Design of a continuously and linearly controlled VSI-based STATCOM for load current balancing purposes

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Article Info

ABSTRACT

In this paper, load current balancing are reviewed in both three-wire and 4-wire systems taking into account linearity, harmonics injection, and control schemes. A linearized static compensator (STATCOM) based on H-bridge voltage source inverter (VSI). The proposed STATCOM is controlled in closed loop mode via equipping it with a new current controller. The DC capacitor voltage of the STATCOM is kept constant without using external energy injection or storage devices via shunting the DC capacitor with a suitable series filter. The simulation results of the current responses of the 220V, 50Hz STATCOM reveal continuous and linear performance during responding to reactive current demands from 123A inductive current to 227A capacitive current. The transition time required for the proposed STATCOM during treatment of a sudden change in reactive current demand from maximum inductive current to maximum capacitive current is less than 40ms. The steady state portions of the STATCOM current responses show pure sinusoids, thus the proposed STATCOM can be promoted as harmonic free static Var compensator. The closed loop continuous mode control and the considerable linearity of the proposed STATCOM promot it as a bipolar susceptance (capacitive and inductive) in applications of load current balancing systems in both three and four wire power systems.

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1. INTRODUCTION

In 1981, an advanced static Var compensator in prototype form was introduced by [1]. The compensator was built using force-commutated inverters. This prototype founded a basis for STATCOM concept. The rapid increasing in the switching frequencies of the solid-state switching devices beside the development in multilevel technologies makes it possible to apply pulse width modulation (PWM) techniques in the STATCOMs designed for high power applications. The control scheme of a PWM-based STATCOM was investigated by [2]. During the model implementation of the controller, the STATCOM was modeled in the discrete time domain. An eight-level reinjection converter based STATCOM was proposed by [3] to provide very low distortion levels compared to a similar configuration using clamping diodes, even though the numbers of the main switching devices in both configurations were equal. STATCOMs are traditionally realized by voltage source converters, but for certain applications such as using a STATCOM as current injection device, current source converter based STATCOMs can introduce better performance [4]. The controlling strategies, harmonic analysis, operating points optimization, voltage unbalance mitigation,

optimal modulation, modulation dynamic, real time analysis, transient response, and configuration layout of different STATCOMs were investigated in [5]-[7]. In [8], the H-bridge DC capacitors were charged initially in a proposed star-connected multilevel STATCOMs in order to guarantee the possibility of their equalization. In [9], a shunt active filter based on one-cycle control for load compensation of a three-phase four-wire system was investigated. In [10], a proposed controlling scheme for cascaded full bridge voltage source inverter (VSI) based STATCOM concentrated on individual balancing of the capacitor voltages of the full-bridge converters (H-bridge converters). The balancing process was carried out by comparing the instantaneous voltage of the H-bridge capacitor voltage with a reference one. A DSTATCOM devised from a low rating voltage source converter (VSC) and a zigzag transformer was introduced by [11] for improving the power quality of a three-phase four-wire distribution system. Voltage control, current control, and integrated control schemes were employed in a three-phase STATCOM for compensating unbalanced voltages and currents [12]. A Δ-connected multilevel cascade converter based STATCOM was proposed by [13]. In the proposed STATCOM, the series reactors were connected in series to mutually coupled reactors. The mutually coupled reactors offered paths for circulating currents to flow.

In this research, a continuously and linearly controlled voltage source inverter (VSI) based full-bridge STATCOM is designed and tested. This STATCOM is characterized by high linearity and is harmonic free, thus it can considerably be exploited for load current balancing and energy saving purposes.

2.   THE PROPOSED LINEARIZED H-BRIDGE VSI BASED STATCOM

A STATCOM in general is either a voltage source inverter (VSI) with its DC source replaced by a DC capacitor or current source inverter (CSI) with its DC source replaced by a DC reactor. Both categories of power converters exchange active power and reactive power with the AC source to some extents through small reactors. These definitions are applicable for both single and three-phase STATCOMs. Since STATCOMs can be employed in both active and reactive power applications, they are usually referred to as static compensators. The single-phase VSI-based STATCOM is shown in Figure 1. The STATCOM solid-state switching devices Z_1, Z_2, Z_3, and Z_4 are insulated-gate bipolar transistors (IGBTs) equipped with fast free-wheeling diodes. v_{AC} and V_{DC} represent the instantaneous voltage of the AC source and the DC capacitor voltage, respectively. The current i_S represents the instantaneous STATCOM current. L_{ST} and R_{ST} are the self-inductance and resistance of the STATCOM reactor. The voltage v_i represents the STATCOM or the VSI generated voltage. The STATCOM of Figure 1 is usually referred to as H-bridge STATCOM. Such STATCOMs are triggered by using sinusoidal pulse width modulation (SPWM) techniques. If V_{DC} is kept constant and the STATCOM is triggered by the unipolar sinusoidal pulse width modulation (USPWM) shown in Figure 2, then v_i will be given by

$$v_i = \frac{V_{DC}}{5}(V_{Z1} - V_{Z3}) \tag{1}$$

Where, V_{Z1} and V_{Z3} are the USPWM triggering signals of Z_1 and Z_3, respectively. β is the STATCOM angle and it represents the phase shift of the modulating signal v_{MOD} with respect to v_{AC}. v_{TRI} is the carrier signal, which is a triangular waveform of amplitude of V_{TRI} and frequency of f_C. Note that v_{MOD} is a sinusoidal signal of amplitude A_{MOD} and frequency f which is the same frequency of the AC source ($f=\omega/2\pi$). The term ($V_{Z1}-V_{Z3}$) is positive when v_{MOD} is positive and vice versa. The modulating signal v_{MOD} can be defined as (2).

$$v_{MOD} = V_{MOD} \sin(\omega t + \beta) \tag{2}$$

For a STATCOM of a modulation index m, the average of v_i within v_{TRI} duration time T_C is designated by V_{iav} and is determined by (3)

$$V_{iav} = \frac{1}{T_C}\int_0^{T_C} v_i\, dt' = \frac{1}{T_C}\left(\int_{t'_1}^{t'_2} V_{DC}\, dt' + \int_{t'_3}^{t'_4} V_{DC}\, dt'\right) = mV_{DC}\sin(\omega t + \beta) \tag{3}$$

The STATCOM modulation index m is defined by (4)

$$m = \frac{A_{MOD}}{A_{TRI}} \tag{4}$$

To make (3) applicable over the carrier signal stream, the time t is substituted by kT_C and ω by $2\pi/T$. Where, T is the time duration of the modulating signal and $k=1, 2, 3$, and so on. Consequently, (3) can be rewritten as (5):

$$V_{iav}(k) = mV_{DC} \, sin\left(\frac{2\pi}{T}kT_C + \beta\right) = mV_{DC} \, sin\left(\frac{2\pi}{N}k + \beta\right) \tag{5}$$

where, N is defined by (6)

$$N = \frac{T}{T_C} \tag{6}$$

The variation of V_{iav} as function of ωt exhibits sinusoidal envelope and is in phase with v_{MOD}, thus it can be considered as the instantaneous fundamental component of voltage v_1 generated by the VSI, which can be expressed by (7)

$$v_1 = mV_{DC} \, sin(\omega t + \beta) \tag{7}$$

Assuming that the STATCOM reactor suppresses all current harmonics, the STATCOM rms fundamental current I_S can be given as (8)

$$I_S = \frac{V_{A.C} - V_1 \angle \beta}{R_{ST} + j\omega L_{ST}} \tag{8}$$

where, V_{AC} is the rms voltage of the AC source and V_1 is the rms voltage of v_1. V_1 can be defined as (9)

$$V_1 = \frac{mV_{DC}}{\sqrt{2}} \tag{9}$$

Assuming that R_{ST} is negligible compared to ωL_{ST}, (8) can be rewritten as (10)

