Balancing of Unbalanced Load and Power Factor Correction in Multi-phase (4-phase) Load Circuits using DSTATCOM

Zakir Husain, Ravinder Kumar Singh and Shri Niwas Tiwari

Abstract— **Multi-phase loads (phases more than three) have gained growing attention in the recent past. Such loads especially in the form of inverter fed induction motor drives are suited to high power and specialized applications. The multi-phase source for such drive applications may be derived from a transformer connection (3-phase to 4-phase) or by a DC link 4-phase inverter. However, these sources may face the problems of unbalance, harmonic distortion and poor power factor operation. In view of these shortcomings, this paper deals with the supply side load balancing and power factor correction in such multi-phase load circuits. As an illustration a four-phase load is assumed. The proposed compensation scheme uses the shunt current source compensation whose instantaneous values are determined by the instantaneous symmetrical component theory. An ideal compensator in place of physical realization of the compensator has been proposed in the form of a current controlled voltage source inverter. The compensation scheme developed in the paper is tested for its validity on 4-phase (4-wire & 5-wire) circuits through extensive simulations for unbalanced loading and phase outages. The simulation results for the compensation theory and the ideal compensator verify the proposed compensation method.**

Index Terms— **Load balancing, Power factor correction, Compensator, DSTATCOM, Multi-phase**

I. INTRODUCTION

Multi-phase machine drives are gaining growing attention [1-8] in recent years due to their several inherent benefits. Such benefits include reduced torque pulsation, harmonic content, current per phase (without increasing the voltage per phase), higher reliability and increased power in the same frame as compared to their three phase counterpart. Multi-phase inverters fed induction motor drives have been found to be quite promising for high power ratings and other specialized applications. The use of such drives and devices present multi-phase load circuits that may get phase outages, unbalanced as well as non-linear loadings similar to their three-phase counter parts. Such conditions may lead to a variety of undesirable effects on the supply system such as additional losses in connecting lines and interfacing devices, oscillatory torques in ac machines, increased ripple in rectifiers, malfunctioning in sensitive equipments, harmonic and excessive neutral currents etc. It is therefore desired to have the balanced power system operation with minimum lower order harmonics even in the presence of such operations.

Current literature survey reveals that a number of methods have been evolved for the compensation of harmonics and unbalances [9-24] for the conventional three phase systems. The majority of the methods are based on the instantaneous reactive power theory [9-14], theory of symmetrical components [12-15], and reference frame theory [20-22]. Utilizing these theoretical concepts, techniques have been developed for balancing three phase load [12-13] and power factor correction [13-14], voltage regulation [10-15] and meeting other objectives.

This paper presents a novel scheme based on instantaneous symmetrical components for balancing the unbalanced multi-phase (4-phase) load and power factor correction on supply side using an ideal switch based compensator. The proposed compensation scheme is verified by extensive simulation studies. The simulated results establish the validity of the proposed scheme.

II. MULTIPHASE COMPANSATION SYSTEM

A. Compensation Principle

The basic compensation scheme for multi-phase (4-phase) load supply from a balanced stiff multi-phase source is shown in Fig. 1 below.

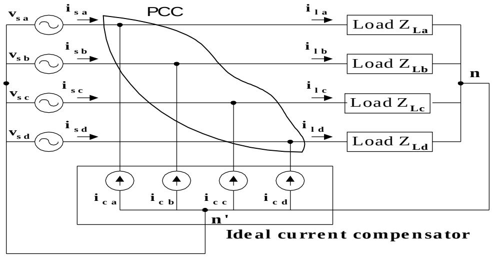

Fig.1 Compensation scheme for 4-phase star connected load.

