Balancing of four wire loads using linearized H-bridge static synchronous compensators

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ABSTRACT

In this paper, a load balancing system is designed to balance the secondary phase currents of 11 kV/380 V, 50 Hz, 100 kVA power transformer in a three phase 4-wire, distribution network. The load balancing system is built of six identical modified static synchronous compensators (M-STATCOMs). Each M-STATCOM is constructed of a voltage source converter-based H-bridge controlled in capacitive and inductive modes as a linear compensating susceptance. The M-STATCOM current is controlled by varying its angle such that it exchanges pure reactive current with the utility grid. Three identical M-STATCOMs are connected in delta-form to balance the active phase currents of the power transformer, whereas the other three identical M-STATCOMs are connected in star-form to compensate for reactive currents. The M-STATCOMs in the delta-connected compensator are driven by 380 V line-to-line voltages, whilst, those connected in star-form are driven by 220 V phase voltages. The results of the 220 V and 380 V M-STATCOMs have exhibited linear and continuous control in capacitive and inductive regions of operation without steady-state harmonics. The proposed load balancing system has offered high flexibility during treating moderate and severe load unbalance conditions. It can involve any load unbalance within the power transformer current rating and even unbalance cases beyond the power transformer current rating.

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1. INTRODUCTION

Static Var compensators (SVCs) and static synchronous compensators (STATCOMs) are usually exploited in the treatment of many issues concerning power quality like harmonic's association, voltage unbalance and unbalanced loads [1]-[26]. Unbalanced loads and poor power factor usually lead to significant losses in both generation station and transmission system. This may restrict or decrease the capability of transmission systems. Power transmission efficiency can be increased by reducing losses through power factor treatment and load compensation techniques [7], [9]. In addition, compensation techniques play significant roles in the management of other challenging issues facing power quality achievement like voltage unbalance and harmonic association. Balancing of loads characterized by large fluctuations is of great importance because it is not economical to supply the required Var from the alternating current (AC) source and the power system is not capable to maintain its terminal voltage within its desirable range [19].

Load balancing systems are usually built of compensating susceptances to accomplish two main functions, which are reactive current compensation and balancing of active currents [9], [15], [26]. The compensating susceptances are required to be linearly controlled in both capacitive and inductive modes in order to accomplish reliable load current compensation [6], [24]. Distribution STATCOMs are widely used to apply load compensation for 4-wire systems [2], [7], [25]. Other technologies approached power converter-based shunt SVCs for achieving minimization of harmonics, current balancing, and voltage compensation [2], [3], [5], [8], [11], [12], [22]. Separate delta and star-connected susceptances are more efficient in accomplishing compensation for current and voltage imbalances than lumped systems [1], [3], [4], [7], [9], [10], [13]-[17], [20]-[23]. Conditions of current imbalance and harmonic issues can be treated using series compensation systems [14].

In this paper, a load current balancing system built of two static compensators is proposed. Both compensators are built of linearized H-bridge STATCOMs as compensating susceptances. The first compensator is built of three identical susceptances connected in delta-form, whereas the second one is built of another three susceptances connected in star-form. Each susceptance is designed such that it has wide range of linearity, control continuity, very low operating losses, fast response, and negligible harmonic's association.

2. LOAD BALANCING OF 4-WIRE SYSTEMS

Two static compensators are required to accomplish current balancing of 4-wire loads [9], [15], [26]. The first compensator is built using three similar susceptances connected in delta-form, whereas the second one is built of three identical susceptances connected in star-form. All susceptances are assumed to be linearly controlled in capacitive and inductive modes [6], [24]. The first compensator is designed to balance active components of the phase currents, while the second one is dealt with cancelling the reactive current components. Figure 1 reveals the proposed balancing mechanism of a 4-wire load energized by the balanced phase voltages V_A, V_B, and V_C. B_{S1AB}, B_{S1BC}, and B_{S1CA} are the susceptances of the delta-connected compensator, whereas B_{S2A}, B_{S2B}, and B_{S2C} are the susceptances of the star-connected compensator. I_{S1A}, I_{S1B}, and I_{S1C} are the line currents of delta-connected compensator, whereas I_{S2A}, I_{S2B}, and I_{S2C} are the phase currents of the star-connected one. I_{LA}, I_{LB}, and I_{LC} represent phase currents of the 4-wire load. I_A, I_B, and I_C are the AC source phase currents, which are intended to be balanced and in phase with their corresponding phase voltages.

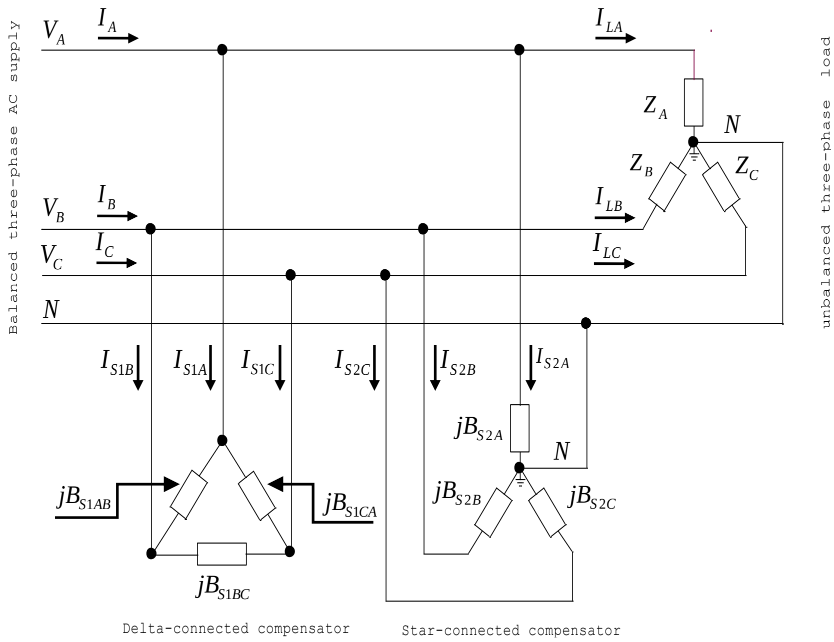


Figure 1. The power circuit of the proposed load current balancing system

The phase voltages V_A, V_B, and V_C are assumed to be balanced in magnitude and phase; thus, they can be expressed as:

$$V_A = V \tag{1}$$

$$V_B = Ve^{j\frac{-2\pi}{3}} \tag{2}$$

$$V_C = Ve^{j\frac{-4\pi}{3}} \tag{3}$$

where, V is the rms magnitude of the balanced phase voltage. The phase currents of the unbalanced load can be given by:

$$I_{LA} = |I_{LA}|e^{j\phi_{LA}} = |I_{LA}|\cos\phi_{LA} + j|I_{LA}|\sin\phi_{LA} \tag{4}$$

$$I_{LB} = |I_{LB}|e^{j\left(-\frac{2\pi}{3}+\phi_{LB}\right)} = (|I_{LB}|\cos\phi_{LB} + j|I_{LB}|\sin\phi_{LB})e^{j\frac{-2\pi}{3}} \tag{5}$$

$$I_{LC} = |I_{LC}|e^{j\left(-\frac{4\pi}{3}+\phi_{LB}\right)} = (|I_{LC}|\cos\phi_{LC} + j|I_{LB}|\sin\phi_{LC})e^{j\frac{-4\pi}{3}} \tag{6}$$

where, φ_{LA}, φ_{LB}, and φ_{LC} are the load current angles of phases A, B, and C respectively. $|I_{LA}|$, $|I_{LB}|$, and $|I_{LC}|$, are the rms magnitudes of I_{LA}, I_{LB}, and I_{LC} respectively. According to this work objectives, the AC source currents I_A, I_B, and I_C should be active and balanced. Thus, they can be defined by:

$$I_A = I \tag{7}$$

$$I_B = Ie^{j\frac{-2\pi}{3}} \tag{8}$$

$$I_C = Ie^{j\frac{-4\pi}{3}} \tag{9}$$

where, I is the rms value of each phase current. The real power P_L delivered to the load is the same real power P fed by the AC source. Thus, it can be written (10).

