Article published in January 2014 issue of IEEMA Journal

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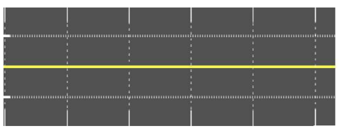

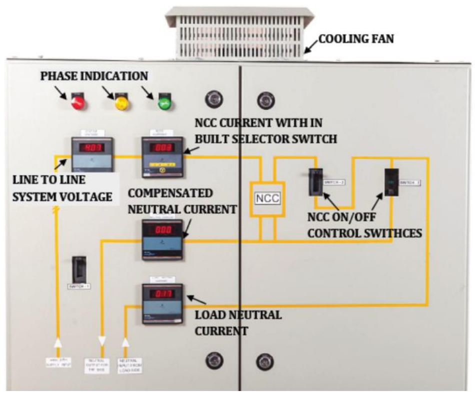

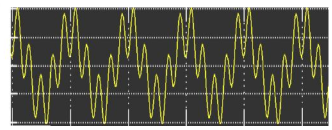

Neutral Current

NCC

Neutral Current

3Φ UPS

3*1Φ Rectifier / Server

IMPROVED OPERATIONAL SYSTEM RELIABILITY

Three Phase UPS and 3*Single Phase Rectifier / Server Loads: Protection and Operational Reliability Improvement Using Line / Neutral Inductances and Neutral Current Compensator

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1.0 Introduction

The use of computers and servers has become an integral part of professional environment and has substantially grown in the past two decades. Every industry and IT / Software parks today use computers and servers (which are sensitive non-linear loads) and look for highest operational reliability or maximum availability of the power supplies which is generally made available from single or three phase Uninterrupted Power Supply (UPS). Most of these loads use a three phase UPS and thereafter an MCCB for its power distribution. The load distribution is single phase (phase and neutral or line and neutral) and the loads are, hence, supplied by different phases.

The server and computer loads use rectifiers or SMPS for supplying the low voltage dc power to its control electronics or electronic cards. If the same neutral gets connected to different SMPS based converters, different switching potentials are imposed on the same neutral at same time(s) and this causes unbalanced and uncontrolled operation of the SMPS based converters resulting in the converters getting switched off. This is an undesirable effect as the power supply is still available but the loads are switched off due to unwarranted switching voltages appearing on the neutral.

On the other hand, when three phase connection is distributed to single phase loads, the neutral many times carries high unbalanced / zero sequence current (consisting of unbalanced components of fundamental, 3^{rd} or triplen harmonics, and also other harmonics) generated by single phase unbalanced loads. This high neutral current results in tripping of the MCCB. This causes tripping of the loads, which is not desired. Further, this high neutral current enters the UPS increasing second harmonic current in its dc bus. This results in higher ripple current (second harmonic current) to be absorbed by the dc bus capacitance and reduces life of the dc bus capacitance and hence that of the UPS.

Both the above discussed problems can be overcome and the operational reliability of the sensitive loads supplied by an UPS can be substantially improved by use of proper / appropriate neutral inductances and a Neutral Current Compensator (NCC).

2.0 Insertion of Neutral Inductances

2.1 For UPS supplying power to normal diode rectifiers

Figure 2.1 shows the load distribution of single phase rectifier loads supplied by different phases using a three phase UPS. The same neutral is distributed to all loads along with phase “a” or phase “b” or phase “c”. The blocks shown by Load A or Load B or Load C may consist of a single or multiple rectifiers. To reduce the commutation effect of rectifier diodes / proper functioning of the rectifiers, it is necessary to introduce proper commutation inductances in each phase. However, since these are single phase rectifiers, both the neutral and phase need commutation inductances. If it is a three phase rectifier, the three phases will have commutation inductances and the neutral will not have any commutation inductance inserted in it as it is not connected to the rectifier stack.

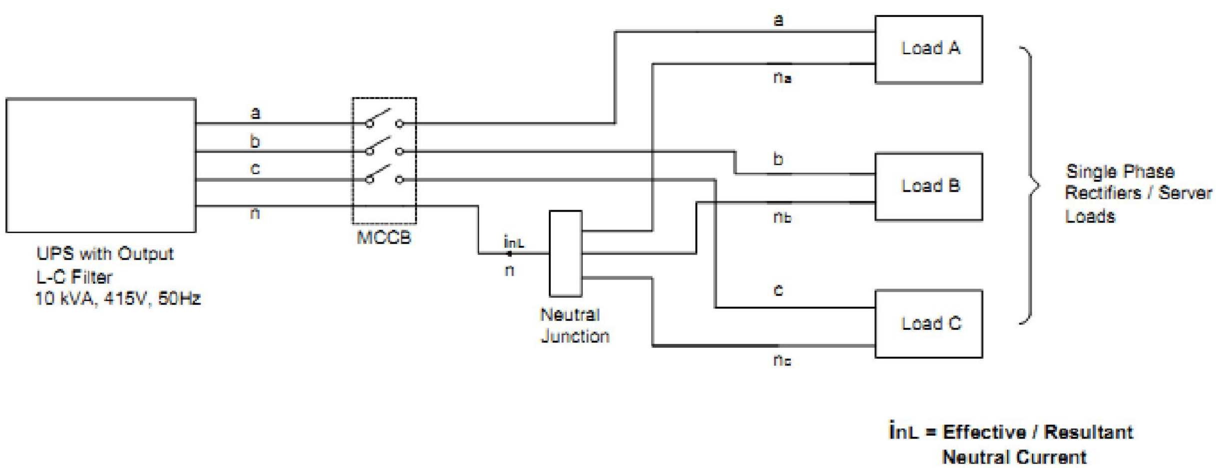


Fig. 2.1: Single phase load distribution with three phase UPS
(Without 3.5% commutation inductances)

The commutation inductance is normally based on the rectifier capacity and its value is calculated based on 3.5% voltage drop across it at full load. This is the normal design practice accepted over many decades for diode / thyristor rectifiers and does not need any further elaboration / experimental verification. Thus, if the single phase rectifier has 10 kVA capacity at 240 V, 50 Hz supply voltage, the commutation inductance will be calculated as below.