$$I_S = \frac{(V_{AC} - V_1 \angle \beta)}{j\omega L_{ST}} \tag{10}$$

If the angle β is small and V_1 is greater than V_{AC}, I_S will be to some extent pure capacitive, while it will be pure inductive if V_1 is less than V_{AC}. In general, small negative values of β make V_1 greater than V_{AC} and according to (10), I_S will be capacitive, while small positive values of β make V_1 smaller than V_{AC} and subsequently, I_S will be inductive. The response of a certain STATCOM to β changing depends on many factors such as inverter switching losses, switching devices ON and OFF times, the dead time T_D between the triggering pulses of the switching devices on the same limb, modulation index, and passive element values. Some controlling techniques adopted phase-shifted sinusoidal PWM (SPWM) to control the current of the H-bridge STATCOM [14]. The study proposed by [15] had adopted the phase-shifted multicarrier unipolar PWM to control the STATCOM current. This type of control helps to decrease the effect of multi-switching during STATCOM triggering. Many techniques subjected STATCOM current control to lookup tables relating β values to the magnitude and phase values of the STATCOM current [8], [16]-[18]. Closed loop techniques are widely used to control STATCOM current by comparing the STATCOM current with a reference one. In these techniques, phase locked loops are usually employed to synchronize the STATCOM with the grid [10], [19]-[20]. Proportional and proportional integral controllers are broadly employed for STATCOM current control [13], [21]-[25].

The STATCOM shown in Figure 1 is modified here to meet the requirements of being continuously and linearly controlled harmonic-free compensating susceptance. The modification is involved in two steps; in the first step V_{DC} is kept constant at a certain level for each compensating current without using external energy injection or storage devices, while in the second step, the reactive compensating current is brought to its steady state value within a shorter time compared with other controlling techniques [16], [17]-[25].

The first step of STATCOM modification is accomplished by using a series harmonic filter connected in parallel with V_{DC} as shown in Figure 3. The second step represents the most important modification and is accomplished by devising a new controlling technique. In this technique, the STATCOM angle β is controlled within a range of -5.73^0 to $+5.73^0$. In this range of β, the modified STATCOM current is guaranteed to be pure reactive (either capacitive or inductive).
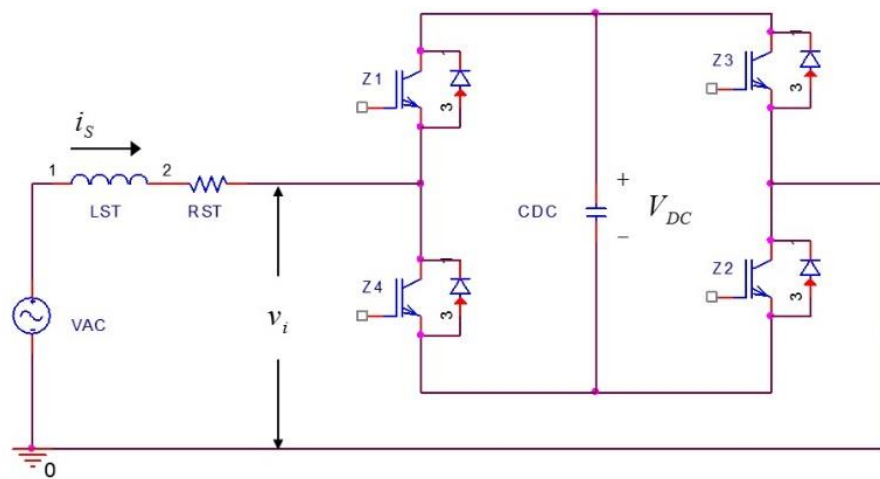
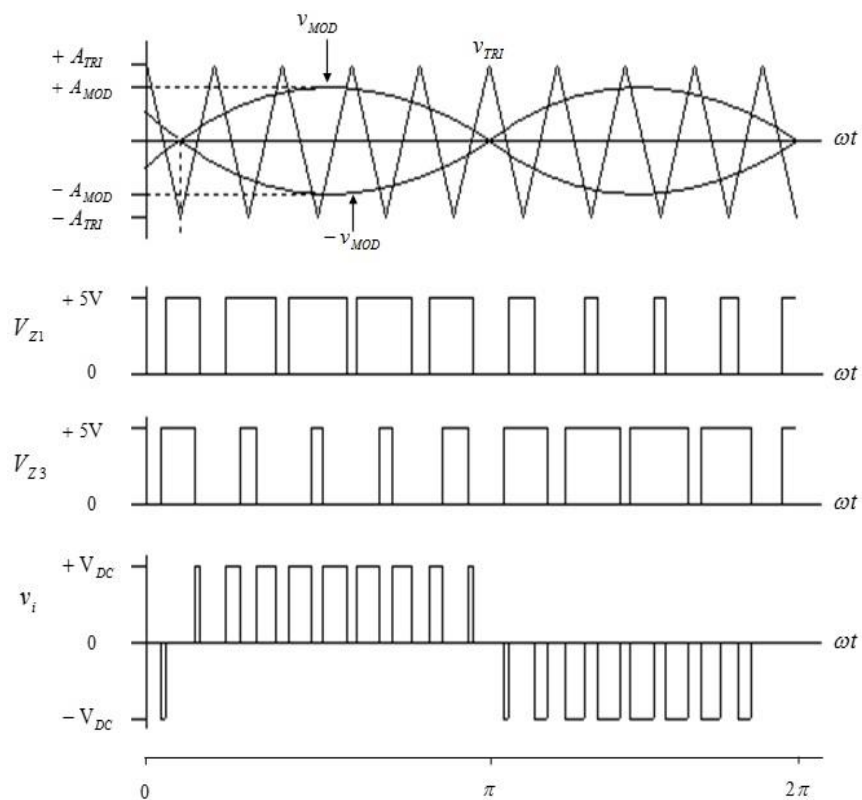Figure 1. The VSI-based H-bridge STATCOM

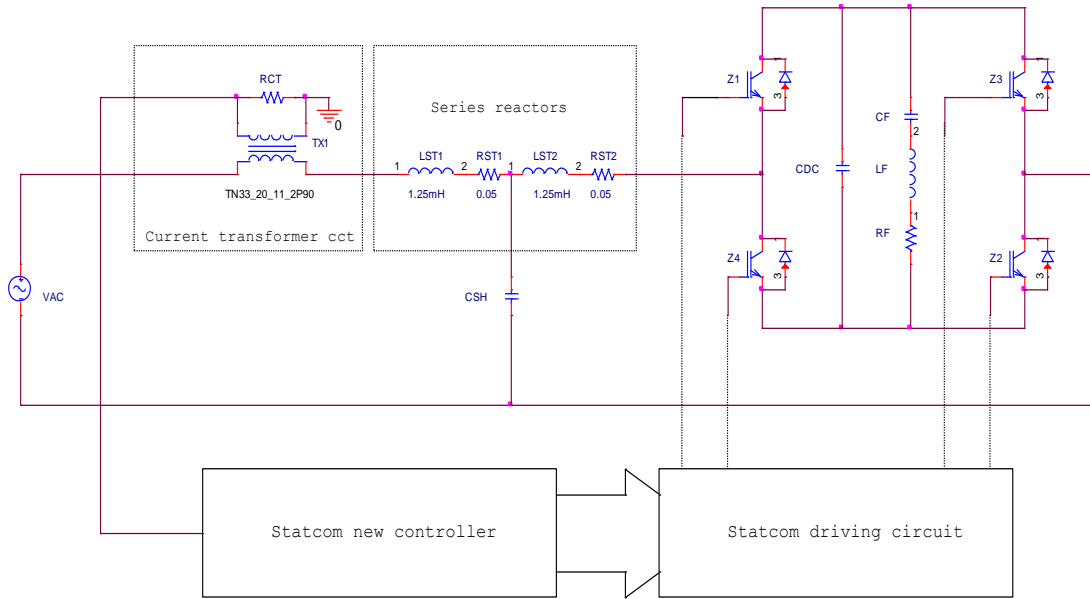Figure 2. USPWM triggering signals generation of the VSI-based STATCOM