In this scheme, the compensator represented by current sources is connected in parallel with the loads at node called common point of coupling (PCC). It is designed to supply the reactive power, where as active power is supplied from the source. The single phase impedance loads connected in star formation can represent a general 4-phase load or multiphase load. The goal of the scheme is to extract the compensator currents from the measured circuit variables, which make the unbalanced loads on the source side balanced. The proposed scheme can be applied to a 4-phase, 4-wire system or a 4-phase, 5-wire system by isolating or connecting the

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Zakir Husain is with the Department of Electrical Engineering, National Institute of Technology (H.P), India (phone: + 91 9816056570; fax: +911972-223834; e-mail: zahusain2@ yahoo.com).

Ravindra Kumar is with Department of Electrical Engineering, MNNIT, Allahabad, India (e-mail: rksingh@mnnit.ac.in).

Shri Niwas Tiwari is with the SPMIT Bhiti Mogaon, Allahabad, India (e-mail: sntiwari1@radiffmail.com).

common points N and n respectively, as shown Fig.1. The instantaneous compensator currents are formulated on the basis of instantaneous symmetrical component analysis of the load current.

B. Instantaneous Symmetrical Component Theory

Let the unbalanced four phase instantaneous load currents be denoted *by* i_a, i_b, i_c, i_d whereas the corresponding sets of four balanced symmetrical components are represented by i_{a0}, i_{a1}, i_{a2}, i_{a3}. The power invariant instantaneous symmetrical components of these components are given by

$$\begin{bmatrix} i_{a0} \\ i_{a1} \\ i_{a2} \\ i_{a3} \end{bmatrix} = \frac{1}{\sqrt{4}} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & m & m^2 & m^3 \\ 1 & m^2 & 1 & m^2 \\ 1 & m^3 & m^2 & m \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \end{bmatrix} \qquad (1)$$

where, $m = \exp\,(j\pi/2)$

All the four components are graphically represented in Fig. 2.

(a) Zero sequence system (b) First-(positive)sequence system

(c) Second sequence system (d) Third (negative) sequence components systems

Fig. 2 Symmetrical Components of Four-Phase System

- The zero sequence system (zero phase differences);
- First-(positive) sequence system (four phasors are displaced 90 deg. relative to each other).
- The second-sequence system (two phasors are displaced 180 deg. relative to each other, each representing two phases, constituting two 2-phase zero sequences in opposition);
- Third (-ve) sequence systems (sequence in the opposite sense of rotation to that of the first-sequence system)

It can be seen that the instantaneous vectors i_{a1} and i_{a3} are complex conjugate and *ia0* is a real quantity, if instantaneous source currents are balanced. The neutral current $i_n = i_a + i_b + i_c + i_d$ will be non-zero if instantaneous current phasors are unbalanced and equal to $4i_{a0}$

C. Derivation of Reference Currents

As known from the symmetrical component theory, a balanced system of current, the zero sequence components will have zero summation value. Accordingly, to provide balanced source currents, the zero sequence components added together must be zero i.e.

$$i_{sa} + i_{sb} + i_{sc} + i_{sd} = 0 \qquad (2)$$

Let Φ be the desired power factor angle between v_{a1} and i_{a1}

$$\angle\{v_{sa} + m v_{sb} + m^2 v_{sc} + m^3 v_{sd}\} = \angle\{i_{sa} + m i_{sb} + m^2 i_{sc} + m^3 i_{sd}\} + \phi \qquad (3)$$

The instantaneous power in a 4-phase 5-wire system is given by $v_{sa}\, i_{sa} + v_{sb}\, i_{sb} + v_{sc}\, i_{sc} + v_{sd}\, i_{sd} = P_{lavg}$ (4)

$$\phi/2 = \angle(A - B)$$

Solving (3), by taking $m = e^{j\pi/2}$ we obtain

$$\phi/2 = \angle(A - B) \qquad (5)$$

where, $A = v_{sa} + j\, v_{sb}$, $B = i_{sa} + j\, i_{sb}$

Taking tangent on both sides of (5), the following relation is obtained

$$\xi = \frac{v_{sb}\, i_{sa} - v_{sa}\, i_{sb}}{v_{sa}\, i_{sa} + v_{sb}\, i_{sb}} \qquad (6)$$

where, $\xi = \tan(\phi/2)$

Simplifying (6), we get

$$i_{sb} = \left(\frac{v_{sb} - v_{sa}\,\xi}{v_{sa} + v_{sb}} \right) i_{sa} \qquad (7)$$

