which adds a constant factor to f_{ref}, bringing the compensation angle back to 0 radians. After that, the frequency loop returns to normal operation.

V. CONCLUSION

A voltage controlled DSTATCOM, connected at the PCC, on the other hand, can operate in both grid connected and islanded modes. The DSTATCOM in this acts as a shunt connected source, which holds the PCC voltage constant to a pre-specified value. The angle of the voltage is obtained from a power flow relation. In the islanded mode, the DSTATCOM is able to supply power shortfall or absorb excess power. The DSTATCOM can fix the PCC voltage to predefined value. However, fixing it to 1 per unit can cause a large amount of reactive power to/from the utility substation. This will result in excessive current and therefore large line loss, which is undesirable. To avoid this, it is prudent to set the PCC voltage magnitude such that the current from the utility flows in the PCC at unit power factor (upf). To overcome the disadvantages of a PI controller, an alternative approach is proposed to use proportional resonance (PR) control, which is the frequency transformation of the dc type controller into an equivalent ac regulator. This is achieved by a voltage magnitude controller that set the reactive power drawn/supplied to the source to zero. This might however result in the decrease/increase of the downstream load bus voltages. Since the LV network may or may not have DERs (depending on the DER type), fixed transformer tap setting can only complicate the problem further

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