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A New High Power Parallel Converter Scheme for Active Power Filters

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Parallel converter scheme for high-power active power filters

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Abstract: A new topology for efficient utilisation of parallel converters as VAR compensators and active power filters (APF) for high power loads is proposed. As a result of the limited power handling capacity of individual devices, paralleling is the choice to increase rating of equipment, while keeping the THD of the current at the PCC within the agency specified standards. It has been reported in the literature that paralleling several converters, rather than switches, is more reliable in sharing of load. From this perspective, multilevel converters carry lot of weight, as their typical power circuit configuration limits the stress on individual devices to an appreciable extent. Also, they have the advantage of low switching frequency and full utilisation of switching devices, which is essential in high-power applications. These advantages have been utilised in parallel combination with a low-power high-frequency current-controlled APF, such that the higher order harmonics can be eliminated. A new parallel converter topology with a three-level neutral point clamped (NPC) converter and an auxiliary current-controlled VSI has been proposed and control techniques have been developed. Extensive simulation study have been carried out in a SABER simulator for linear and non-linear loads.

1 Introduction

With the rapid progress in semiconductor device technology, active solutions to VAR compensation and harmonic elimination of loads are preferred to passive filter solutions owing to the availability of fast-acting switching devices with moderate power ratings. However, the long tail current associated with the device characteristics prohibits high switching frequency operation at high power. Also, at high power, the efficiency of active power filters (APF) is lower due to significant switching losses. Therefore, current quality control in high-power applications faces difficulties. To address this problem, a new technique, which combines high-power low-frequency devices and low-power high-frequency devices, has been reported to give superior performance in VAR compensation [1, 2]. A high-power converter (three-level NPC main converter), which consists of high-power low-switching-frequency devices, is operated at low-frequency to deliver the VAR requirement of the load. Another converter (auxiliary converter), which consists of low-power high-frequency devices, is operated in parallel to it. The auxiliary converter eliminates the harmonics produced by the main converter and the load so that the utility current THD is less than the specified value in the IEEE-519 standard for a particular level of current. Additionally, the power rating of the auxiliary converter is low, as it does not handle the reactive load current. The main converter is a voltage source inverter (VSI), which is controlled by the selective harmonic elimination technique so that a few lower-order harmonics are eliminated with moderate switching frequency of about 400 Hz.

To show the usefulness of the proposed control scheme, an extensive simulation study has been carried out using a SABER simulator.

2 Power circuit configuration

A three-phase three-wire star connected utility is considered. The combined active power filter is connected in parallel to the load. The main converter is neutral point clamped (NPC) three-level inverter (Fig. 1), with high-power low-frequency devices (such as GTOs). By keeping the switching frequency to the fundamental only, the switching loss is minimised and the full utilisation of the current-carrying capability of switching devices is realised. Thus the main converter can carry the high reactive power demand of the load.

The auxiliary converter consists of low-power high-frequency devices (such as IGBTs), controlled by the current-controlled modulation technique. It eliminates the main converter current harmonics and the load current harmonics from flowing to the utility current by high-switching-frequency operation. The two converters share the same DC link capacitor leading to a compact structure. To avoid circulating currents between the two converters, the auxiliary converter is connected in parallel to the load as well as the main converter via an isolation transformer. This prevents a circulating reactive current between the two converters even though they share the common DC link. The effects of both linear and non-linear loads have been studied. The non-linear load under study is a phase-controlled rectifier, which simultaneously produces VAR and large current harmonics.

With the increase in the number of levels of voltage in the multilevel converter, the converter-produced harmonics

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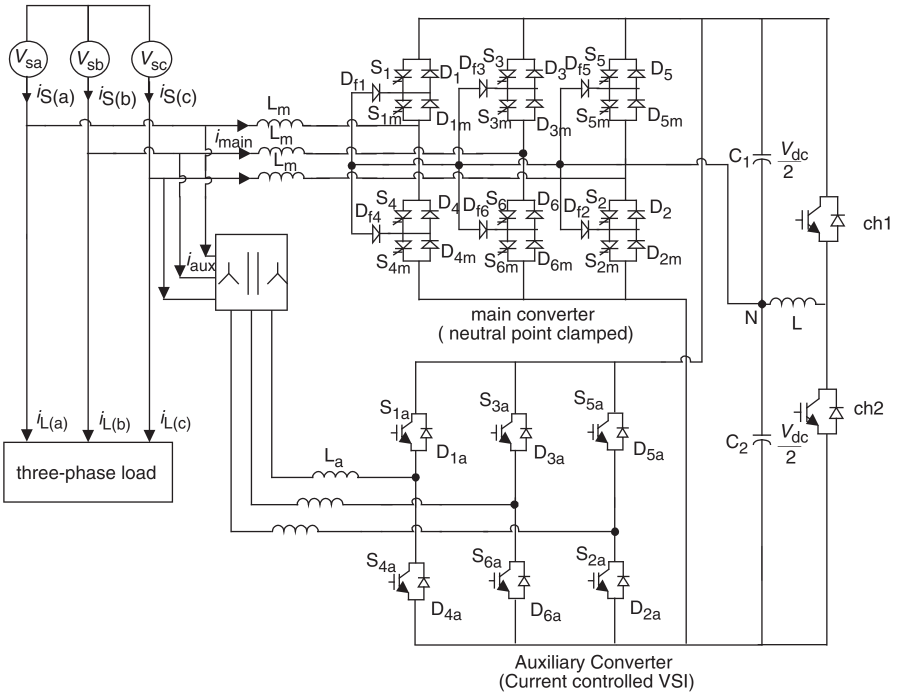