Equation (4), on simplification, gives

$$i_{sa}\, v_{sa} + i_{sb}\, v_{sb} = P_{lavg}/2 \qquad (8)$$

For a balanced operation, all sequence components except positive sequence will be zero. Employing the fact (Fig. 2 b) that $i_{sc} = -i_{sa}$, $i_{sd} = -i_{sb}$, and solving (8) and (7), the source currents are obtained as

$$i_{s\,a,c} = \pm \frac{v_{sa} + v_{sb}\xi}{2\left(v^2{}_{sa} + v^2{}_{sb}\right)} P_{lavg} \qquad i_{s\,b,d} = \pm \frac{v_{sb} - v_{sa}\xi}{2\left(v^2{}_{sa} + v^2{}_{sb}\right)} P_{lavg} \qquad (9)$$

is possible to write (from Fig. 1)

$$i_{c\,p} = i_{l\,p} - i_{s\,p} \, (p = a, b, c, d) \qquad (10)$$

Using (9) in (10), the reference currents for compensator are obtained as

$$\left.\begin{aligned} i_{ca} &= i_{la} - \frac{v_{sa} + v_{sb}\,\xi}{2\,(v_{sa}^2 - v_{sb}^2)} P_{lavg} \\ i_{cb} &= i_{lb} - \frac{v_{sb} - v_{sa}\,\xi}{2\,(v_{sa}^2 + v_{sb}^2)} P_{lavg} \\ i_{cc} &= i_{lc} + \frac{v_{sa} + v_{sb}\,\xi}{2\,(v_{sa}^2 + v_{sb}^2)} P_{lavg} \\ i_{cd} &= i_{ld} + \frac{v_{sb} - v_{sa}\,\xi}{2\,(v_{sa}^2 + v_{sb}^2)} P_{lavg} \end{aligned}\right\} \qquad (11)$$

III. A FOUR PHASE COMPENSATION REALIZATION

Current controlled voltage source inverter may be used practically for realization of the compensator. Using this principle, an ideal switch based compensator is proposed. Let it be called as a 'four-phase DSTATCOM' as its circuit topology is an extension of a conventional three-phase DSTATCOM.

A. Topology of four-phase compensator

The topology of the proposed four-phase DSTATCOM has been derived from its three-phase counterpart where an inverter circuit is employed with a self-charged capacitor as DC source and unbalanced load circuit connected at PCC as load to the inverter. The proposed four-phase compensator consists of four arms of a single-phase H-bridge inverter circuits as shown in Fig. 3 with split capacitor for providing the neutral point **n′** of the compensator. A single capacitor instead of two capacitors can be used if neutral point of the converter is not required as in four-phase four-wire system. In case of two-capacitor topology, it has been reported in literature that capacitor voltages becomes unbalanced and therefore may lead to unstable operation in a three-phase circuit. To avoid the unbalanced operation of capacitors, a chopper can be used to balance the capacitor voltage. The chopper is controlled in such a way that capacitor voltages are dynamically regulated to have equal average voltage.

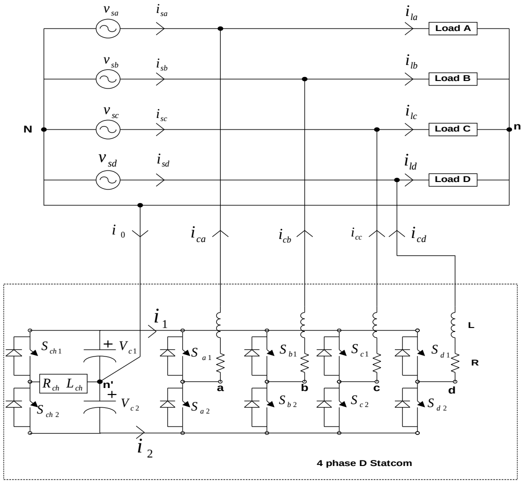

Fig. 3 Four-phase 5-wire distribution system with DSTATCOM

B. Analysis of four-phase DSTACOM

To illustrate the working of the converter, phase -a of the 4-phase compensator shown in Fig. 3 has been analyzed. The equivalent circuit of phase "a" with switch S_{a1} closed is shown in Fig. 4. The current through the switch S_{a1} is the series current i_{ca}, which can be determined by applying KVL in the circuit.