Figure 3. The layout of the proposed linearized STATCOM

a.   The devised controlling technique

The schematic modeling of the devised controlling technique is shown in Figure 4. After detecting the STATCOM instantaneous current i_S by the current transformer and converting it to the voltage signal $k_S i_S$, the latter signal is processed within the sample and hold circuits to get the analogue voltage $k_S I_{Sm}$. Where, I_{Sm} is the amplitude of i_S and k_S is a constant depending on the current transformer primary to secondary turn ratio and the resistor R_{CT}. The analogue voltage $k_S I_{Sm}$ is subtracted from $k_S I_{Dm}$ which is another analogue signal proportional to the amplitude of the required reactive demand I_{Dm}. The result of subtraction is $\Delta k_S I_{Sm}$ which is an analogue voltage proportional to the amount of deviation of the actual STATCOM current from the required reactive current demand. Note that I_{Sm} is a polar quantity. Its value is positive during capacitive reactive current demand and negative during inductive current demand. This means that detecting I_{Sm} means detecting the magnitude and phase of the STATCOM current. The most important part of the above controller is the STATCOM angle controller. It involves two identical NPN bipolar junction transistors Q_1 and Q_2 which are biased in the active regions near cutoff. $V\gamma$ is the cut in threshold voltage of these transistors. According to the biasing status of Q_1 and Q_2, their base currents i_{B1} and i_{B2} can be expressed as (11) and (12)

$$i_{B1} = \frac{\Delta V(\beta)}{R_{B1}}, \Delta V(\beta) \geq 0 \tag{11}$$

$$i_{B2} = \frac{-\Delta V(\beta)}{R_{B2}}, \Delta V(\beta) \leq 0 \tag{12}$$

Where, $\Delta V(\beta)$ is an analogue voltage signal proportional to the error of the STATCOM angle β. If Q_1 and Q_2 are in their active regions, then their collector currents i_{C1} and i_{C2} can be determined as (13) and (14):

$$i_{C1} = h_{FE} i_{B1} = \frac{h_{FE} \Delta V(\beta)}{R_{B1}}, \Delta V(\beta) \geq 0 \tag{13}$$

$$i_{C2} = h_{FE} i_{B2} = \frac{-h_{FEE} \Delta V(\beta)}{R_{B2}}, \Delta V(\beta) \leq 0 \tag{14}$$

Where, h_{FE} is the forward DC current gain of the common emitter configuration. The DC forward current gain is used in this analysis, since the transistor's input voltages are slow varying signals. In case of saturation, the currents i_{C1} and i_{C2} can be given by (15) and (16)

$$i_{C1} = \frac{V_{CC} - V(\beta)}{R_{C1}}, \Delta V(\beta) \geq 0 \tag{15}$$

$$i_{C2} = \frac{V(\beta) + V_{CC}}{R_{C2}}, \Delta V(\beta) \leq 0 \tag{16}$$
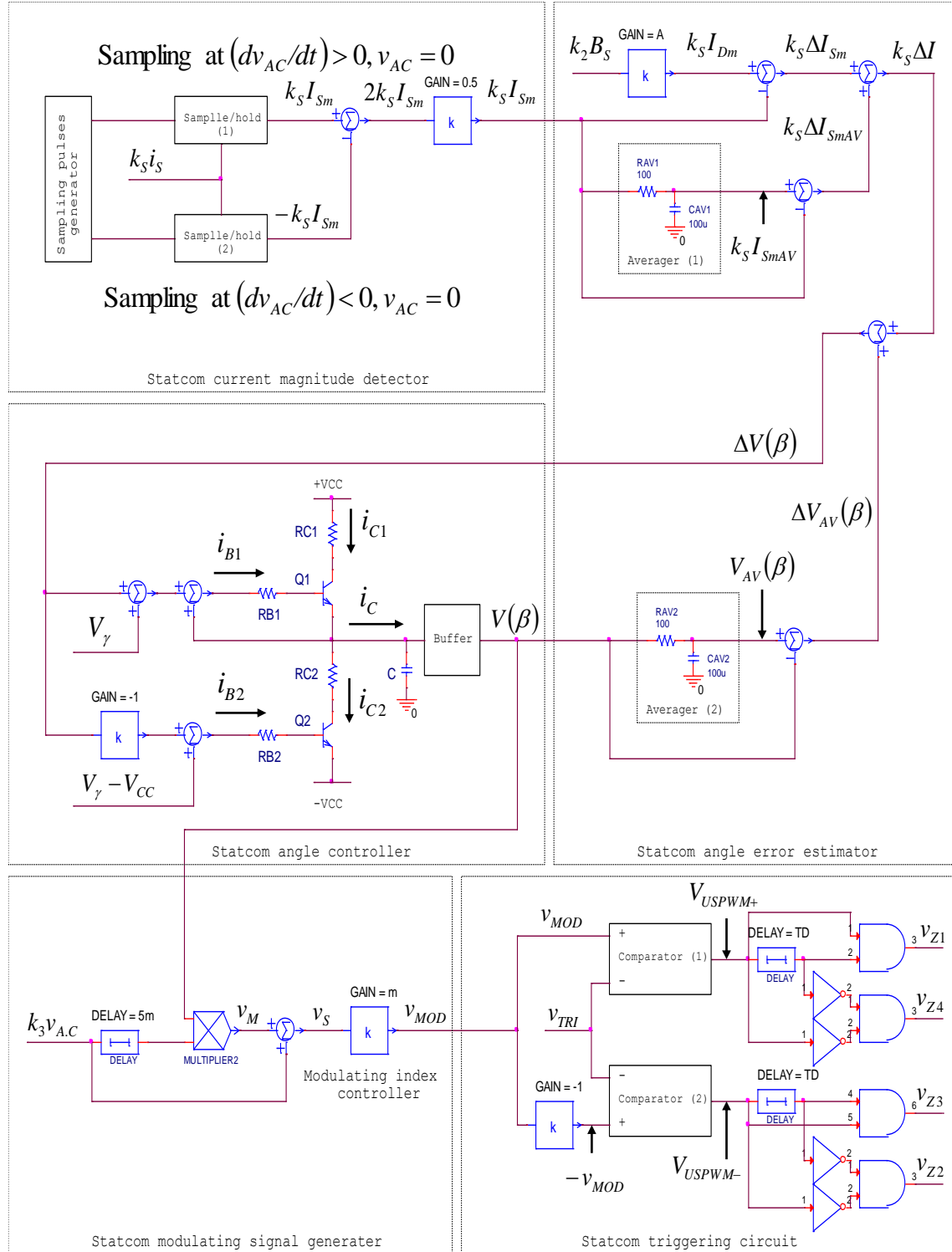

Figure 4. The devised controlling scheme

Where, $V(\beta)$ is an analogue voltage signal proportional to the STATCOM angle. If $V(\beta)$ is more positive than V_{CC} or more negative than $-V_{CC}$, then (15) and (16) are no longer being applicable. The current i_C of the capacitor C is determined as (17):

$$i_C = \begin{pmatrix} i_{C1} + i_{B1}, \Delta V(\beta) \geq 0 \\ -i_{C2}, \Delta V(\beta) \leq 0 \end{pmatrix} \tag{17}$$