Nominal fundamental rms current (I_1) = 10 * 1000 / 240 Eq. (2.1)

This gives I_1 as 41.67 A

$0.035 = 41.67 * \omega * L_c / 240$ Eq. (2.2)

Where ω = 2*π*50 = 314

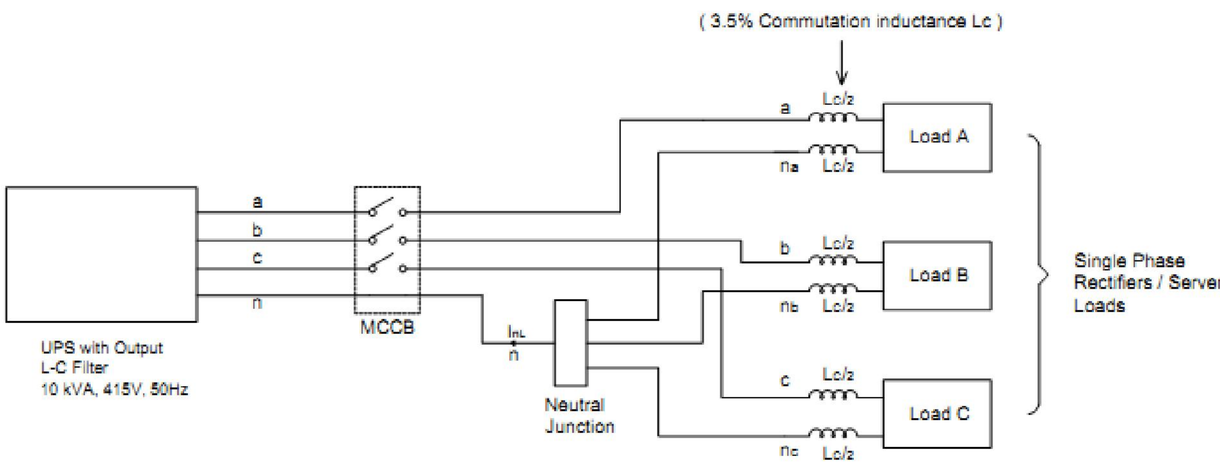
Equation (2.2) yields

L_c = 0.035*240 / (41.67 * 314)

= 0.000642 H

= 642 μH   Eq. (2.3)

Thus, if a UPS is supplying three single phase rectifier loads of 10 kVA each, then each of the single phase rectifiers needs 642 μH inductance to be inserted in it phase. Further, since the neutral is common, the neutral for each rectifier needs an inductance. Further, the L_c can be divided in two equal parts and 321 μH can be connected in each phase and neutral connection entering the single phase rectifier. This is shown in fig. 2.2.



i_{nL} = Effective / Resultant Neutral Current

Fig. 2.2: Single phase load distribution with three phase UPS

(With 3.5% commutation inductances)

For the same above data, a Matlab / Simulink model is prepared and shown in fig. 2.3. The model shows a 10 kVA UPS (with output LC filter) supplying power at 415 V, 50 Hz, to three single phase rectifiers consuming approximately 3.5, 2.9, and 2.5 kW.

Case -1: Without 3.5% commutation inductances

Figure 2.4 gives the load voltages and currents for each of the rectifier (or the phase voltages and currents of the UPS) and also the effective / resultant unbalanced current (i_{nL}) flowing through the MCCB into the UPS. Figure 2.5 gives the phase voltage and current distortion which is approximately 5% and 120% respectively. The current distortion is mainly caused by the presence of large 3rd harmonic. The flattening of the voltage waveforms at positive and negative peaks is based on rectifier load and is visible because the rectifiers have dc capacitances and absence of the commutation inductances.

Case -2: With 3.5% commutation inductances

Figures 2.6 and 2.7 give similar results or waveforms, as discussed above, with the presence of commutation inductances. The flattening of the voltage waveforms at positive and negative peaks is almost absent. Further, the voltage and current distortion observed is approximately 3.25% and 94%. Thus the distortion also decreases.

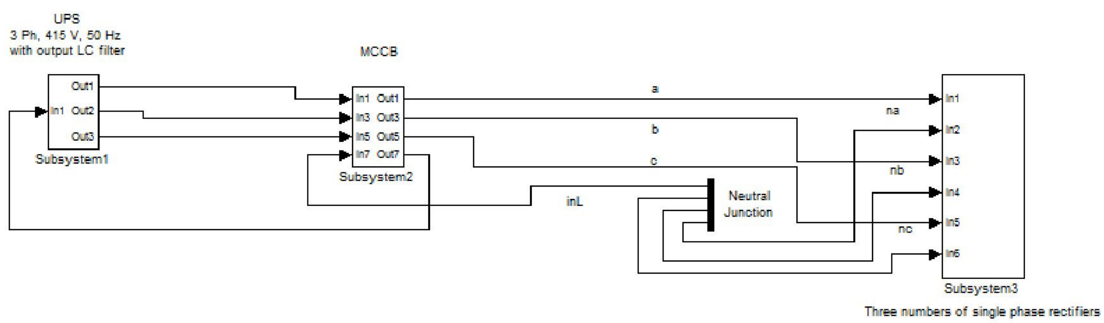


Figure 2.3: Matlab / Simulink model for 10 kVA UPS supplying power to three single phase rectifier unbalanced kW loads

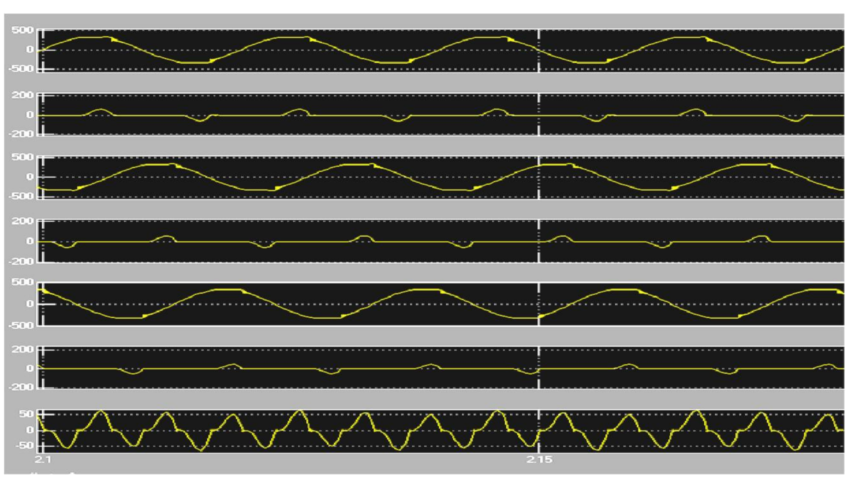


Figure 2.4: Load / UPS voltages and currents along with effective / resultant neutral current (without 3.5% commutation inductances)