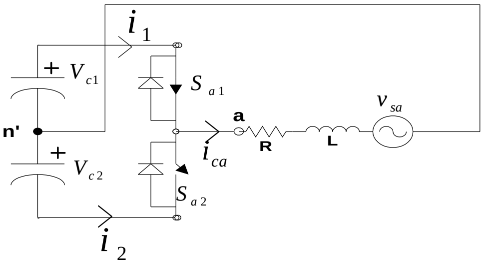

Fig. 4 Equivalent Circuit for phase "a" operation of the converter with switch S_{a1} is closed.

The resulting equation is given by

$$\frac{di_{ca}}{dt} = -\frac{R}{L} i_{cb} + S_a V_{c1} - \overline{S}_a \frac{V_{c2}}{L} - \frac{v_{sa}}{L} \tag{12}$$

where S_a is switching function define by (12) and $\overline{S}_a$ complement of the switching function of S_a..

$$S_a = \begin{cases} 1 & if \quad switch \quad is \quad on \\ 0 & \quad otherwise \end{cases} \tag{13}$$

The sources are assumed to be ideal and the impedance blocks shown in Fig. 1 express loads for each phase. For the physical realization of the converter circuit, the loss occurring in all elements of the compensator and connecting inductor or transformer must be compensated by exchange of real power from source to DC side capacitor of the DSTATCOM. Therefore the reference currents expressed in (11) are replaced by additional loss term (P_{loss}) in the power. The modified version for compensator current for phase-a is given by

$$i_{ca} = i_{la} - \frac{v_{sa} + \beta v_{sb}}{|\Delta|} (p_{lavg} / 2 + p_{loss}) \tag{14}$$

C. Mathematical Modelling and Simulation for 4-phase DSTACOM

The state space equations has been written in terms of the switching functions ($S_a, S_b \cdots$) of the converter and (S_u & S_l) of chopper of the DSTATCOM

$$\begin{aligned}
\frac{di_{ca}}{dt} &= -\frac{R}{L} i_{ca} + S_a V_{c1} - \overline{S}_a \frac{V_{c2}}{L} - \frac{v_{sa}}{L} \\
\frac{di_{cb}}{dt} &= -\frac{R}{L} i_{cb} + S_b \frac{V_{c1}}{L} - \overline{S_b} \frac{V_{c2}}{L} - \frac{v_{sb}}{L} \\
\frac{di_{cc}}{dt} &= -\frac{R}{L} i_{cc} + S_c \frac{V_{c1}}{L} - \overline{S_c} \frac{V_{c2}}{L} - \frac{v_{sc}}{L} \\
\frac{di_{cd}}{dt} &= -\frac{R}{L} i_{cd} + S_d \frac{V_{c1}}{L} - \overline{S_d} \frac{V_{c2}}{L} - \frac{v_{sd}}{L}
\end{aligned} \tag{15}$$

The chopper dynamics has been realized by writing the state space equations for the circuit shown in Fig. 3. Let i_1 and i_2 be the currents in circuit of the chopper (Fig. 3) then (16) and (17) represent the relation of these in terms of switching function and the converter currents.

$$i_1 = S_a * i_{ca} + S_b * i_{cb} + S_c * i_{cc} + S_d * i_{cd}$$

(16)

$$i_2 = \overline{S_a} * i_{ca} + \overline{S_b} * i_{cb} + \overline{S_c} * i_{cc} + \overline{S_d} * i_{cd} \tag{17}$$