Fig. 1 *Power circuit configuration of parallel converter scheme*

would have been reduced, but the number of components of the converter would have increased [3], and control would have been more complex. In the present scheme, the main converter harmonics are taken care of by a low-power high-switching-frequency auxiliary converter and the NPC converter is operated at fundamental power frequency for load reactive power compensation to reduce control complexity.

As found from Fig. 1, half of each phase leg is split into two series-connected switches and the mid-point of each pair is connected by diodes (like D_{f1} and D_{f4} in phase A) to the midpoint N of the two capacitors. Here the voltages across the switches are only half the DC link voltage. Figure 2 shows the NPC converter output voltage for phase A and line-to-line voltage V_{AB}. When the voltage is positive, switches S_1, S_{1m} conduct, and when the voltage is negative, S_4, S_{4m} conduct. When the phase voltage is connected to the neutral point N (i.e. zero voltage), switches S_{1m}, S_{4m} conduct [4]. The present NPC converter topology leads to doubling the number of switches in addition to two extra clamping diodes. However, doubling the number of switches with the same voltage rating makes the DC voltage rating double, and this increases the power-handling capability of the converter.

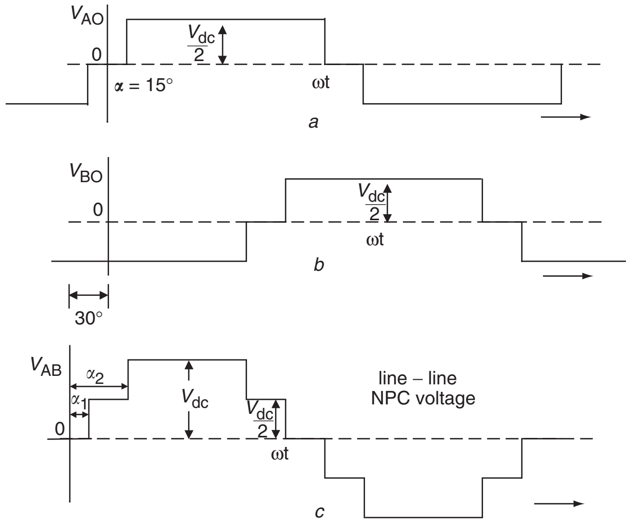

Fig. 2 *Typical phase and line voltage of NPC converter*
a Phase-to-neutral voltage of NPC converter (V_{AN})
b Phase-to-neutral voltage of NPC converter (V_{BN})
c Line–line voltage of NPC converter (V_{AB})

The per-phase equivalent circuit of the main converter for the fundamental frequency is shown in Fig. 3. Since the main converter is responsible for supplying the fundamental VAR requirement of the load, the main converter current is compared with the fundamental reactive load current to generate a reactive current error. The reactive current error is processed through a PI controller to control the voltage delay angle δ of the main converter for indirect current control. The change of δ leads to a change of active power flow between the utility and the main converter. Thus, the DC link voltage undergoes variation with change of δ. Since, V_{cm1} (converter fundamental voltage) is a function of V_{dc}, δ variation leads to change of V_{cm1}. Hence, the main converter current varies according to the following equation.

$$I_{cm1} = \left(\frac{V_s - V_{cm1} \angle - \delta}{Z_{main}} \right) \tag{1}$$

where V_s is the supply voltage, Z_{main} is the impedance of the inductor (L_m) connecting the main converter to the supply,

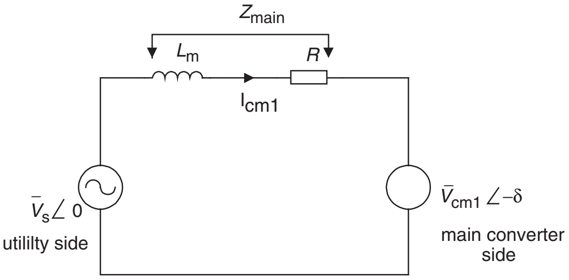

Fig. 3 *Per-phase equivalent circuit of main converter with fundamental frequency voltage and current*

and I_{cm1} is the fundamental RMS current of the main converter. With knowledge of δ, the modulating signals are adjusted to trigger the main converter switches.