The voltage across the capacitor C, is $V(\beta)$ which represents the analogue signal controlling a part in this controller responsible for generating the modulating signal v_{MOD}. The analogue signal $V(\beta)$ can be expressed as (18):

$$V(\beta) = \frac{1}{C} \int i_C dt \tag{18}$$

The error signal $\Delta V(\beta)$ is determined by (19)

$$\Delta V(\beta) = \Delta V_{AV}(\beta) + k_S \Delta I \tag{19}$$

where, $\Delta V_{AV}(\beta)$ and ΔI are defined by (20) and (21)

$$\Delta V_{AV}(\beta) = V_{AV}(\beta) - V(\beta) \tag{20}$$

$$\Delta I = \Delta I_{Sm} + \Delta I_{SmAV} \tag{21}$$

where, $V_{AV}(\beta)$ represents the instantaneous average value of $V(\beta)$, and the current error components ΔI_{Sm} and ΔI_{SmAV} are defined by (22) and (23)

$$\Delta I_{Sm} = I_{Dm} - I_{Sm} \tag{22}$$

$$\Delta I_{SmAV} = I_{SmAV} - I_{Sm} \tag{23}$$

Where, I_{SmAV} is the instantaneous average value of I_{Sm}. As i_C grows positive rapidly, $V(\beta)$ builds up rapidly too and it may make significant overshoots. The error signals defined by the terms $k_S \Delta I_{SmAV}$ and $\Delta V_{AV}(\beta)$ decrease the chances for $V(\beta)$ to exhibit overshoots and make the STATCOM current tend faster toward its desired value. Both terms vanish as $V(\beta)$ attains its steady state value. The analogue voltage $V(\beta)$ determines the phase angle by which, the modulating signal v_{MOD} will be shifted from the original AC voltage applied across the STATCOM terminals. $V(\beta)$ varies in the range of $-V_{CC}$ to $+V_{CC}$. If $\Delta V(\beta)$ is positive, C will charge through Q_1 towards V_{CC}, while C will discharge towards $-V_{CC}$ through Q_2 if $\Delta V(\beta)$ becomes negative. The STATCOM modulating signal generator is built of a time delayer of 5msec, analogue multiplier, summer, and a voltage amplifier of forward gain of m which is related directly to the STATCOM modulation index. The analogue voltage $k_3 v_{AC}$ is a low voltage sinusoidal signal proportional to the AC supply voltage. For a 50-Hz AC power supply, the 5msec delay represents a phase delay of $\pi/2$. If the AC voltage v_{AC} is expressed as $V_m sin(\omega t)$, then the output of the analogue multiplier v_M will be determined as (24):

$$v_M = k_3 V_m \sin\left(\omega t - \frac{\pi}{2}\right) V(\beta) A_M = -V(\beta) A_M k_3 V_m \cos(\omega t) \tag{24}$$

where, V_m is the amplitude of v_{AC} and A_M is the gain of the analogue multiplier. The summing amplifier output v_S can be given by (25)

$$\begin{aligned} v_S &= k_3 v_{A.C} + v_M = k_3 V_m \sin(\omega t) - V(\beta) A_M k_3 V_m \cos(\omega t) \\ &= k_3 V_m \left(\sqrt{(A_M V(\beta))^2 + 1}\right) \sin\left(\omega t - \tan^{-1}(A_M V(\beta))\right) \end{aligned} \tag{25}$$

If $|A_M V(\beta))|$ is very much less than unity, (25) can be reduced to (26)

$$v_S \cong k_3 V_m \sin(\omega t - A_M V(\beta)) = k_3 V_m \sin(\omega t + \beta) \tag{26}$$

where, β is defined by (27)

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$$\beta = -A_M V(\beta) \tag{27}$$

By varying β in the range of (-0.1 to +0.1) radians, the voltage generated by the STATCOM varies from minimum to maximum. This radian range corresponds to a degree range of -5.73^0 to $+5.73^0$. The maximum capacitive current of the STATCOM corresponds to β of -5.73^0, while the maximum inductive current corresponds to β of $+5.73^0$. By varying β from $+5.73^0$ to -5.73^0, the STATCOM current can be varied from maximum inductive to maximum capacitive.

b.   Design of the proposed linearized STATCOM

Figure 5 shows the PSpice implementation of the modified statcom. In this figure, the STATCOM controller involves the generated electronic parts simulating the schematic design items shown Figure 4.

Figure 5. The PSpice implementation of the modified STATCOM
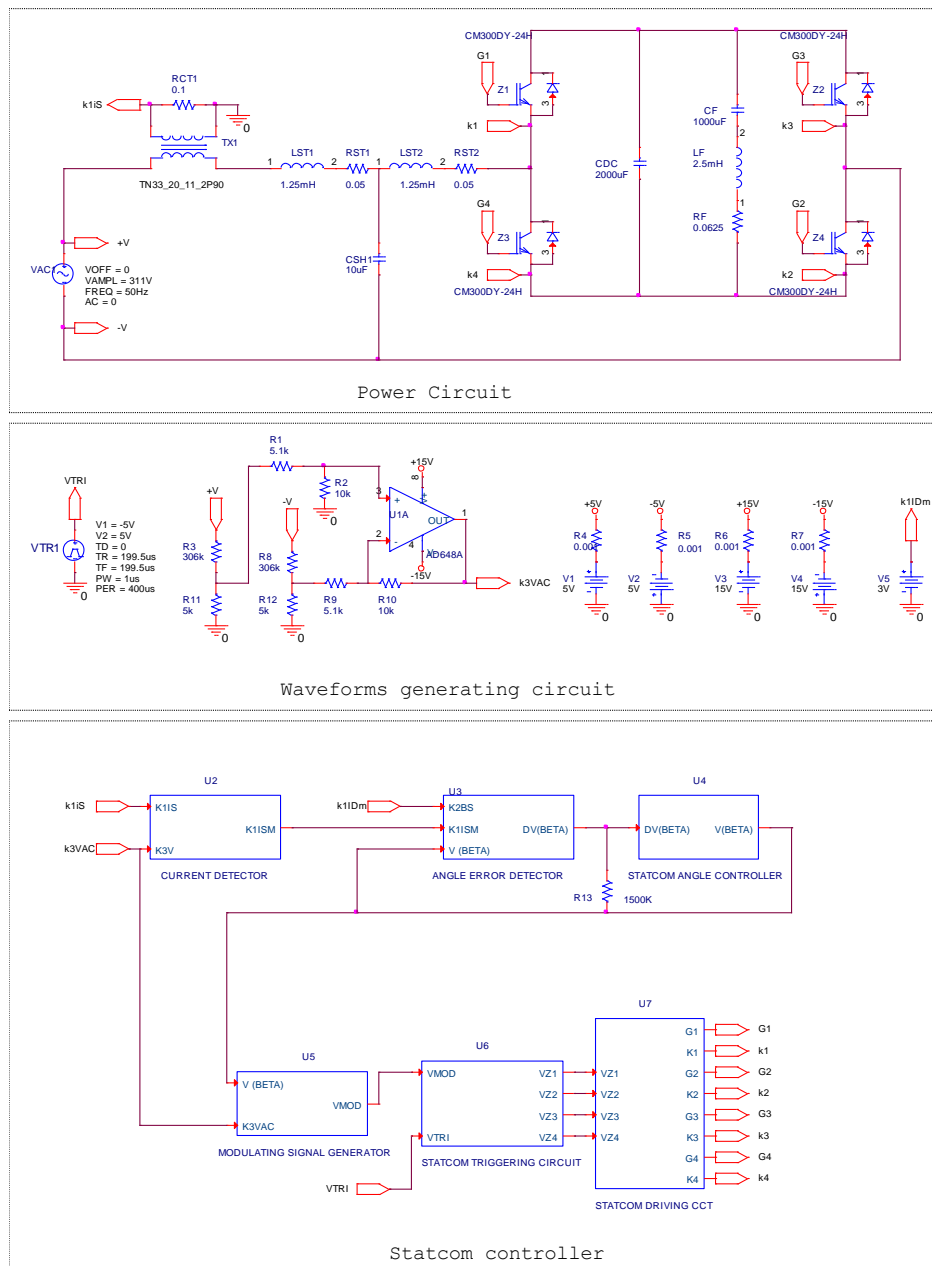
The current transformer used in the designed STATCOM, has a primary to secondary turn ratio of 0.2, therefore the constant k_S is calculated to be 0.02Ω taking into account the 0.1Ω value of R_{CT} (the resistor shunting the current transformer). The voltage source V_5 represents the analogue signal k_1I_{Dm}. Negative and positive values of V_5 are corresponding to capacitive and inductive reactive current demands, respectively. The AC voltage used is of amplitude of 311V (220V rms value) and frequency of 50Hz. The IGBT used is of the type of CM300DY-24H which has maximum continuous voltage and current ratings of 1200V and 300A, respectively. The carrier frequency is 2.5 KHz and m is about 0.98. The modified STATCOM is designed to satisfy a peak reactive current demand of 250A (capacitive or inductive). The driving circuit of the STATCOM is shown in Figure 6. It is composed of four identical sub-driving circuits; each one of them is responsible for driving one IGBT of the STATCOM.
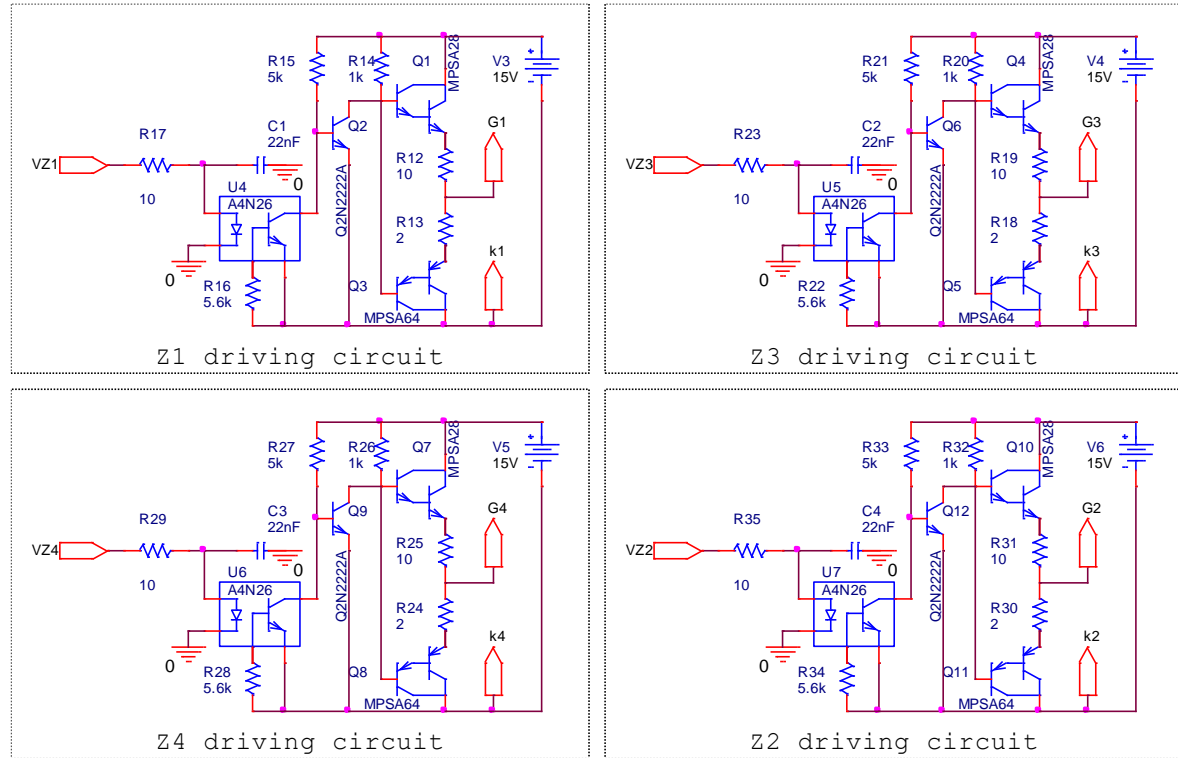