Ch1: Phase "a" voltage (load or UPS) Ch2: Phase "a" current (load or UPS) Ch3: Phase "b" voltage (load or UPS)

Ch4: Phase "b" current (load or UPS)   Ch5: Phase "c" voltage (load or UPS)   Ch6: Phase "c" current (load or UPS)

Ch7: Effective / resultant neutral current from load flowing through the MCCB into UPS (i_{nL})

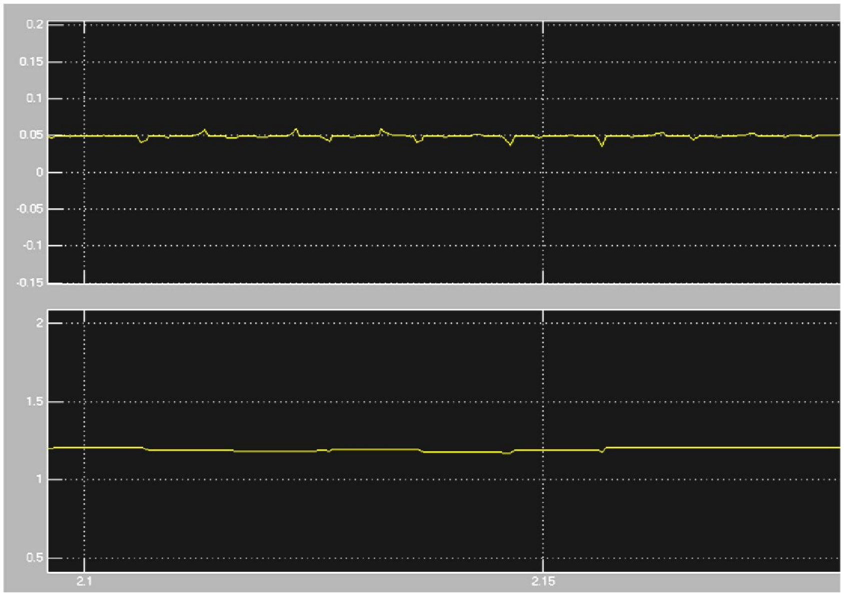


Figure 2.5: Load / UPS voltage and current distortion

Ch1: Phase "a" voltage distortion   Ch2: Phase "a" current distortion

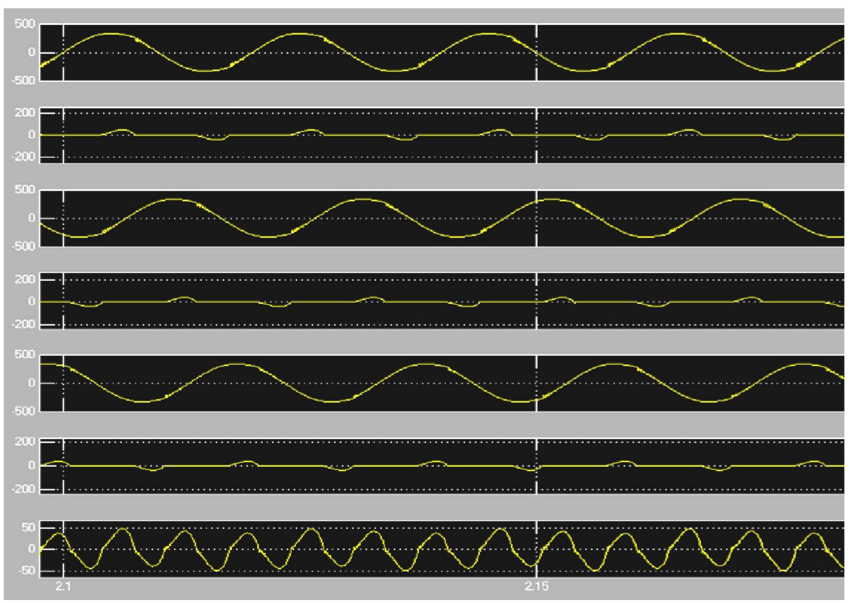


Figure 2.6: Load / UPS voltages and currents along with effective / resultant neutral current (with 3.5% commutation inductances)

Ch1: Phase "a" voltage (load or UPS)   Ch2: Phase "a" current (load or UPS)   Ch3: Phase "b" voltage (load or UPS)

Ch4: Phase “b” current (load or UPS)   Ch5: Phase “c” voltage (load or UPS) Ch6: Phase “c” current (load or UPS)

Ch7: Effective / resultant neutral current from load flowing through the MCCB into UPS (i_{nL})

Figure 2.7: Voltage and current distortion at UPS (with 3.5% commutation inductances)

Ch1: Phase “a” voltage distortion at load or UPS   Ch2: Phase “a” current distortion at load or UPS

2.2 For UPS supplying power to SMPS based rectifiers

If instead of normal diode rectifiers, the loads use Switched Mode Power Supply (SMPS) for the power supply conversion, then the phases do not require any commutation inductances. However, to avoid different switching potentials getting imposed on the same neutral at same time(s) (causing unbalanced and uncontrolled operation of the SMPS based converters resulting in the converters getting switched off), the neutral at each single phase load (using SMPS) needs at least 1% isolation inductance which can be calculated based on equations (2.1) to (2.3). This recommendation is based on long experience of the author in dealing with design and practical implementation of Four Quadrant Voltage Source Converters using Insulated Gate Bi-polar Transistors (IGBTs).

2.3 Net result

It should be noted that the any step down transformer impedance and / or cable inductance does not suffice for proper functioning of the single phase loads (either rectifiers or SMPS based).

The suggested method thus allows the loads (either rectifiers or SMPS based) function properly when supplied by a three phase UPS.