$$P_L = V(|I_{LA}|\cos\phi_{LA} + |I_{LB}|\cos\phi_{LB} + |I_{LC}|\cos\phi_{LC}) = P = 3I \tag{10}$$

Therefore, the active I can be equated to (11).

$$I = \frac{|I_{LA}|\cos\phi_{LA}+|I_{LB}|\cos\phi_{LB}+|I_{LC}|\cos\phi_{LC}}{3} \tag{11}$$

The compensating susceptances are equated by [9], [15], [26] as follows:

$$B_{S1AB} = \frac{2(|I_{LA}|\cos\phi_{LA}-|I_{LB}|\cos\phi_{LB})}{3\sqrt{3}V} \tag{12}$$

$$B_{S1BC} = \frac{2(|I_{LB}|\cos\phi_{LB}-|I_{LC}|\cos\phi_{LC})}{3\sqrt{3}V} \tag{13}$$

$$B_{S1CA} = \frac{2(|I_{LC}|\cos\phi_{LC}-|I_{LA}|\cos\phi_{LA})}{3\sqrt{3}V} \tag{14}$$

$$B_{S2A} = \frac{|I_{LB}|\cos\phi_{LB}-|I_{LC}|\cos\phi_{LC}-\sqrt{3}|I_{LA}|\sin\phi_{LA}}{\sqrt{3}V} \tag{15}$$

$$B_{S2B} = \frac{|I_{LC}|\cos\phi_{LC}-|I_{LA}|\cos\phi_{LA}-\sqrt{3}|I_{LB}|\sin\phi_{LB}}{\sqrt{3}V} \tag{16}$$

$$B_{S2C} = \frac{|I_{LA}|\cos\phi_{LA}-|I_{LB}|\cos\phi_{LB}-\sqrt{3}|I_{LC}|\sin\phi_{LC}}{\sqrt{3}V} \tag{17}$$

the values of the above susceptances are polar Quantities. Positive values mean capacitive susceptances. The negative values refer to inductive susceptances.

2.1. The modified STATCOM (M-STATCOM)

Figure 2 shows the power circuit of the proposed H-bridge STATCOM. It is a voltage source converter (VSC) based type. In this circuit, the STATCOM reactor L_{ST} is partitioned into two identical series reactors L_{ST1} and L_{ST2}. The small capacitor C_{SH} is used to reduce the effects of voltage spikes. The STATCOM DC voltage V_{DC}, which appears across C_{DC} is smoothed by the series filter formed by C_F, L_F, and R_F. R_{ST1}, R_{ST2}, and R_F are the self or ohmic resistances of the reactors L_{ST1}, L_{ST2}, and L_F, respectively.

The AC source voltage v_{ac} is stepped down and shifted by an angle β to produce the modulating signal v_{MOD}, which is expressed by (18).

$$v_{MOD} = A_{MOD}\, sin(\omega t + \beta) \tag{18}$$

Where, A_{MOD} (5V) is its amplitude and ω ($2\pi f$) is the angular frequency of the AC source. The angle β is the STATCOM angle.

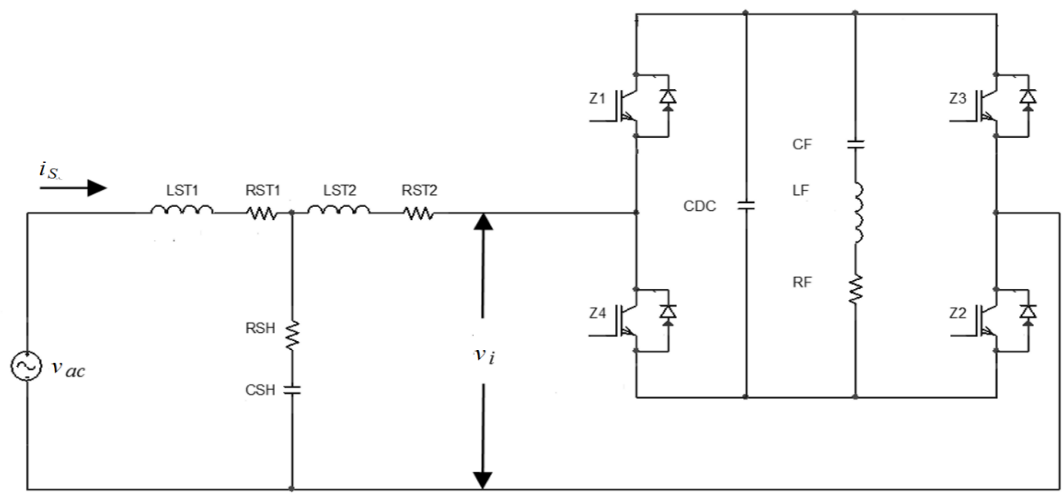


Figure 2. The proposed modified STATCOM

The sinusoidal pulse width modulation shown in Figure 3 is used to trigger the proposed STATCOM. The signal v_{MOD} is compared with a triangular voltage v_{TRI} to produce the triggering signal V_{Z1} of the IGBT Z_1, whereas $-v_{MOD}$ is compared with v_{TRI} to produce the triggering signal V_{Z3} of Z_3. The voltage v_i shown in Figures 2 and 3 can be given by (19) [24].

$$v_i = \frac{V_{DC}}{5}(V_{Z1} - V_{Z3}) \tag{19}$$

The fundamental component of v_i is v_1 and it can be given by (20) [24].

$$v_1 = mV_{DC}\, sin(\omega t + \beta) \tag{20}$$

Where, m represents the modulation index which can be given by (21).

$$m = \frac{A_{MOD}}{A_{TRI}} \tag{21}$$

Where, A_{TRI} is the amplitude of v_{TRI}. The STATCOM rms current I_S can be given by (22).

$$I_S = \frac{V_{A.C} - V_1 \angle \beta}{R_{ST1} + j\omega L_{ST1} + R_{ST2} + j\omega L_{ST2}} \tag{22}$$

If the reactances of the STATCOM reactors are very much greater than their ohmic resistances, then (22) can be approximated to:

$$I_S = \frac{V_{A.C} - V_1 \angle \beta}{j\omega L_{ST1} + j\omega L_{ST2}} \tag{23}$$

if β is controlled in the range of ±0.1rad, then v_{ac} and v_1 are approximately in phase and I_S is purely reactive. Negative values of β make V_1 greater than V_{AC} and 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.