The final expressions (18) - (20) can be obtained by applying the principle of KCL and KVL

$$\frac{dV_{c1}}{dt} = -S_a * \frac{i_{ca}}{C} - S_b * \frac{i_{cb}}{C} - S_c * \frac{i_{cc}}{C} - S_d * \frac{i_{cd}}{C} - S_u * \frac{i_{ch}}{C} \tag{18}$$

$$\frac{dV_{c2}}{dt} = \overline{Sa} * \frac{i_{ca}}{C} + \overline{S_b} * \frac{i_{cb}}{C} + \overline{S_c} * \frac{i_{cc}}{C} + \overline{S_d} * \frac{i_{cd}}{C} + S_l * \frac{i_{ch}}{C} \tag{19}$$

$$\frac{di_{ch}}{dt} = \frac{R_{ch}}{L_{ch}} + S_u \frac{V_{c1}}{L_{ch}} - S_l \frac{V_{c2}}{L_{ch}} \tag{20}$$

The variables used in the expressions (18)-(20) are indicated in the circuit diagrams. The capacitor voltages decrease if not compensated for the losses in the connecting transformer/ inductor, which can be accounted by changing the duty cycle of the chopper. The change in duty of the chopper is based on the change in the capacitor voltage from the set reference voltage. The difference in the capacitor voltage and set voltage (i.e. the error voltage) is put forward to a proportional - integral (PI) controller. The PI controller estimates the P_{loss} component as stated in (14) and determines the duty cycle of the chopper to maintain the capacitor voltage at a pre specified set reference voltage. The set values are taken approximately 1.3 times the peak AC voltage of the source voltage for compensator to work satisfactorily

IV. SIMULATION STUDIES

The proposed compensation scheme for 4-phase system is verified by simulation. In this section, the simulation results are presented and discussed

A. *Study of Simulation*

The voltages $v_{si}(i=a,b,c,d)$ and impedances $Z_i(i=a,b,c,d)$ are given below in (21) and (22) respectively.

$$v_{si} = 325.26\sin(100\pi\, t - i*\pi/2) \tag{21}$$

where, i = 0, 1, 2, 4 corresponding to phase a, b, c, d respectively.

$$Z_a = 15 + j10, \qquad Z_b = 10 + j5, \qquad Z_c = 10 + j20,$$
$$Z_d = 15 + j10 \tag{22}$$

The isolation transformer parameters are taken as follows: R= 1Ω and L= 200 mH.

The control parameters for regulating the capacitor voltage of the chopper are adjusted heuristically and are given as $K_p = 1$ and $K_i = 0.01$

The inverter current and capacitor have voltage hysteresis band of 100 mA and 40 V respectively. It is desired to get unity power factor operation for source. The system is run, with unbalanced load for one cycle (0.02 sec) which follows turning ***on*** of the DSTATCOM. The system is run with unbalanced load for one cycle (0.02 sec) and run for another five cycles (0.10 sec) with the proposed compensator. It can be seen from Fig. 5(b) and Fig. 5(c) that the source currents i_{sp} (p = a, b, c, d) and load currents i_{lp} (p = a, b, c, d) are equal and unbalanced when compensator is ***off***. At the time 0.02 sec., the compensator is turned ***on*** the source currents become perfectly balanced as shown in Fig. 4(c). In order to compensate unbalanced load currents, the instantaneous compensator currents i_{cp} (p = a, b, c, d) become unbalanced accordingly as shown in Fig. 5 (d).