Having understood importance of insertion of inductance in neutral associated with each phase, the other problems of UPS life getting affected by high neutral current and MCCB tripping caused due to high neutral current can now be solved by using a "Neutral Current compensator (NCC)".

3.0 Effect of Neutral Current caused by Three Single Phase Unbalanced Loads

3.1 Life of dc bus capacitors

Many times a three phase UPS is used to supply power to three single phase loads, with or without a transformer.

If there is no transformer used on output side of the UPS, the load neutral is usually connected to the star point of output filter capacitors, which is also connected to the midpoint of the dc bus capacitors. When the three single phase loads produce unbalanced currents, the effective / resultant load neutral current enters the star point of the output filter capacitors and hence to the midpoint of the dc bus capacitors.

If there is a transformer used on output side of the UPS, it can then be Y/Y or Δ/Y connected. The neutral connection is tapped from star point of secondary side Y winding. When the three single phase loads produce unbalanced currents, the effective / resultant load neutral current enters the star point of the Y connected secondary.

Thus, whether the transformer is connected or not connected, the three phase currents at the output of UPS remain unbalanced and produce unbalanced per phase VA / kVA.

A major component of the unbalanced neutral current is the 3rd harmonic produced by the rectifier loads. Figure 3.1 gives a typical current waveform of a practically working server rectifier peaky load current delivered by a 10 kVA UPS, which has approximately 72% of 3rd harmonic presence. As will be seen later, this major harmonic can be almost reduced to zero value (when present as part of effective / resultant three single phase rectifier loads supplied by a single three phase UPS).

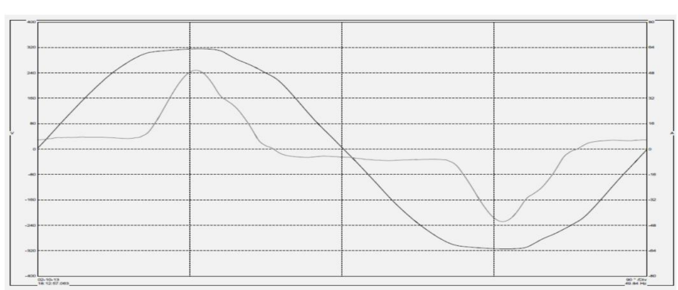


Figure 3.1: Typical output voltage and current waveforms of a 10 kVA UPS supplying power to a single phase server / rectifier load

This unbalanced VA / kVA produces second harmonic (proportional to the unbalanced loading) which has to be absorbed by the dc bus capacitors. The increased value of the unbalanced loading, thus, increase the second harmonic absorption by the dc bus capacitors and reduce / constrain the life of the dc bus capacitors.

Refer fig. 3.2 which explains above situations.

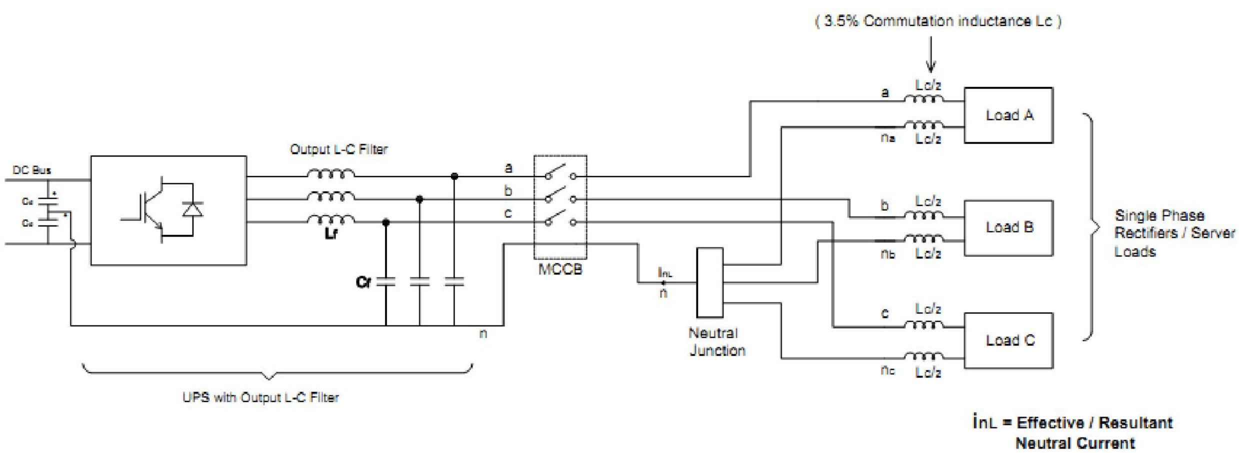


Fig. 3.2 (a): Three phase UPS supplying power to three single phase rectifier loads (Without output transformer)

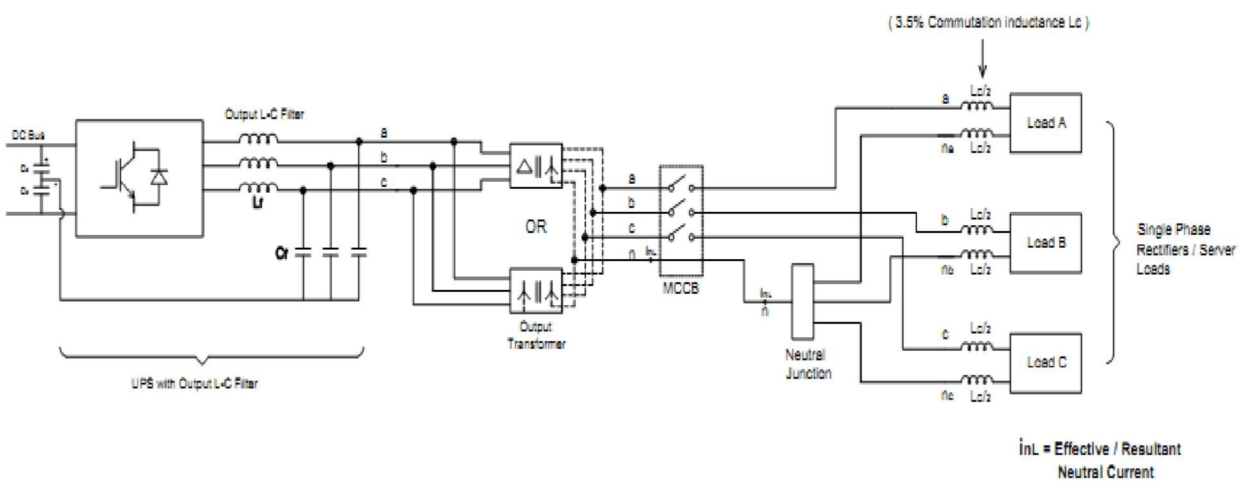


Fig. 3.2 (b): Three phase UPS supplying power to three single phase rectifier loads (With output transformer)

3.2 Unwanted tripping of MCCB

The three single phase loads carry return current in neutral associated with each phase supplying power to the corresponding single phase load. When the three neutrals get connected together to complete the “return path”, they add up to produce the net unbalanced current (effective / resultant neutral current) which is returned to the UPS directly or returned to the star point of Y secondary if there is an output side transformer for the UPS as discussed above.