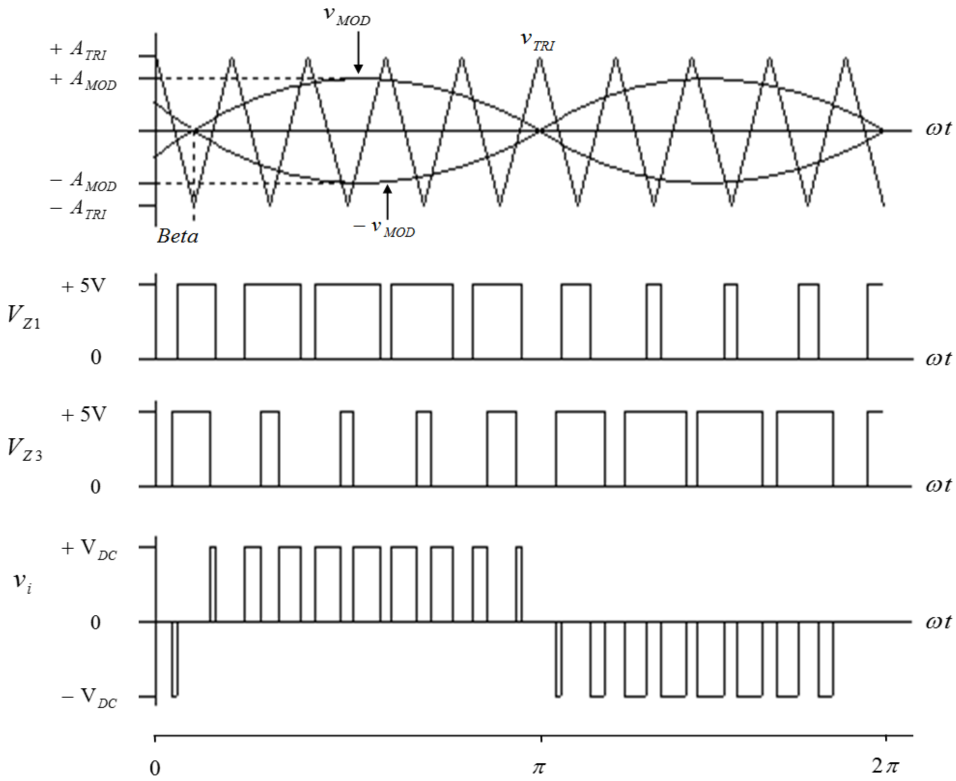


Figure 3. The STATCOM triggering mechanism

2.2. Design of the 380 V M-STATCOM

The proposed system is required to balance the phase currents at the secondary side of an 11 kV/ 380 V power transformer having an apparent power rating of 100 kVA in a 380 V, 50 Hz, 4-wire system. At the secondary side, the peak value of the phase rated current is 214 A. The consumer power factor is assumed to be 0.8 lagging as an average value. In this work, the delta-connected compensator is designed to balance the load active currents when one phase current is zero and the other two phases are running at their rated currents with unity power factor. According to (11), the active current I of the AC source is 142.67 A (peak value). If phase C of the load carries the zero current, then according to (12)-(14) the compensating susceptances are calculated as: B_{S1AB}=0, B_{S1BC}=0.265 ℧, and B_{S1CA}=-0.265 ℧. In this work, the delta-connected compensator is built of three identical 380 V, 50 Hz modified STATCOMs. According to the calculated susceptances, the 380 V modified STATCOM should be designed such that it responds equally to both capacitive and inductive current demands. The maximum capacitive current is $B_{S1BC}\times V_{AC}$ =0.265 ℧×537 V=142.67 A (peak value). The maximum inductive current is $B_{S1CA}\times V_{CA}$=-0.265 ℧×537 V=142.67 A=-142.67 A (peak value).

Figure 4 shows the PSpice design of the 380 V modified STATCOM. The controller of the modulating signal is a built-in library in PSpice [24]. It is denoted by the part "M-STATCOM VMOD controller", which is excited by three analog signals. These signals are k_4B_S, k_3V_L, and k_Si_S. The line-to-line voltage V_L is stepped down to 5 V (peak value) to form k_3V_L, which represents the modulating signal v_{MOD}. The signal k_4B_S is proportional to the required 380 V STATCOM susceptance. The susceptance current i_S is detected by the current transformer (CT) and converted to the analog voltage k_Si_S, which has a maximum amplitude of 10 V. The signal voltage k_4B_S governs the STATCOM current i_S via shifting v_{MOD} by small angle β proportional to the required compensating susceptance B_S. The generated v_{MOD} is compared with v_{TRI} in the PSpice part "M-STATCOM TRIGGERING CCT" to produce the triggering signal V_{Z1} and -v_{MOD} is compared with v_{TRI} to produce V_{Z2}. The triangular voltage v_{TRI} has an amplitude of 5 V and a carrier frequency of 2.5 kHz.