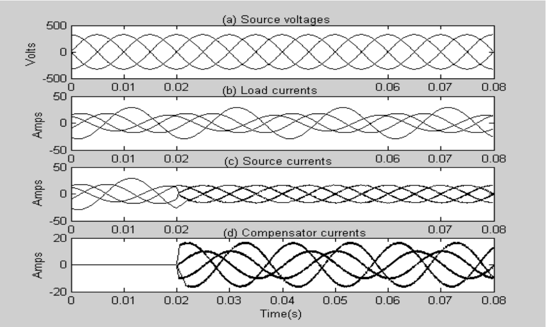

Fig. 5 Variation of source voltages and load, source and compensator Currents of 4-phase 5-wire supply system

The three instantaneous powers namely source; load and compensator powers are shown in Fig. 6 (a) & (c), while two neutral currents (source & load neutral currents) are plotted in Fig. 6 (b). It can be seen that before compensation, that is, when compensator is switched ***off,*** source power and load power have the same magnitude and are of oscillating nature as shown in Fig. 6 (a). This is due to unbalance in load currents. But after compensation (when compensator is turned ***on)*** the source power attains a steady state value as can be seen from Fig. 6 (a), while load power is oscillating Fig. 6 (a). Moreover, the source neutral current attains zero value when the compensator is turned ***on*** and can be seen from Fig. 6(b) as it balances the source currents. This also implies that the sum of the instantaneous compensator currents is equal to load neutral current

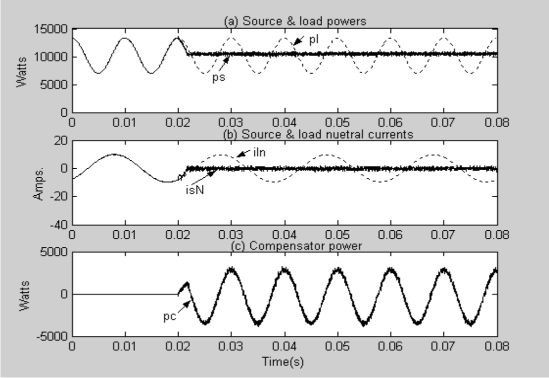

Fig. 6 Variation of powers and neutral currents for 4-phase 5-wire supply system

Co-phasors variation of voltage and current show unity power factor operation with compensator as evident from Fig. 7 (a)-(d)

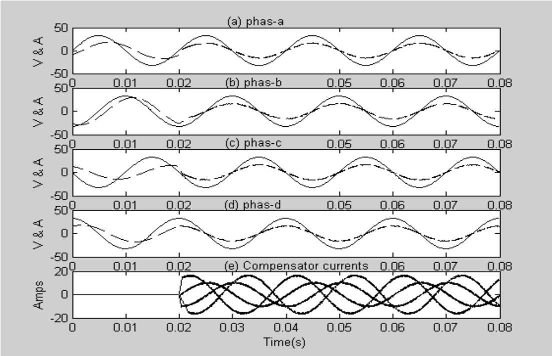

Fig. 7 (a)-(d) (1:10) scaled source voltages (solid line), source currents (dashed line) (e) variation of compensator currents portraying unity power factor operation for a 4-phase 5-wire supply system

It is to be noted that the capacitor voltage remains constant as can be seen from Fig. 8. Please note that the capacitor voltage is assumed to be initially charged or pre-charged

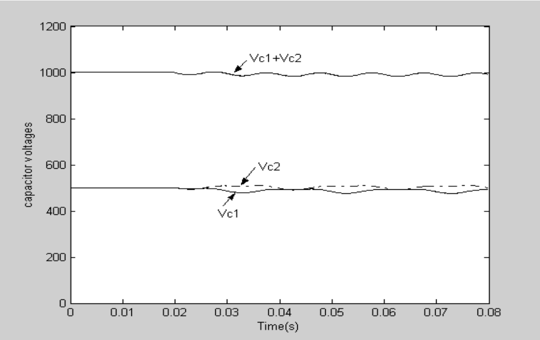

Fig .8 Capacitor voltage variation

B. *Load Compensation for phase outages*

As stated earlier that advantage of multiphase loads (such as motor) is in its capability to operate with phase outages. The motor operates with degraded performance and source sees an unbalanced operation and therefore other loads connected to such a source get affected. The proposed compensator has also been tested with various combination of phase outages and it has been found that it works satisfactorily even with two phases open (with phase outages a, b) in a four-phase source.