If the return path conductor carries high unbalanced current, it will naturally get heated up. The return path also passes through the power distribution MCCB and the MCCB can trip on sensing higher unbalanced current. This results in non availability of power at load end, even though UPS power is still available. This situation is unwanted / unwarranted.

Refer fig. 3.2 where the above situation is properly shown.

3.3 Other effects

Refer fig. 3.2. The return path current or the effective / resultant neutral current produced by the three single phase unbalanced loads flows into the UPS directly or returned to the star point of Y secondary if there is an output side transformer for the UPS as discussed above.

This gives rise to what is called as “neutral shifting”. This means the star point potential is no longer maintained close to or equal to zero potential with respect to earth. Thus, it further gives rise to changing or fluctuating phase to neutral voltages which could affect the loads or even shut down certain loads as over / under voltages are sensed by the electronics associated with internal power supplies of the loads (as the loads are basically active or non-linear loads).

4.0 Overcoming the Effect of Neutral Current caused by Three Single Phase Unbalanced Loads

4.1 Solution with Neutral Current Compensator (NCC)

It is clear from the above details that the the return path or the resultant neutral current cannot be avoided in case of three single phase loads. However, it is also necessary to find a solution for avoiding tripping of MCCB caused by this current as well as avoiding this current entering the UPS. This solution is shown in fig. 4.1.

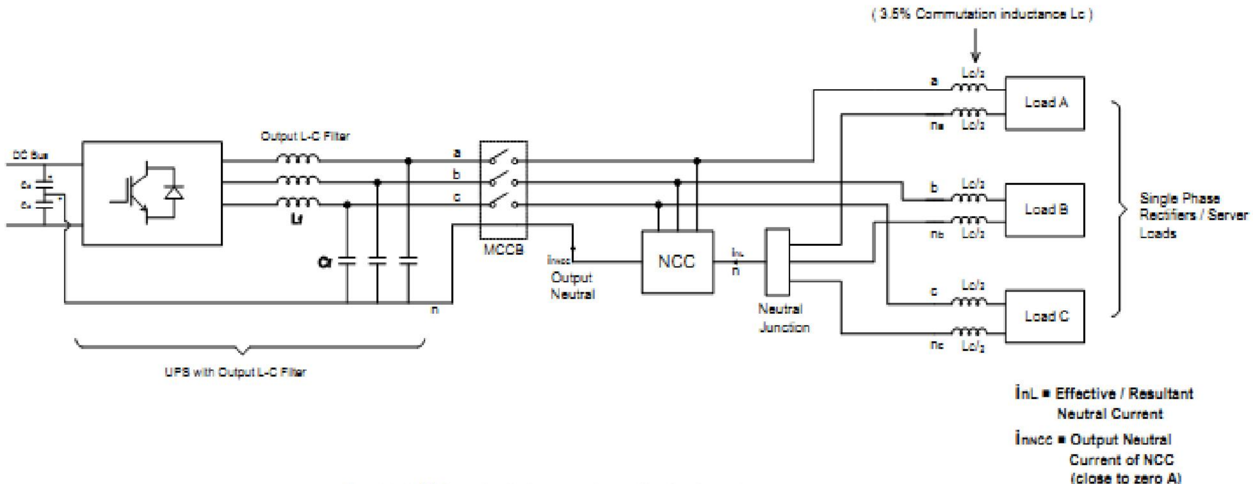


Fig. 4.1: NCC based solution to reduce effective / resultant neutral current to almost zero

The solution is based on use of "Neutral Current Compensator (NCC)" which needs to be connected at appropriate location as given in fig. 4.1.

The details of the NCC are given in Annexure –I.

As shown in fig. 4.1, the neutral current (i_{nNCC}) flowing out of the NCC is almost close to zero Amperes irrespective of whatever may be the return path or the effective / resultant neutral current (i_{nL}). Thus, the effective neutral current flowing through the MCCB as well as flowing into the UPS is maintained close to zero.

For the same data considered earlier, a Matlab / Simulink model is prepared as shown in fig. 4.2. The model shows a 10 kVA UPS (with output LC filter) supplying power at 415 V, 50 Hz, to three single phase rectifiers consuming approximately 3.5, 2.9, and 2.5 kW and uses NCC for making the effective / resultant unbalanced neutral current flowing through the MCCB into the UPS close to zero. The effective / resultant unbalanced neutral current caused by the loads is represented by "i_{nL}" and the neutral current (close to zero) flowing through the MCCB into the UPS is represented by "i_{nNCC}".

4.2 Simulation results

Figure 4.3 gives the load voltages and currents for each of the rectifier and also the effective / resultant unbalanced current (i_{nL}) flowing into the NCC. Figure 4.4 gives the phase voltage and current distortion at the load. This is approximately 3.8% and 93.5% respectively.

Figure 4.5 gives the UPS output voltage for phase "a", its current, voltage distortion, and the current distortion. The voltage distortion is 2.4% and the current distortion is 53%. These figures show considerable reduction in the distortion as compared to the load voltage distortion and load current distortion. This is also visible from the current waveform in this figure as well from the fig. 4.6. Figure 4.6 also gives the output three phase currents of the UPS, effective / resultant unbalanced current (inL) flowing into the NCC, and the neutral current (i_{nNCC}) flowing through the MCCB into the UPS. The current "i_{nNCC}" is close to zero. The UPS output current waveforms show clearly the absence of the 3rd harmonic, which is the largest component of the effective / resultant unbalanced load current (i_{nL}), flowing into the NCC. The NCC also removes unbalance caused by harmonics, other than 3rd or triplens, present in the load currents. Thus the ratings of harmonic filters, if required for the UPS, considerably reduce.