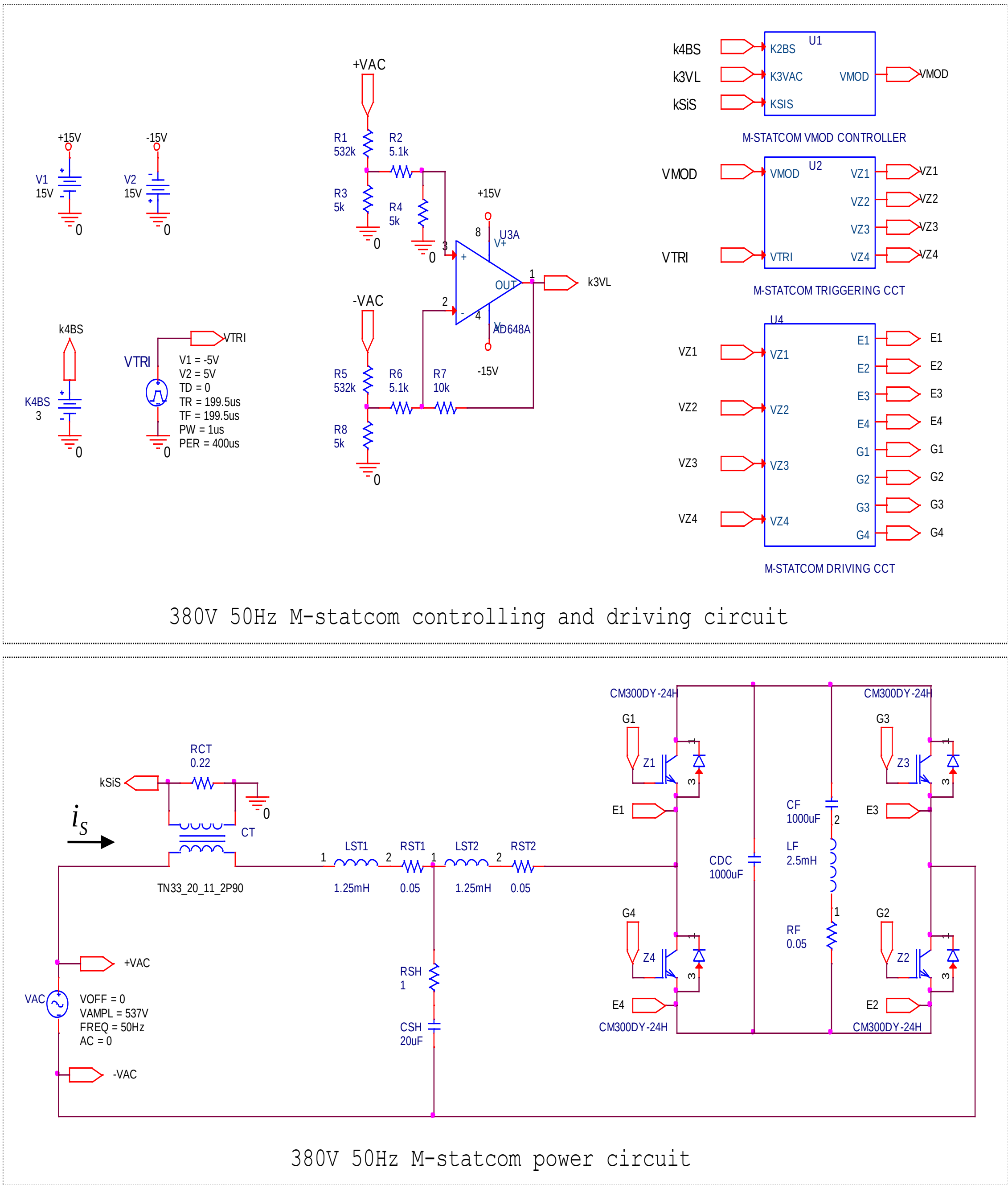


Figure 4. The 380 V, 50 Hz M-STATCOM

2.3. Design of the 220 V M-STATCOM

The circuit design of the 220 V, 50Hz M-STATCOM is shown in Figure 5. It is similar to the 380 V, 50 Hz M-STATCOM. It is operated by the phase voltage. The capacitive and inductive ratings for this STATCOM can be calculated by considering an unbalance case occuring during the open circuit of one phase of a load carrying the rated current with 0.8 lagging power factor. Assumining that phase A is open circuited, then the real or active current components of phases B and C are 214×0.8=171.2 A (peak value). Note that in this unbalance case, the power factor angles of phases B and C are φ_{LB}=-37^0 and φ_{LC}=-37^0, respectively. Their inductive reactive currents are 214×sinφ_{LB} =-0.6×214= -128.4 A (peak value) and 214×sinφ_{LC} =-0.6×214= -128.4 A (peak value). According to these calculated active and reactive current components and (15)-(17), the calculated susceptances of the star-connected static compensator are B_{S2A}=0, B_{S2B}=0.73 ℧, and B_{S2C}=-0.07945 ℧. The maximum capacitive current expected to be provided by the 220 V STATCOM is V_B×B_{S2B} =311 V×0.73 ℧=227 A (peak value).

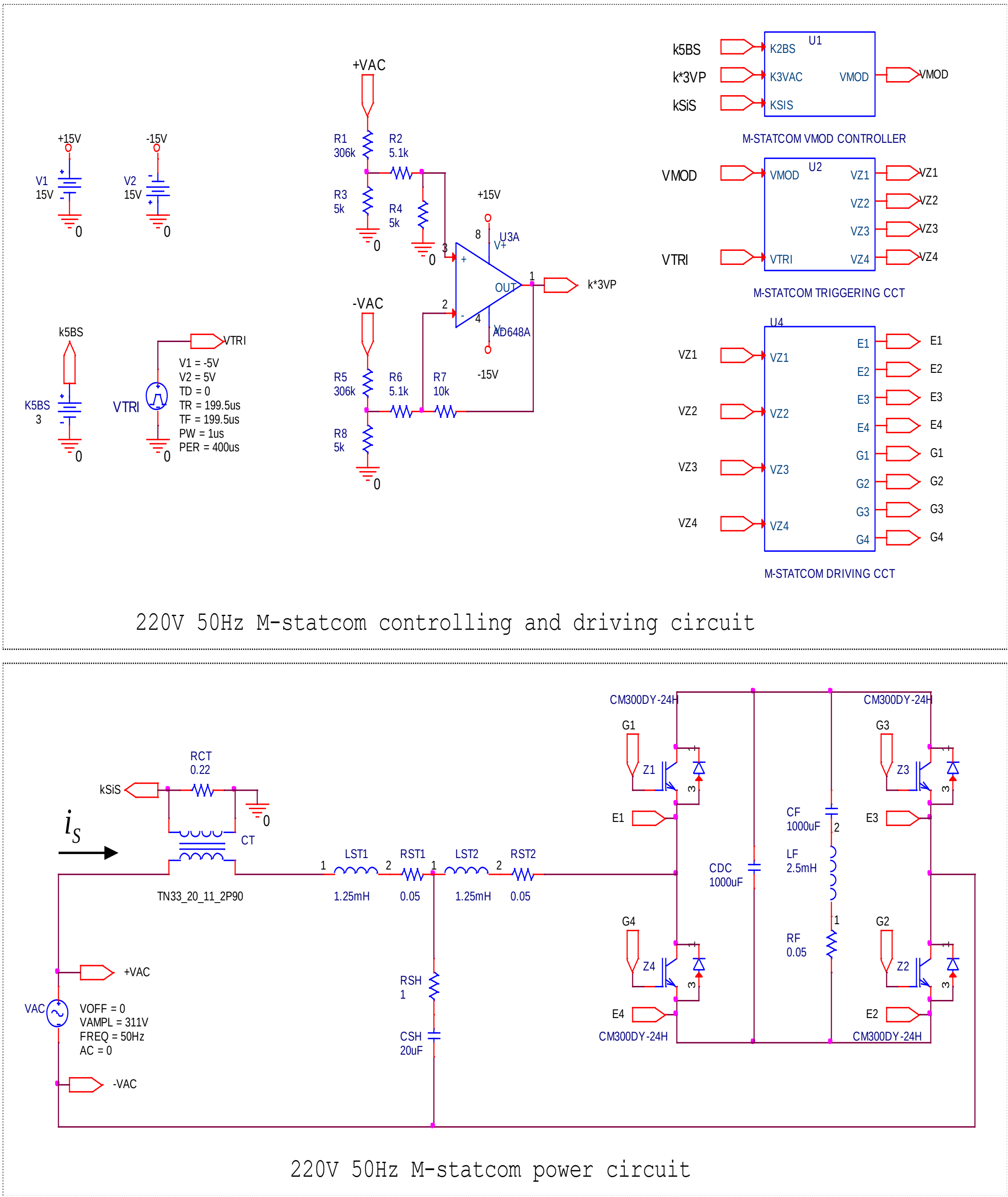


Figure 5. The 220 V, 50 Hz M-STATCOM

2.4. The PSpice design of the proposed load current balancing system

Figure 6 shows the circuit diagram of the proposed load current balancing system for a three-phase grounded load in 380 V, 50 Hz distribution network. The AC voltages detection circuit and current transformer used in this system have the same PSpice implementation of those shown in Figures 4 and 5, except that the resistance values of the AC voltages detection circuit in this system are chosen such that k^*_3 and k_3 are 0.016 and 0.0093, respectively. The delta-connected static compensator is built of three identical 380 V M-STATCOMs. Each STATCOM is capable of supplying a linear reactive current controlled in both capacitive and inductive modes of operation. The maximum rating of each STATCOM is about ±150 A (peak value). The star-connected static compensator is built of three identical 220 V M-STATCOMs. Each STATCOM is capable of supplying a linear reactive current controlled in both capacitive and inductive modes of operation. The maximum capacitive current rating of each STATCOM is 227 A (peak value).