The results are shown in Fig. 9 to Fig. 11. It can be seen from Fig. 9 & 10 that source currents and source power are balanced whereas the source neutral current goes to zero with compensator ***on*** as it balance source neutral currents which implies that sum of the instantaneous compensator currents is equal to load neutral current in case of phase outages too.

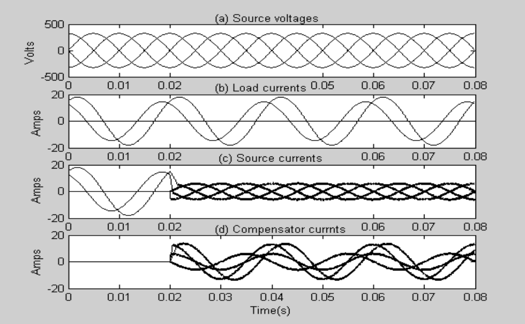

Fig. 9 Variation of source voltage & various currents for the phase outage (a, b) of the load for a 5-wire supply system

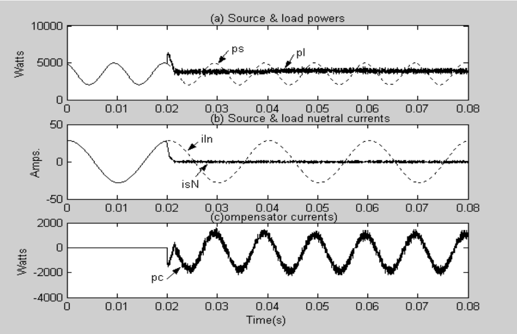

Fig. 10 Variation of power and neutral current for phase outage (a, b) of load for a 5-wire supply system

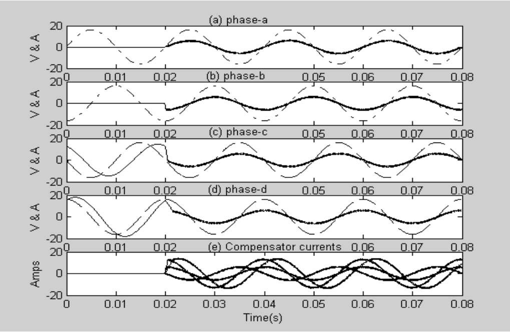

Fig. 11 (a)-(d) (1:20) scaled source voltages (dash line), source currents (solid line) & (e) variation of compensator currents portraying unity power factor operation for phase outage (a, b) of the load for a 4-phase 5-wire supply system

Fig. 12 shows that the capacitor voltages remain constant

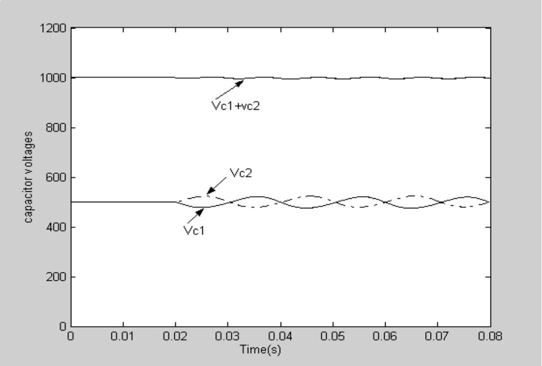

Fig. 12 show capacitor voltage variation for phase outages (a, b) of load

V. CONCLUSION

In this paper, the problem of load balancing and power factor correction at the source side for multi-phase load circuits in the event of linear unbalance loading and phase outages is addressed. For the purpose, a multi-phase compensator (4-phase) has been realized as a multi-phase DSTATCOM extending the approach developed for three phase system in the literature. The dynamic behaviour of the compensator is also simulated during the load compensation process. An elaborate study has also been made on source voltages, load currents, source currents, and compensator currents during non-compensating and compensating period. The capacitor voltage variations and the variation of the load and source powers are also analyzed. The variation of the compensator power at the time of its rise has been explained. The analysis has confirmed unity power factor operation of the source in all cases as evidenced by the voltage and current waveforms.

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