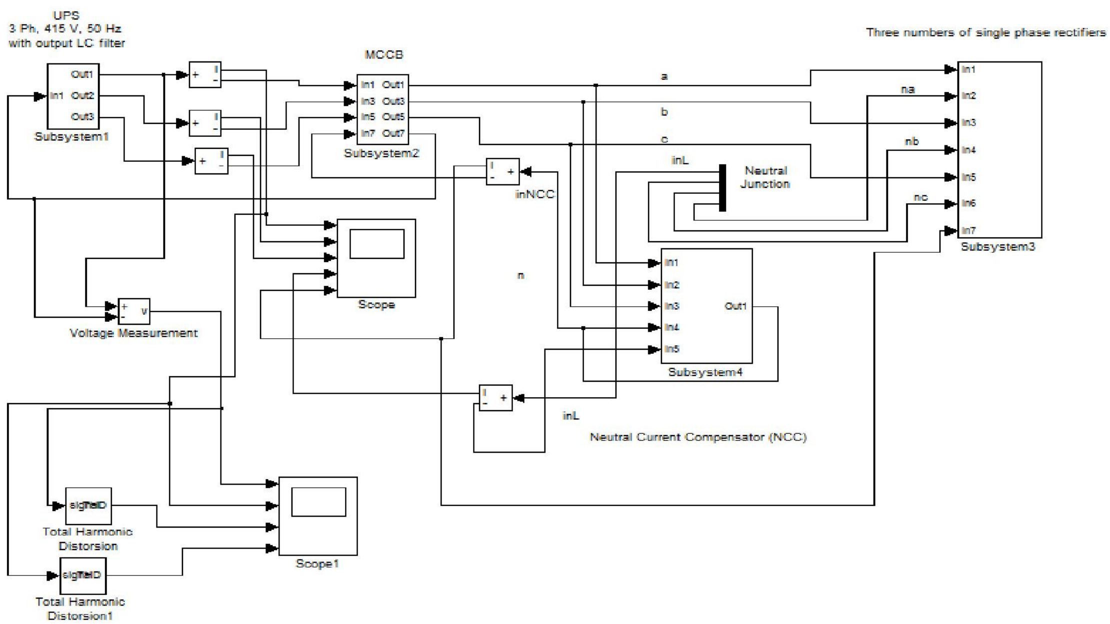


Figure 4.2: Matlab / Simulink model for 10 kVA UPS supplying power to three single phase unbalanced kW rectifier loads

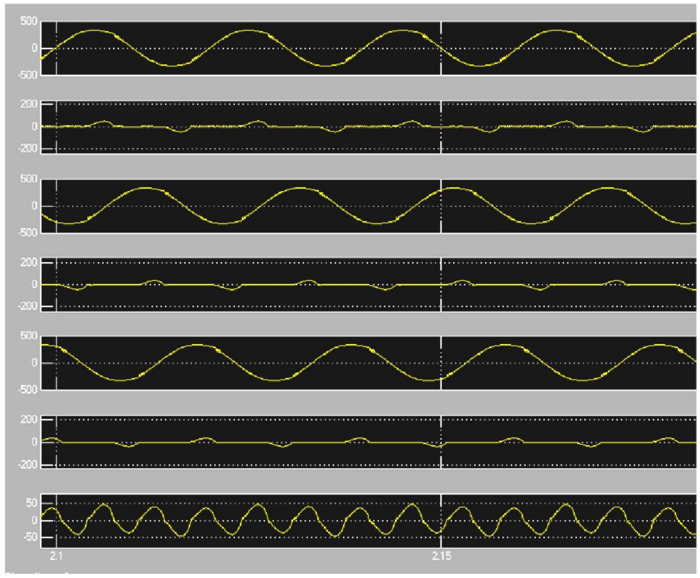


Figure 4.3: Load voltages and currents for each of the rectifier and also the effective / resultant unbalanced current ($_{inL}$) flowing into the NCC

Ch1: Phase "a" voltage (load) Ch2: Phase "a" current (load) Ch3: Phase "b" voltage (load)

Ch4: Phase "b" current (load) Ch5: Phase "c" voltage (load) Ch6: Phase "c" current (load)

Ch7: Effective / resultant unbalanced load neutral current ($_{inL}$) entering the NCC

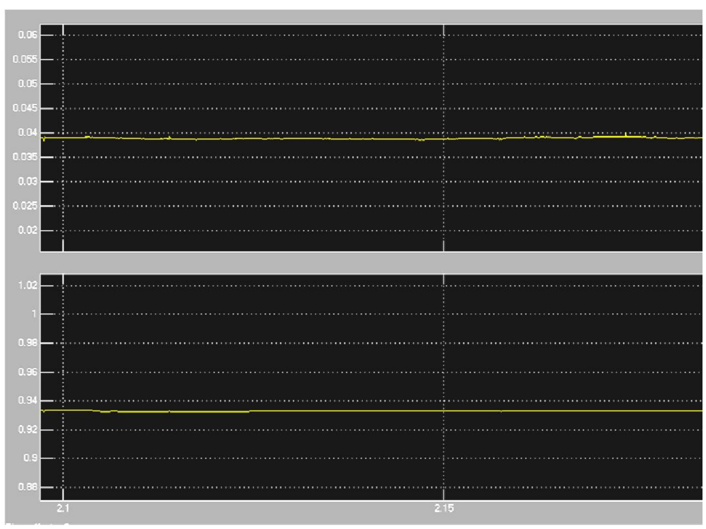


Figure 4.4: Load voltage and current distortion

Ch1: Phase "a" voltage distortion at load Ch2: Phase "a" current distortion at load