Figure 6. The PSpice implementation of the STATCOM driving circuit

3. RESULTS AND DISCUSSION

In this section, there are two groups of results; the first reflects the the performance of the adopted current controller, while the second reveals the performance of the propsed STATCOM at different reactive current demands.

3.1. Performance of the adopted current controller

The performance of the PSpice implemented STATCOM is reflected in the test results shown in Figure 7 to Figure 9. These figures show that the linearized STATCOM current i_S approaches its steady state value within a time less than 100msec which is the time less than any time elapsed in other controlling techniques [16], [17]-[25]. A +3V value of k_1I_{Dm} corresponds to a capacitive reactive current demand of 150A (peak value), while -3V corresponds to inductive reactive current demand of 150A (peak value). Figure 7 shows that the STATCOM current is pure capacitive, while Figure 8 shows that its current is pure inductive. Figure 9 shows that the STATCOM current tends to zero during zero reactive current demand. The nature of the STATCOM current (capacitive or inductive) is revealed within the first cycle of v_{AC}, although the DC capacitor requires long charging time. Overall, the proposed STATCOM responds precisely to reactive current demand within its range of operation without harmonics association, thus it can be promoted as an adaptive bipolar (capacitive and inductive) static Var compensator (SVC) showing continuously and linearly controlled harmonic-free compensating susceptance.
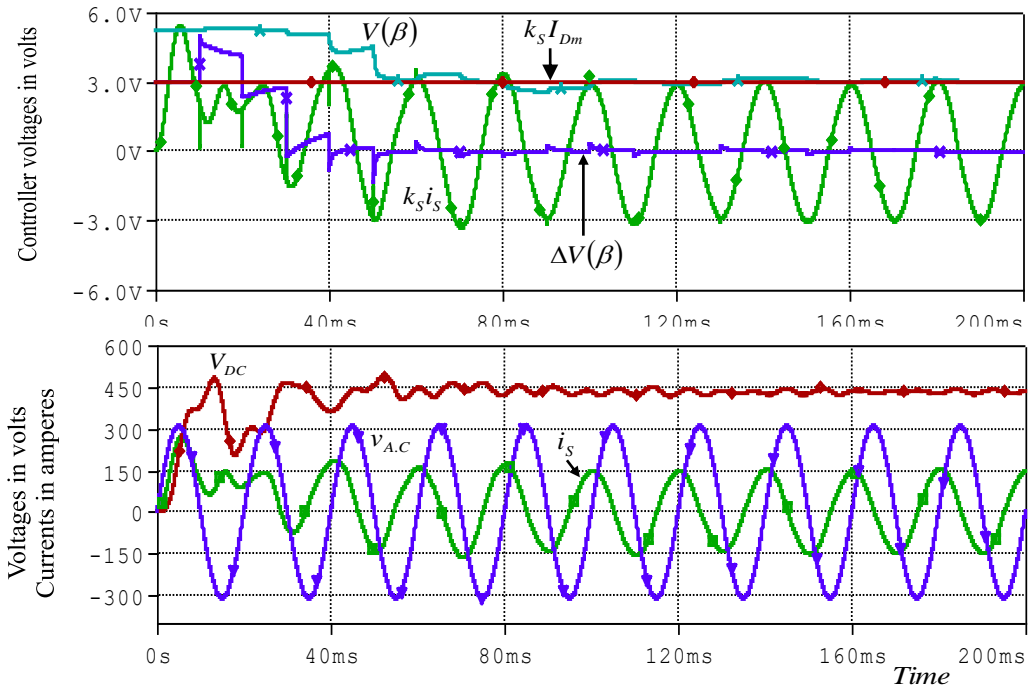
Figure 7. Controller and STATCOM responses to capacitive current demand of 150A (peak value)
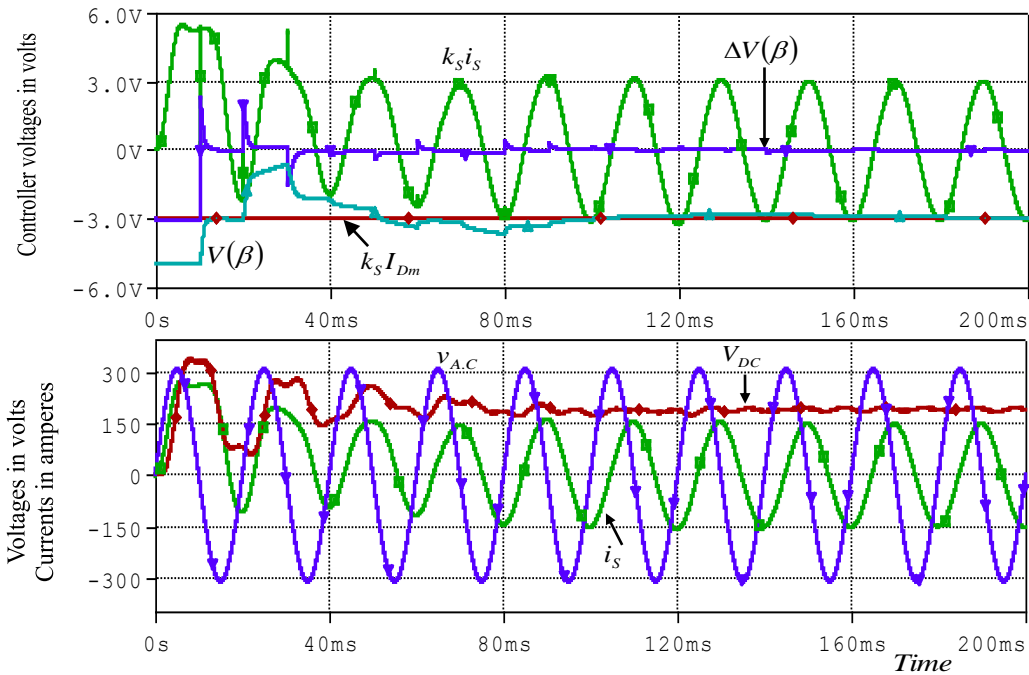