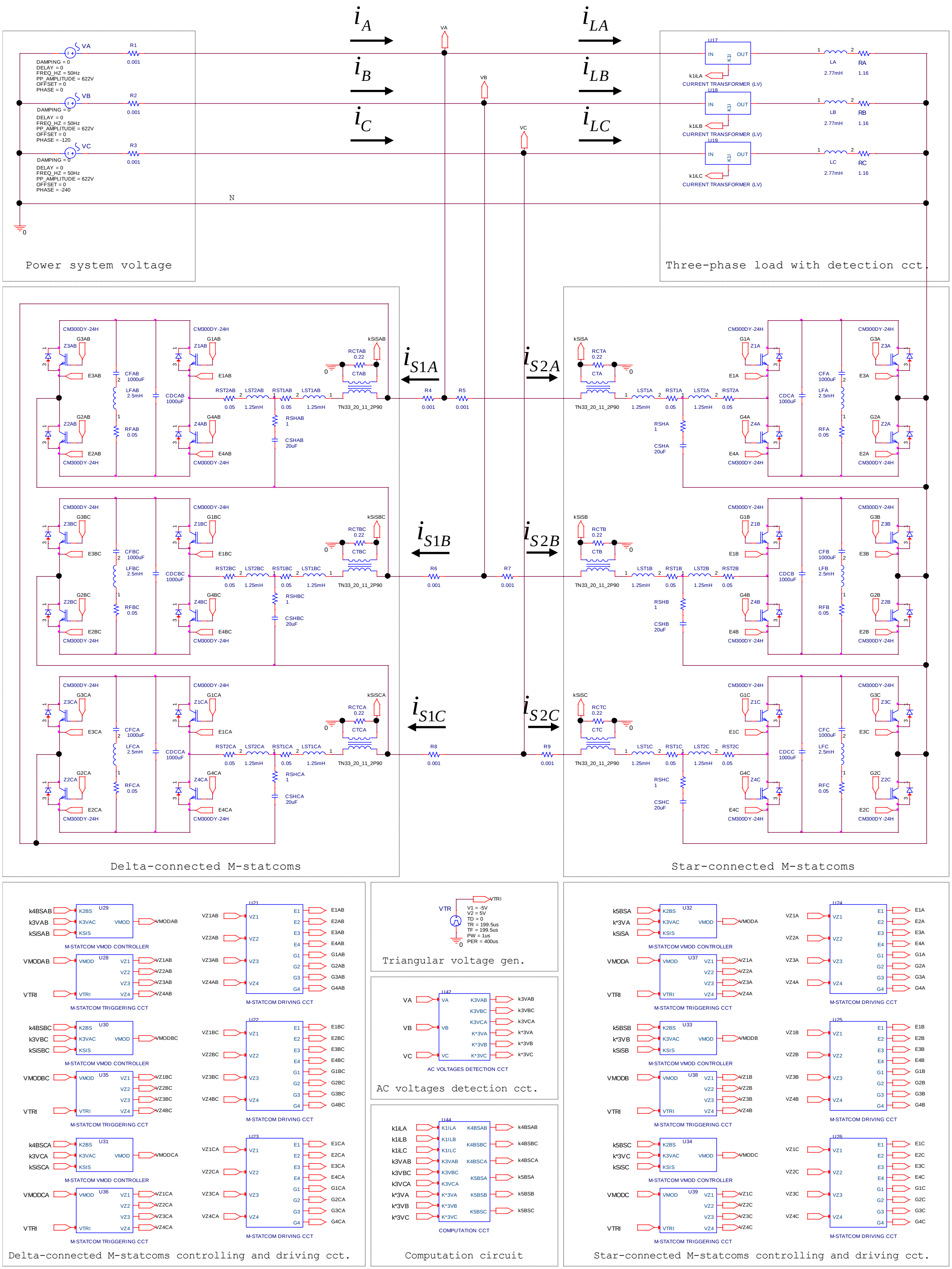


Figure 6. Circuit design of the proposed load current balancing system

The computation circuit of this system is shown in Figure 7. In this circuit, the load current signals are sampled at the positive peaks and negative slope zero-crossing points of their corresponding phase voltages to obtain the active and reactive components of load phase currents, respectively. The delta-connected compensator susceptances are computed using (12)-(14), while the star-connected compensator susceptances are computed by using (15)-(17).