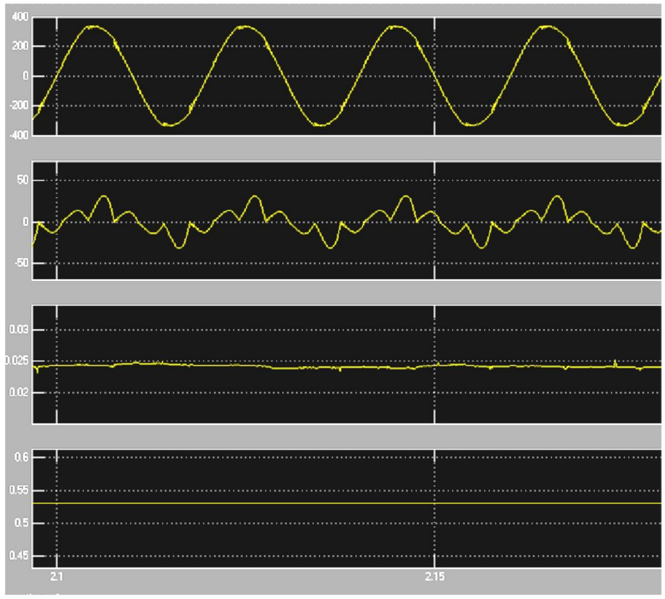


Figure 4.5: UPS phase voltage, current, and their distortions

Ch1: Phase "a" voltage at UPS **Ch2: Phase "a" current of UPS**

Ch3: Phase "a" voltage distortion at UPS **Ch4: Phase "a" current distortion at UPS**

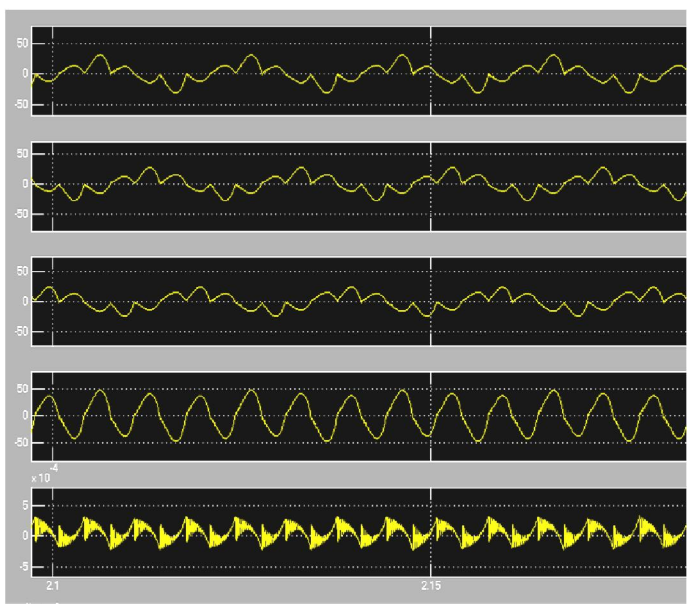


Figure 4.6: UPS currents, effective load current, and UPS neutral current

Ch1, Ch2, Ch3: Phase "a", "b", "c" currents at UPS

Ch4: Effective / resultant unbalanced load neutral current (i_{nL}) entering the NCC

Ch5: Almost zero (10^{-4}) neutral current (i_{nNCC}) from NCC flowing through the MCCB into the UPS

The NCC construction is based on use of transformers and it does not make use of any active devices such as Diode, Thyristor, and IGBT (Insulated Gate Bipolar Transistor). Thus, the NCC once connected is fit and forget kind of a solution. Other advantages of the NCC can be checked from the Annexure –I.

4.3 Rating of NCC

For determining the rating of the NCC, following parameters are needed.

- UPS output voltage and frequency and their expected (±) percentage variation
- UPS VA and VA of the three single phase loads
- RMS value of effective / resultant neutral current i_{nL} (in fig. 3.2 or in fig. 4.1)
- Typical waveform (for 3-8 cycles) of return path or resultant neutral current. This is preferred.
- List of presently faced problems or issues (as discussed here or other than those discussed here)

With the above details known, the NCC rating can be calculated. Usually, this rating will be 1/3 of the UPS VA (or summation of the VA rating of the three single phase loads).

5.0 Conclusion

The article highlights use of proper line and neutral inductances for separately used three single phase rectifier loads providing power to server and computer loads.

It also brings out the problems arising from unbalanced single phase loads / effective neutral current produced by the unbalanced loads; namely heating of the neutral section carrying the total unbalanced current, tripping of distribution MCCB, and increased second harmonic in UPS dc bus affecting life of dc bus capacitors and hence that of the UPS. To overcome these problems and enhance the overall operational reliability of the total system, a simple and cost effective solution is suggested based on use of Neutral Current Compensator (NCC).

Annexure –I

Neutral Current Compensator (NCC)

<u>Simple and Reliable Solution Eliminates Neutral</u>

<u>Current Problems in LV to HV Systems</u>

1.0 Neutral Current Causes, Effects, and Mitigation

1.1 Causes

- Unbalanced Fundamental active and or reactive currents
- Unbalanced current harmonics

  (drawn by non-linear loads in three-phase systems)

1.2 Effects

- Heating of neutral busbar or burning/ insulation failure of neutral cables
- Shifting of supply neutral potential with respect to earth potential based on earth resistance and the neutral current
- Unacceptable <u>unbalance or asymmetry in phase to neutral voltages</u> damaging sensitive loads such as in medical applications
- Disconnection from supply neutral point or earth resulting in phase to phase voltages appearing across loads and subsequently causing damage to loads (example: Tube Lights, Bulbs, Fans, TVs, Refrigerators, and other household appliances)
- Disturbances in synchronization voltages for connected active power converter
- Large unbalanced loads causing voltage disturbances to other loads connected on same bus, sometimes resulting in visible flicker
- Reduction in life of incoming supply transformer
- Associated monitory / financial loss due to non-availability of load

2.0 Salient Features / Advantages of the NCC

- Can be used for star as well as delta connected supply feeding power to star connected balanced / unbalanced and linear / non-linear load
- Reduces neutral current flowing in the supply (directly or through earth) to near zero value, irrespective of the type of non-linear load
- Helps in retaining supply neutral voltage (star point) close to earth or zero potential even when earth resistance is high (earth pit goes dry) or supply neutral

point gets disconnected from earth or load neutral gets disconnected from supply neutral point or load neutral gets disconnected from earth