Figure 8. Controller and STATCOM responses to inductive current demand of 150A (peak value).
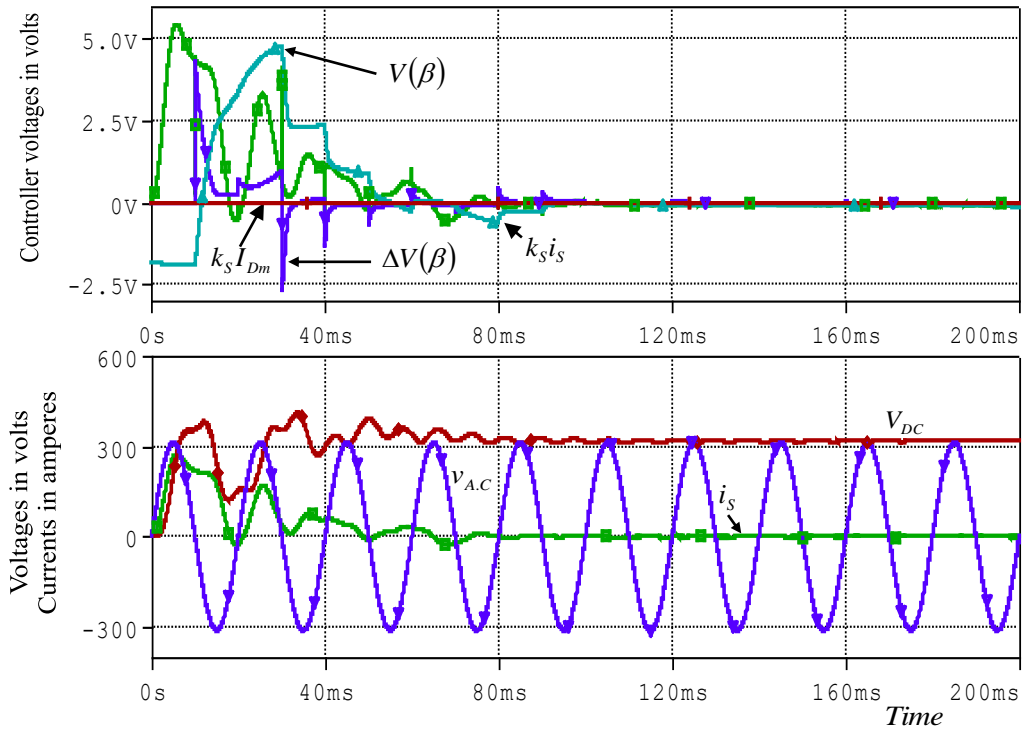
Figure 9. Controller and STATCOM responses to zero reactive current demand

3.2. Performance results of 220-V, 50-Hz linearized STATCOM

The circuit diagram of 220-V, 50-Hz linearized STATCOM is shown in Figure 10. The harmonic contents, control continuity and linearity of this STATCOM were investigated on PSpice. The AC voltage used during PSpice tests was a zero phase sinusoidal voltage having frequency of 50Hz and amplitude of 311V (corresponding to an rms value of 220V). The parameters measured through PSpice tests were the STATCOM current i_S, the DC capacitor voltage V_{DC}, and the AC phase voltage v_P. The basic controlling signal of this statcom is k_1I_{Dm}. The transient and steady state responses of this statcom during zero reactive current demand (corresponded to $k_1I_{Dm}=0$) are shown in Figure 10.
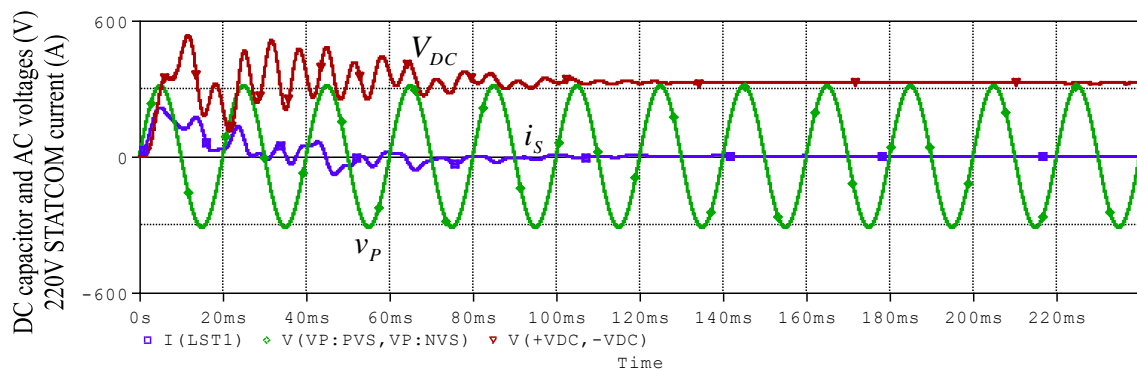

Figure 10. Transient and steady state responses of the proposed STATCOM to zero reactive current demand

Figure 11 shows the transient and steady state responses of the 220-V, 50-Hz linearized STATCOM to an inductive reactive current demand of 61.5A (peak value). This amount of reactive current demand corresponded to k_1I_{Dm} of a value of -1.23V. As specified above, the maximum capacitive reactive of this STATCOM is 227A (peak value) and maximum inductive current rating is 123A (peak value). Figure 12 shows the transient and steady states operation of the 220-V, 50-Hz linearized STATCOM during its

response to a maximum inductive current demand of 123A (peak value). This current corresponded to $k_1 I_{Dm}$ of -2.46V.
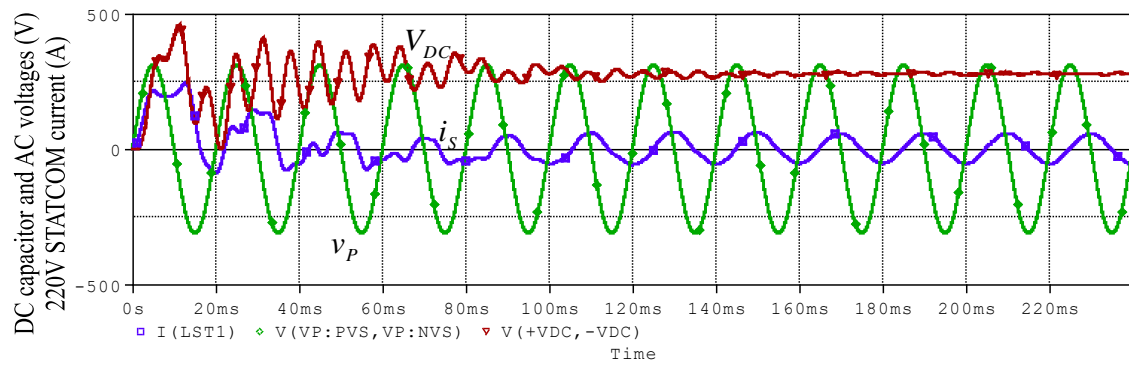