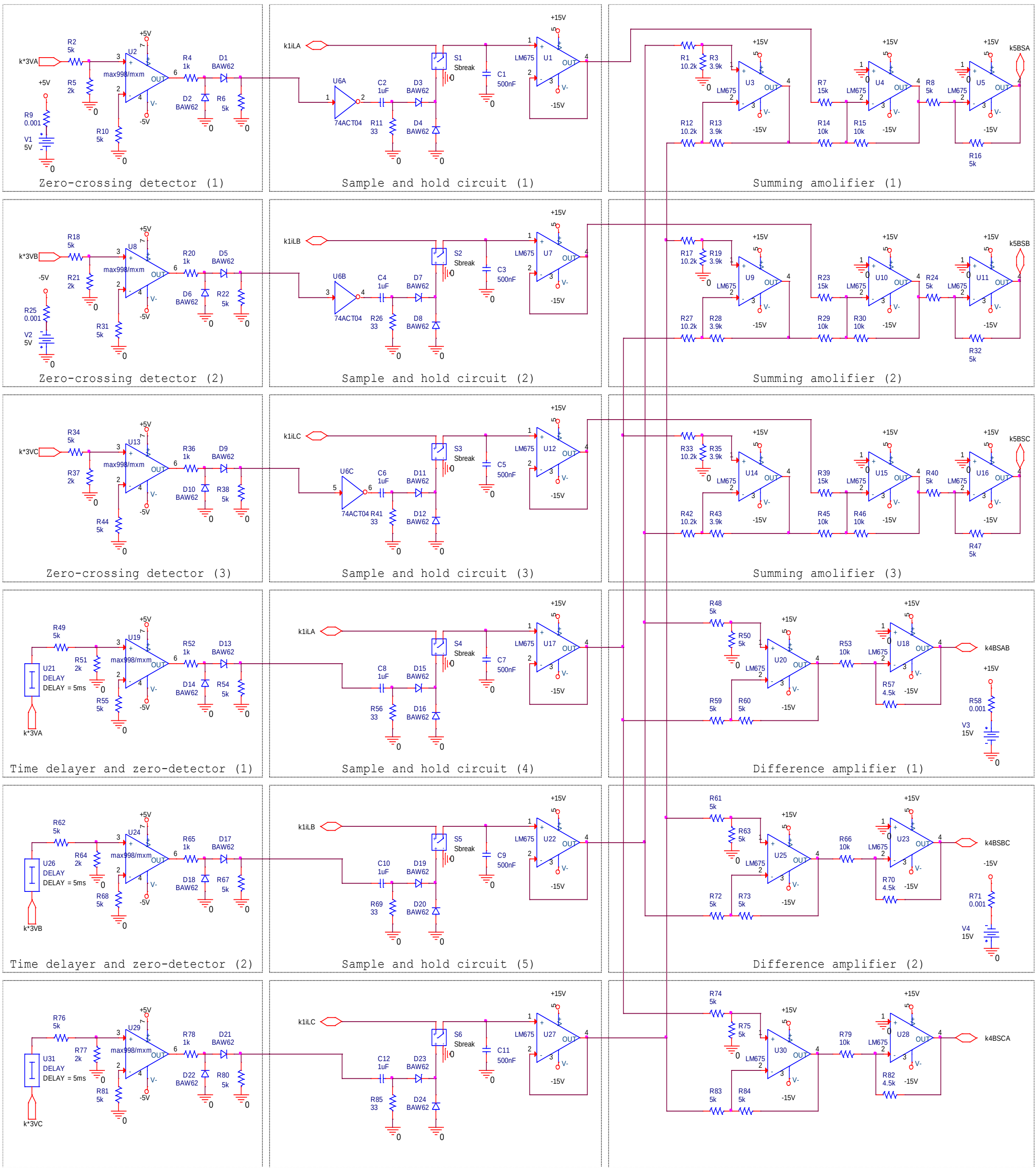


Figure 7. Computation circuit of the load current balancing system

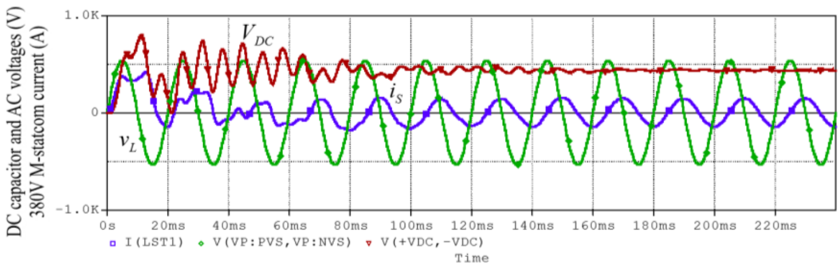
3. RESULTS AND DISCUSSION

The circuits of Figures 4-6 were tested on PSpice to investigate their performances at different loading conditions. The targeted parameters are STATCOM currents, load phase currents, static compensators currents, and AC source phase currents. Different unbalance cases are treated by the proposed balancing system.

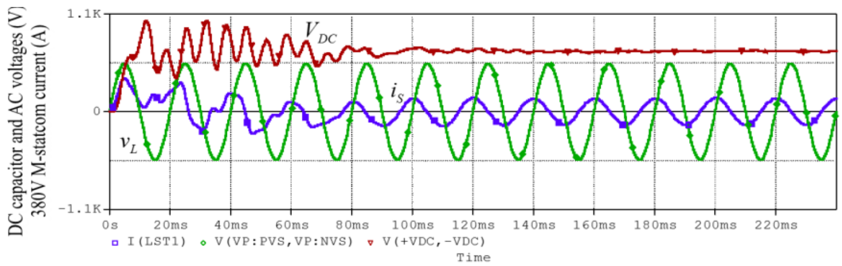
3.1. Performance results of 380 V M-STATCOM

The 380 V, 50 Hz M-STATCOM shown in Figure 4 was tested on PSpice. The above STATCOM was tested on PSpice for the investigation of harmonic contents, control continuity, and linearity. The parameters measured through PSpice tests were the STATCOM current i_S, the DC capacitor voltage V_{DC}, and the AC voltage v_L. The basic controlling signal of the compensator is k_4B_S. Figure 8 shows responses to maximum demands. Figure 8(a) shows v_L, i_S, and V_{DC} of the 380 V M-STATCOM during its response to its maximum inductive reactive current demand, whereas Figure 8(b) shows v_L, i_S, and V_{DC} of this STATCOM during its response to maximum capacitive reactive current demand. These responses corresponded to k_4B_S of ±6.6 V. 6.6 V corresponds to a capacitive reactive current demand of 150 A (peak value), whereas -6.6V corresponds to an inductive current demand of -150 A (peak value). The figure states that the response settled within 5 cycles of the power system fundamental voltage without any harmonic association.

The potency of the M-STATCOM controller is realized during it response to sudden change in reactive current demand from maximum inductive to maximum capacitive. Figure 9 shows the performance of the 380 V M-STATCOM during a sudden change in reactive current demand from maximum inductive to maximum capacitive. The change from inductive to capacitive reactive current demand had occurred at t=200 ms and the STATCOM changed the nature of its current from inductive to capacitive within a time less than 20 ms. It acquired it steady state current within 40 ms since the instant of reactive current demand change.



(a)



(b)

Figure 8. The AC voltage v_L, the current i_S, and the capacitor DC voltage V_{DC} of the 380 V M-STATCOM during response to maximum (a) inductive reactive current demand and (b) capacitive reactive current demand

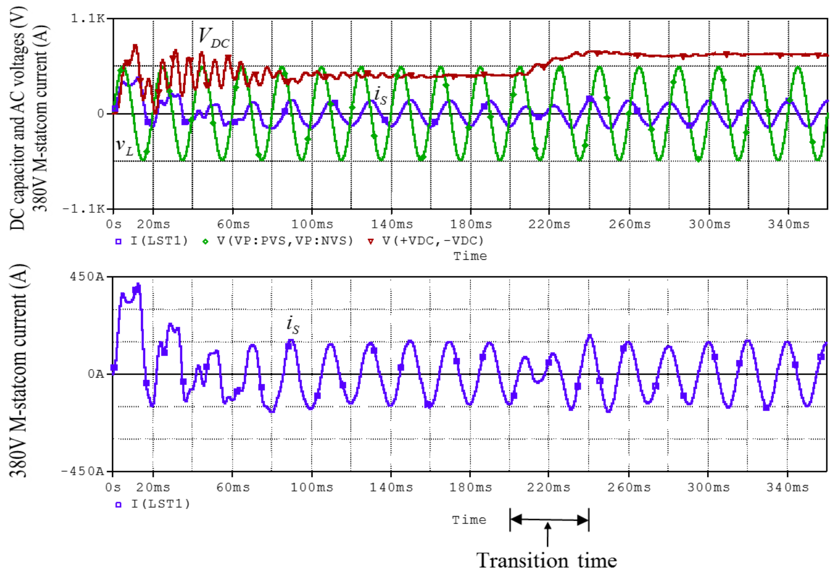


Figure 9. Performance of the 380 V M-STATCOM during sudden change in reactive current demand from maximum inductive to maximum capacitive

Figure 10 shows the current of the 380 V M-STATCOM against reactive current demand. The linearity the M-STATCOM as a compensating susceptance is verified by the graph of this figure. The graph is obtained by plotting the actual STATCOM reactive current against current demand.

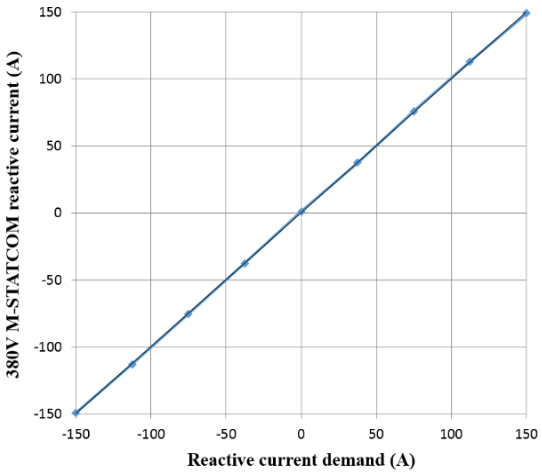


Figure 10. The 380 V M-STATCOM current against reactive current demand

3.2. Performance results of 220 V M-STATCOM

The circuit diagram of 220 V M-STATCOM shown in Figure 5 was tested on PSpice. The AC voltage used during PSpice tests was a zero-phase sinusoidal voltage having a frequency of 50 Hz and amplitude of 311 V (corresponding to an rms value of 220 V). The basic controlling signal of this STATCOM is k_5B_S. The linearity of this STATCOM is shown in Figure 11. Overall, Figure 11 verifies the linearity and continuous control of the 220 V M-STATCOM as a compensating susceptance in capacitive and inductive modes of operation.