- Eliminates "performance" dependency of load neutral connection to supply neutral point or earth
- Reduces unbalance current caused by triplens as well as by other unbalance in other harmonics present in the load currents
- Reduces asymmetry in phase to neutral voltages (deviation from average value) by almost 50%, which further helps in reducing the unbalanced load neutral current.
- Uses only magnetic components offering high reliability
- Robust (fit and forget)
- Easy to manufacture, erect, and commission
- Very economical

3.0 NCC Matlab Simulation Results

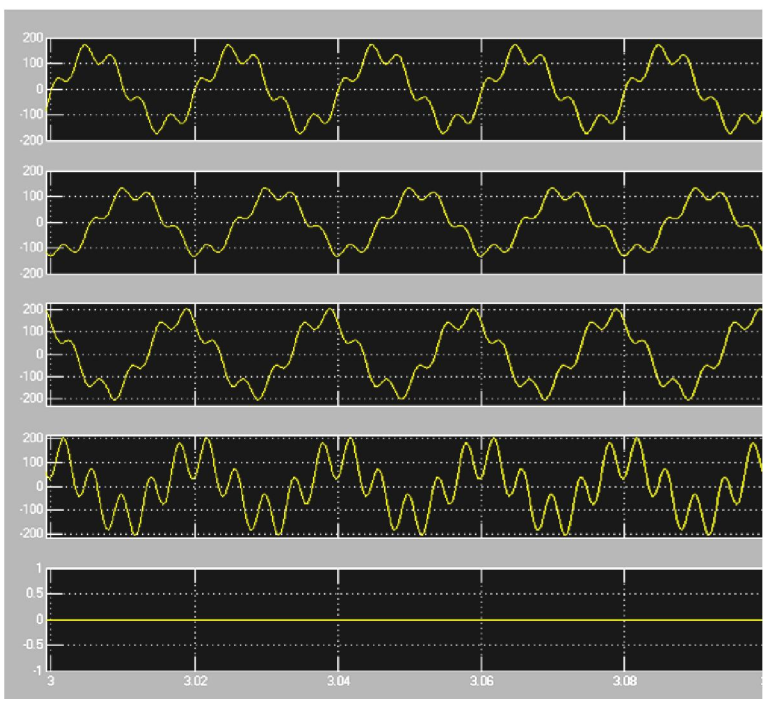


Figure A3.1: Simulation results for unbalanced non-linear load

Ch1, Ch2, Ch3: Line currents i_a, i_b, i_c (100[+] to 200 A peak to peak)

Ch4: Uncompensated Neutral Current i_{nL} (200 A peak to peak) of the load

Ch5: Compensated Neutral Current i_{nNCC} (0 A) flowing out from the NCC

4.0 NCC Experimental Results for 30 kVA Unbalanced Load with NCC installed at a Hospital in Sangli

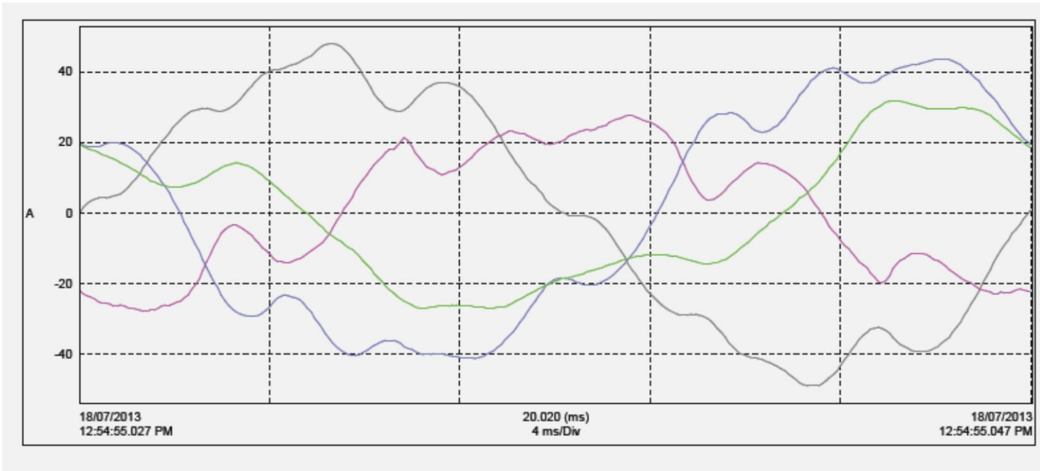


Figure A4.1: The three load currents and neutral current shown by Green (with peak approaching 35 A without NCC installation) entering the supply neutral point

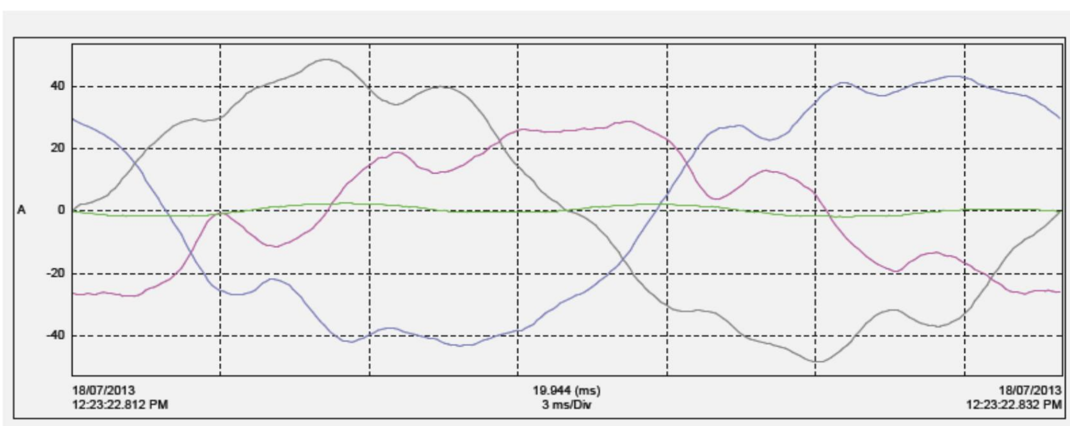


Figure A4.2: The three load currents and neutral current shown by Green (almost close to zero with NCC installation) entering the supply neutral point