Figure 11. Transient and steady state responses of the proposed STATCOM to an inductive current demand of 61.5A (peak value)
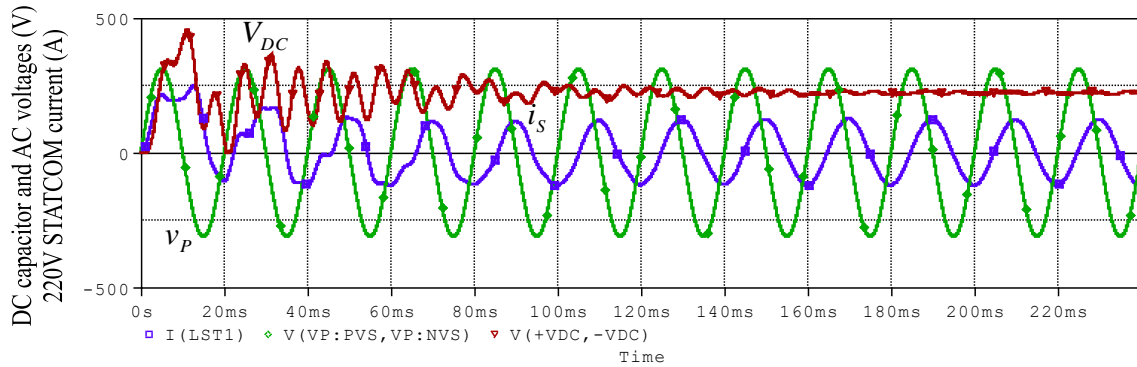

Figure 12. Transient and steady state responses of the proposed STATCOM to an inductive current demand of 123A (peak value)

The transient and steady states operation results of this Transient and steady state responses of the proposed STATCOM to during capacitive mode of operation are shown in Figure 13 to Figure 16. These figures reflect the Transient and steady state responses of the proposed STATCOM performance during different capacitive reactive current demands starting from 25% up to 100% of the STATCOM capacitive reactive current rating. The maximum capacitive susceptance of this statcom corresponds to a capacitive reactive current demand of 227A, thus the value of this susceptance is calculated to be 227A/311V=0.723℧. This value of susceptance corresponds to $k_1 I_{Dm}$ of 4.54V. Figure 13 states that the DC capacitor voltage settled to its steady value within 100msec since the first plug in instant of the 220-V, 50-Hz STATCOM to the AC source. The nature of the capacitive current appears after 20ms since the first plug in instant of the 220-V, 50-Hz STATCOM to the AC source.
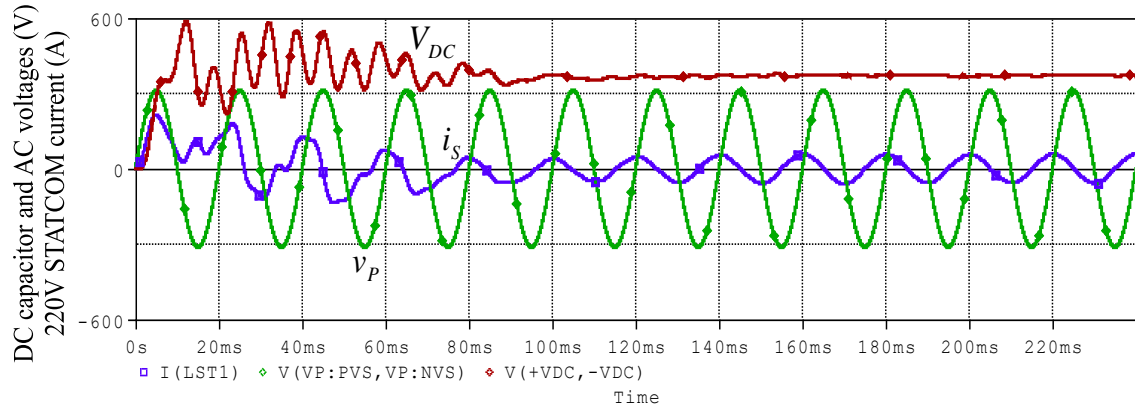
Figure 13. Transient and steady state responses of the proposed STATCOM to a capacitive reactive current demand of 56.75A (peak value)
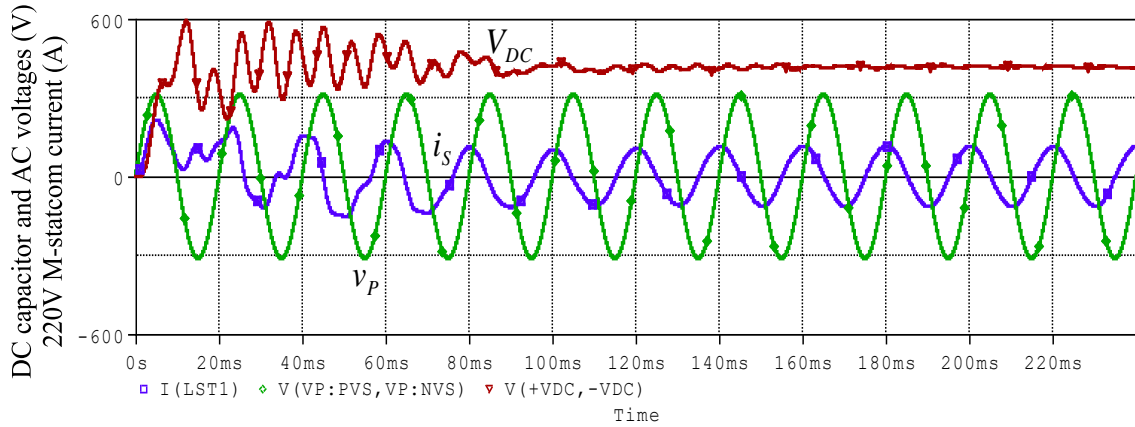

Figure 14. Transient and steady state responses of the proposed STATCOM to a capacitive reactive current demand of 113.5A (peak value)
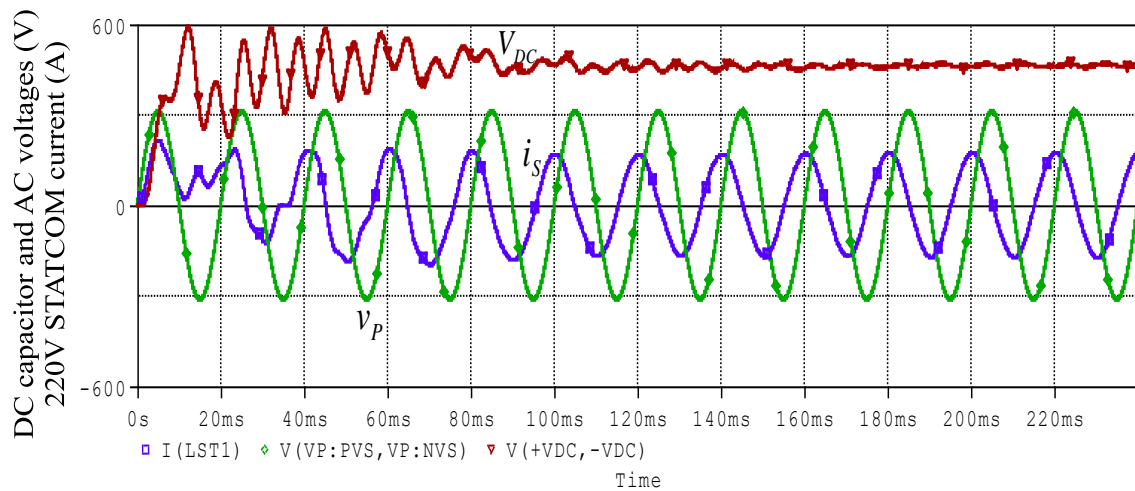