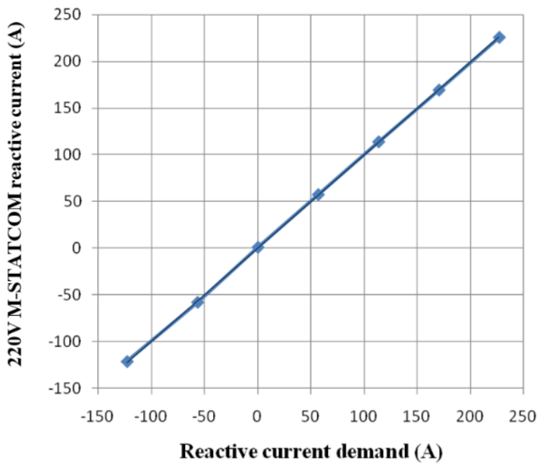


Figure 11. 220 V M-STATCOM current against reactive current demand

3.3. Performance results of the proposed load current balancing system

This system shown in Figure 6 was investigated under different unbalance conditions. The basic parameters measured were the AC source voltages v_A, v_B, and v_C; the AC source currents i_A, i_B, and i_C; the load currents i_{LA}, i_{LB}, and i_{LC}; first compensator currents i_{S1A}, i_{S1B}, and i_{S1C}; second compensator currents i_{S2A}, i_{S2B}, and i_{S2C}. Figure 12 shows the treatment of a load unbalance resulted from the disconnection of one phase of a balanced three-phase rated load at 0.8 lagging power factor.

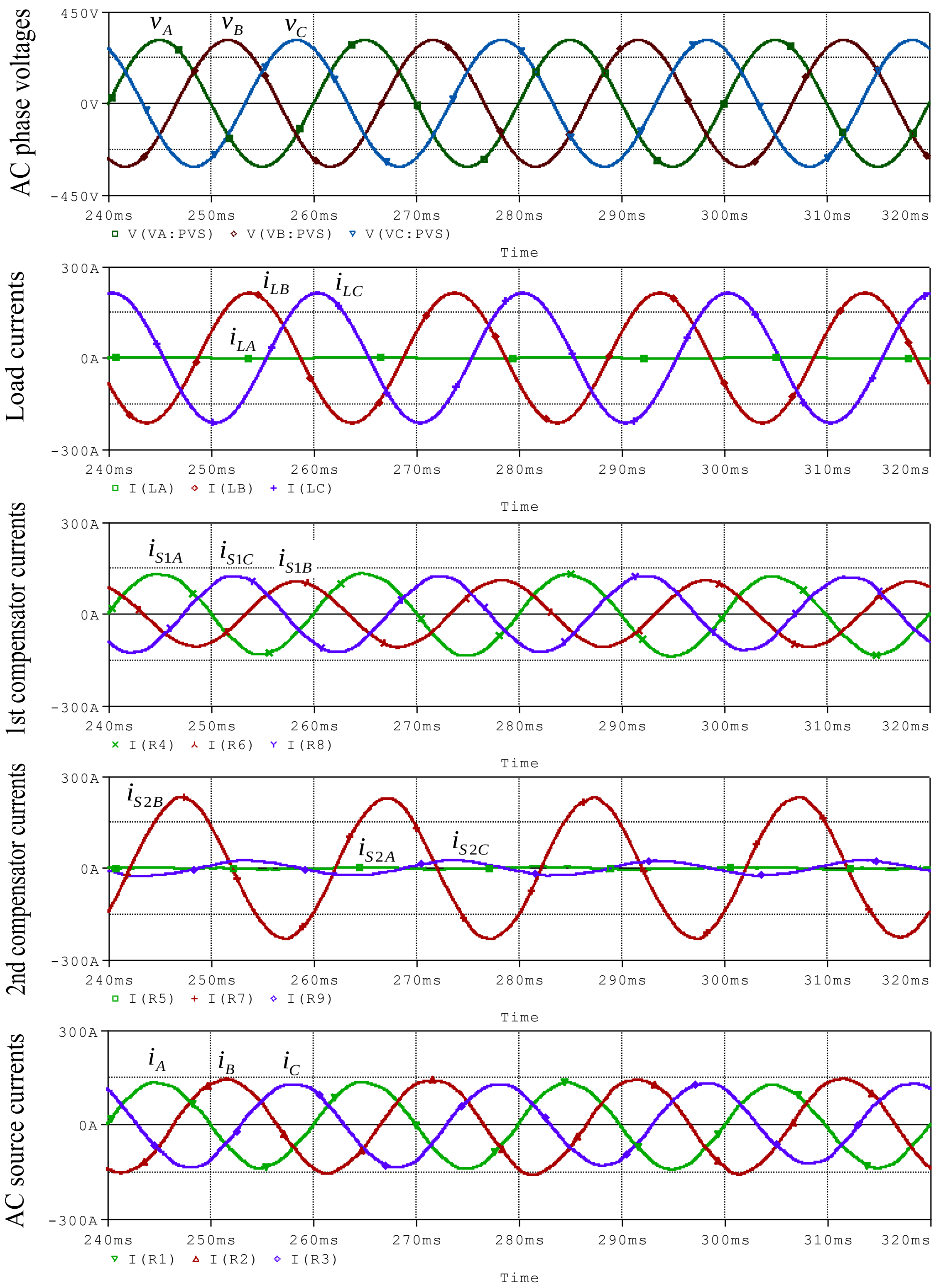


Figure 12. Load balancing system treatment to a load unbalance resulted from the disconnection of one phase of a balanced three-phase rated load at 0.8 lagging power factor

The treatment of the above unbalance condition had resulted in balanced real currents drawn from the AC source (power transformer). Figure 13 shows the treatment of a load unbalance in which one of the phase currents of an unbalanced three-phase load was exceeding the power transformer rated current. The treatment of this load unbalance had resulted in driving the phase currents of the power transformer below their rating values as balanced real currents associated with significant reductions in their magnitudes.