Figure 15. Transient and steady state responses of the proposed STATCOM to a capacitive reactive current demand of 170.25A (peak value)
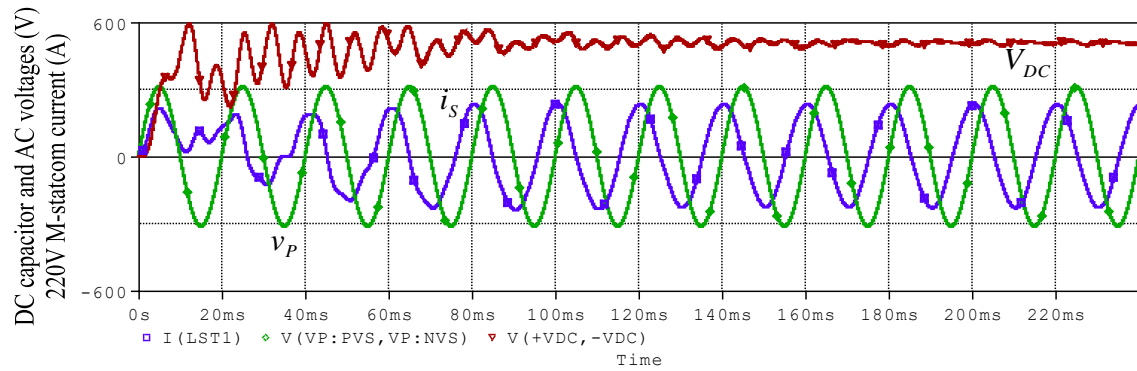
Figure 16. Transient and steady state responses of the proposed STATCOM to a capacitive reactive current demand of 227A (peak value)

In inductive and capacitive modes of operation, the STATCOM current exhibits peaks at the zero crossing points of the AC source voltage. Consequently, it can be said that the proposed 220-V, 50-Hz STATCOM is a pure reactive device. The response of this STATCOM to sudden change in reactive current demand from maximum inductive to maximum capacitive is shown in Figure 17. The change in reactive demands occurred at t=200ms and the transition period elapsed 40ms. The linearity of this STATCOM is demonstrated by the graph shown in Figure 18. The graph is accomplished through exploiting the steady state responses shown in Figure 10 to Figure 16. It is obvious that there are negligible current components in the STATCOM current in steady state regions of the current responses. Overall, the proposed 220-V, 50-Hz STATCOM is verified as continuously and linearly controlled harmonic-free compensating susceptance. The proposd current controller has short response time compared to controlling schemes mentioned in [16], [17]-[25].
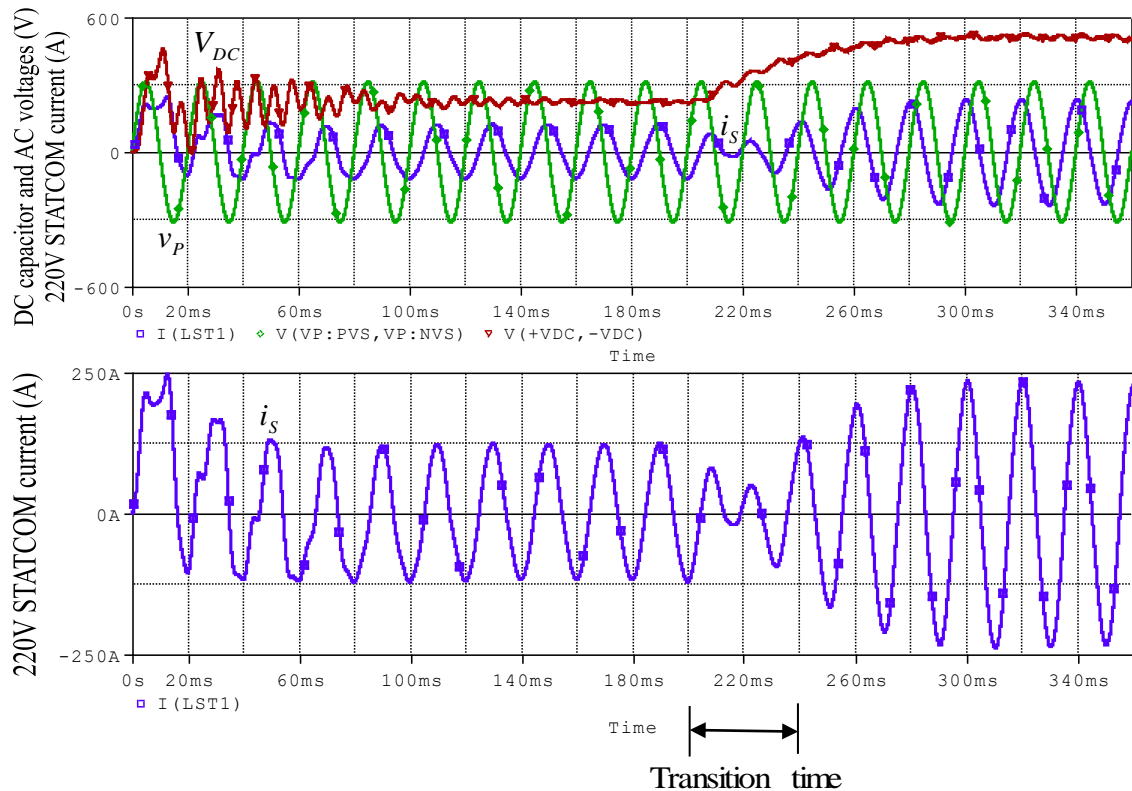

Figure 17. STATCOM performance during sudden change in reactive current demand from maximum inductive to maximum capacitive
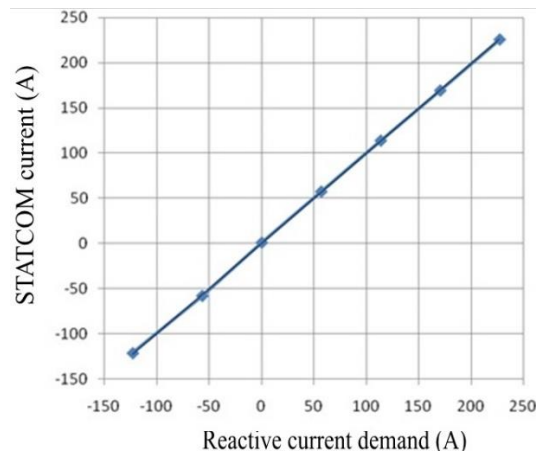
Figure 18. The proposed STATCOM current against reactive current demand

4.   CONCLUSION

The proposed STATCOM has been demonstrated as a continuously and linearly controlled susceptance in capacitive and inductive mode of operations, thus it can considerably be exploited in load current balancing systems to achieve better power quality and energy saving. The promotion is achieved through the modification of the traditional H-bridge VSI based STATCOM via devising new current controller and keeping the STATCOM DC capacitor voltage constant at a certain level for each compensating current without using external energy injection or storage devices. The response of this STATCOM to sudden change in reactive current demand from maximum inductive to maximum capacitive requires a transition period of 40ms.

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