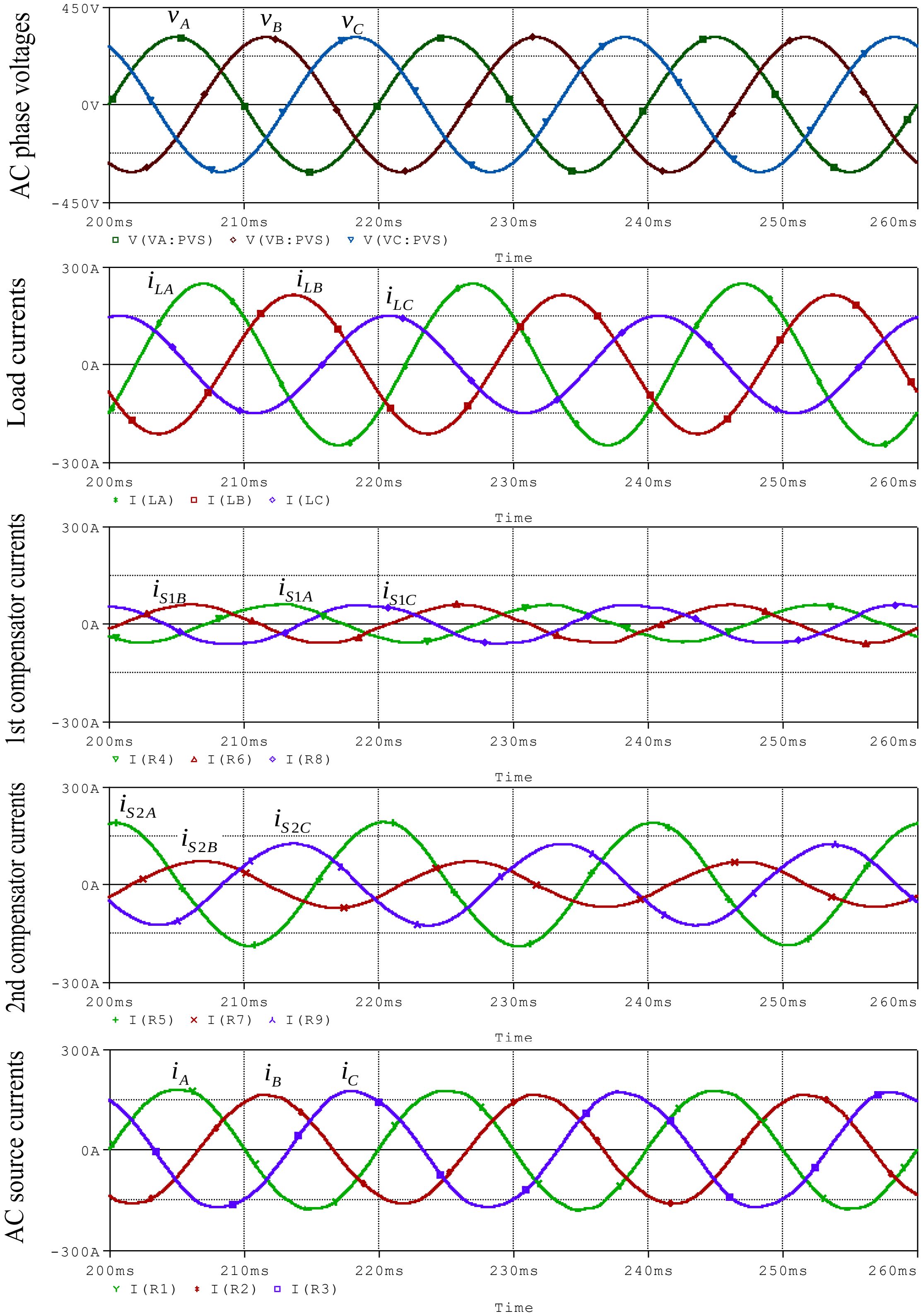


Figure 13. Load balancing system treatment to a load unbalance in which one phase current was exceeding the power transformer rating

Figure 14 shows the treatment a load unbalance in which all the phase currents of an unbalanced three-phase load were exceeding the power transformer current rating. The treatment had driven all the phase currents drawn from the power transformer below their rated values as balanced real currents. This load unbalance was due a somewhat significant phase unbalance.

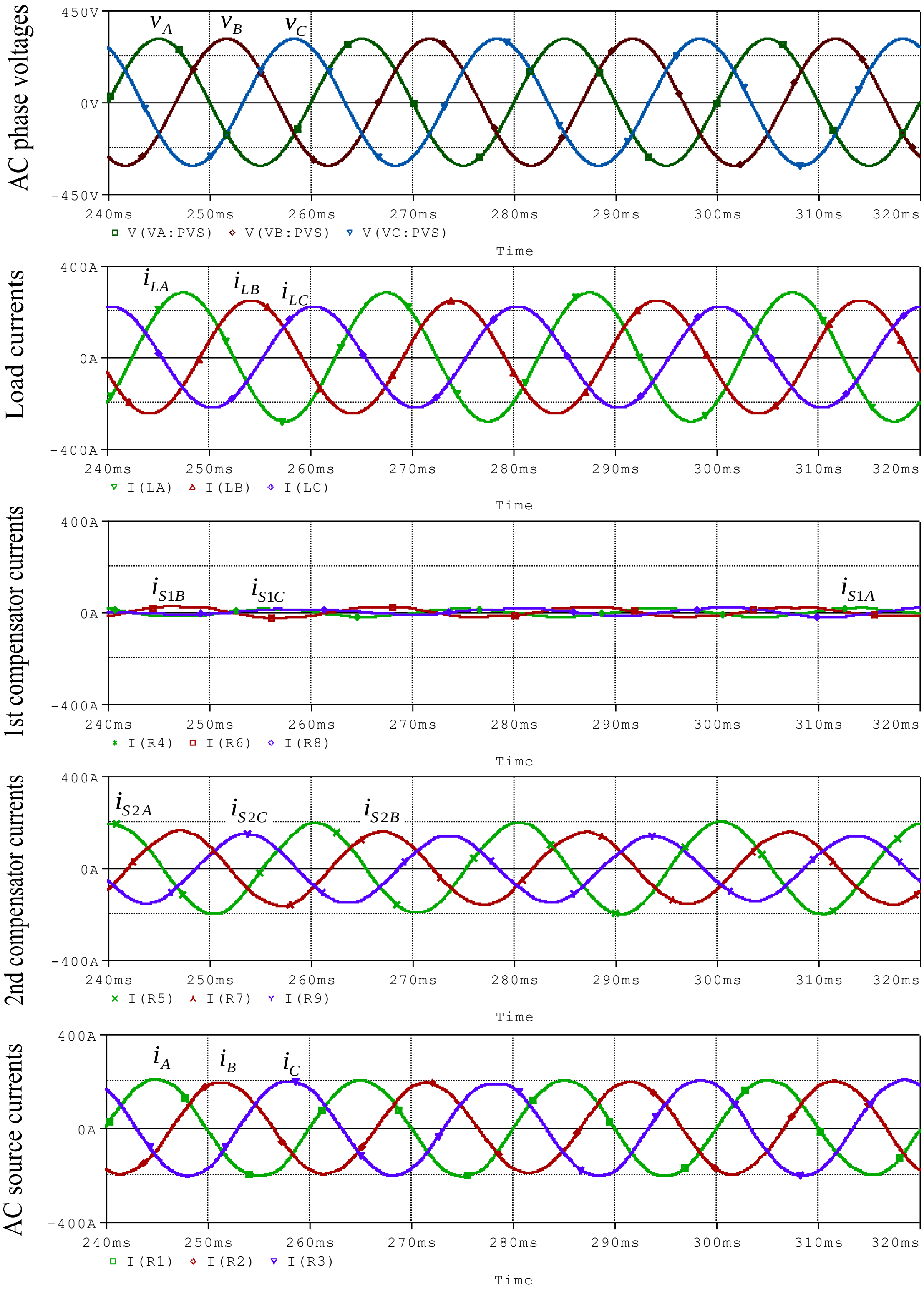


Figure 14. Load balancing system treatment to a load unbalance in which all the phase currents were exceeding the power transformer rating

4. CONCLUSION

In this work, a load balancing system is designed to balance the phase currents of a three-phase, 380 V, 50 Hz, 100 kVA power transformer in 4-wire distribution network using six identical linearized H-bridge STATCOMs. These STATCOMs are exploited as continuously and linearly controlled compensating susceptances in both capacitive and inductive modes. They are controlled in such a manner that they never lose synchronization with grid. The performance results of the 220 V and 380 V M-STATCOMs have revealed the potency of their linearities and control continuities. Each M-STATCOM approximately sticks to steady-state reactive current demand within a period of less 5 cycle of the power system network fundamental. In addition, it satisfies the reactive current demand despite the AC voltage status (below or above its rated value). The steady-state portion of the STATCOM reactive current exhibits pure sinusoidal envelope, which certifies the the absence of harmonic's association. The proposed load balancing system had reflected high flexibility during managing different load unbalances. It can involve any load unbalance within or below the power transformer current rating which was designed for compensating its phase currents. In addition, the system showed efficient performance during treating unbalance cases beyond the power transformer current rating. It showed excellent performance in comparison with other four-wire load compensation systems.

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