2.1 *Estimation of the rating of various components of the compensator*

The main three-level converter has to supply the reactive power of the load as well as the reactive power required by the series inductor, L_m. Hence the main converter rating should be

$$V_s I_{cm1} + I_{cm1}^2 Z_{main} \text{ p.u.} \tag{2}$$

If 231 V (RMS phase voltage) is taken as the base voltage (V_{base}) and 100 kVA power is taken as base kVA (P_{base}), then $I_{base} = P_{base}/3V_{base} = 144.3$ A. The base impedance $(Z_{base}) = V_{base}/I_{base} = 1.6\,\Omega$. From (2) we can write

$$\text{main converter rating} = 1 * I_{cm1} + I_{cm1}^2 * 1.96 \text{ p.u} \tag{3}$$

where I_{cm1} is the main converter RMS current p.u. The auxiliary inverter rating should be

$$V_s I_{aux} + I_{aux}^2 Z_{aux} \text{ p.u.} \tag{4}$$

From (4) we can write

$$\text{auxiliary converter rating} = 1 * I_{aux} + I_{aux1}^2 * 0.78 \text{ p.u} \tag{5}$$

where I_{aux} is the auxiliary converter RMS current p.u.

The ratio of the main to auxiliary converter is not fixed but largely depends on the ratio of harmonic currents to load (THD). In the present analysis the ratio was found to be 27% for non-linear load. The ratings of the other associated components of the compensator are given in Table 1.

Table 1: Rating of associated components of parallel converter scheme

Component	Rating	Per unit rating
Main converter inductance, L_m	10 mH	$Z_{main} = 1.96$ p.u.
Aux. converter inductance, L_a	4 mH	$Z_{aux} = 0.78$ p.u.
DC link capacitor value, $C_1 = C_2 = C$	1000–4000 μF, 800–1000 V each	
Chopper circuit components, L	10 mH	$Z = 1.96$ p.u.
Coupling transformer rating	Star/star 1:1, 400 V (line)	0.02 p.u. impedance, VA rating = 1.*I_{aux} p.u.
Load	100 kVA	
Switch rating of main converter	maximum of DC link voltage (1000 V), and rated reactive current, which needs to be catered for	
Switch rating of auxiliary converter	full DC link voltage (2000 V), but current ratio is much less compared to that of main converter	

3 Control scheme

The complete system control block diagrams for the scheme is given in Fig. 4. It is desirable that the utility should supply only the active component of load current and the loss component of the converters at unity power factor. Therefore, the supply current should be always in phase with the respective phase voltage. In the ideal case, the angle δ is supposed to be zero, as the main converter current caters only for the load reactive current, which is at quadrature with the supply voltage. However, because of the converter losses, the capacitor voltage tends to fall and requires a small amount of active current from the supply to maintain the charge. So the angle δ acts as a measure of converter losses, and a control signal proportional to δ is added to the active component of load current ($|i_{Lact}|$) to determine the reference magnitude of the source current. This amplitude, multiplied by a sine-template (in phase with the respective utility phase voltage) gives the reference utility current (i_s^*) for the respective phase.

3.1 *Estimation of δ and reference current*

For non-linear loads, a bandpass filter is used to extract the fundamental component of load current, and its active and reactive components are separated out. The reactive component of the fundamental load current ($|i_{Lreact}|$) is compared with the reactive component of the main converter current ($|i_{main\_reactive}|$) and the error is processed through a PI controller. The output of the controller acts as the information δ (for indirect current control), and modulating signals of the main converter are modified accordingly.

Inverters with low impedance and fast response tend to be overloaded in the transient situation. So, for start-up, the auxiliary converter is initially not triggered. When the main converter current reaches a steady value and the reactive power of the load is supplied locally from the main converter, the utility supplies the active component of the currents and some higher order harmonics. After the auxiliary converter is switched on, higher-order harmonic currents are supplied from the auxiliary converter and the utility supplies only the fundamental active component of current. The magnitude of the utility current reference is the addition of two signal components, namely the fundamental active load component of current ($|i_{Lact}|$), and a component that brings information about δ (for the loss component of the converters). This amplitude multiplied by appropriate sinusoidal template of each phase in the reference current generator produces the utility current reference (i_s^*). The actual supply current (i_s) is then compared with i_s^* in a hysteresis controller and the output of the controller determines the switching of the auxiliary converter.

As seen in Figs. 2*a* and *b* (the phase voltage of the NPC converter), if α is the firing angle, the converter voltage (e_{npc}) would be [4, 5]:

$$e_{npc} = \frac{4}{\pi n} \sum V_1 \cos n\alpha \sin n\omega t \tag{6}$$

where ω corresponds to the fundamental power frequency and $V_1 = 0.5$ V DC. If $\alpha = 18°$, the 5th harmonic will be zero, If $\alpha = 12.85°$, the 7th harmonic will be zero, etc.

Figure 2*a* shows the typical line-to-line voltage of an NPC converter. Here, the *n*th harmonic voltage would be $V_{Ln} = V_1\cos(n\alpha_1) + V_2\cos(n\alpha_2)$. As V_1 and V_2 are equal to 0.5 V DC and $\alpha_1 = (\pi/3 – \alpha_2)$,

$$V_{Ln} = \left[\cos n\left(\frac{\pi}{3} - \alpha_2\right) + \cos(n\alpha_2)\right], \tag{7}$$

where α_2 can be selected to eliminate any particular harmonic, so as to reduce the total harmonic distortion. Eliminating one particular harmonic will not significantly improve the wave shape; therefore minimising the total harmonic distortion (THD) would be desirable. It has been

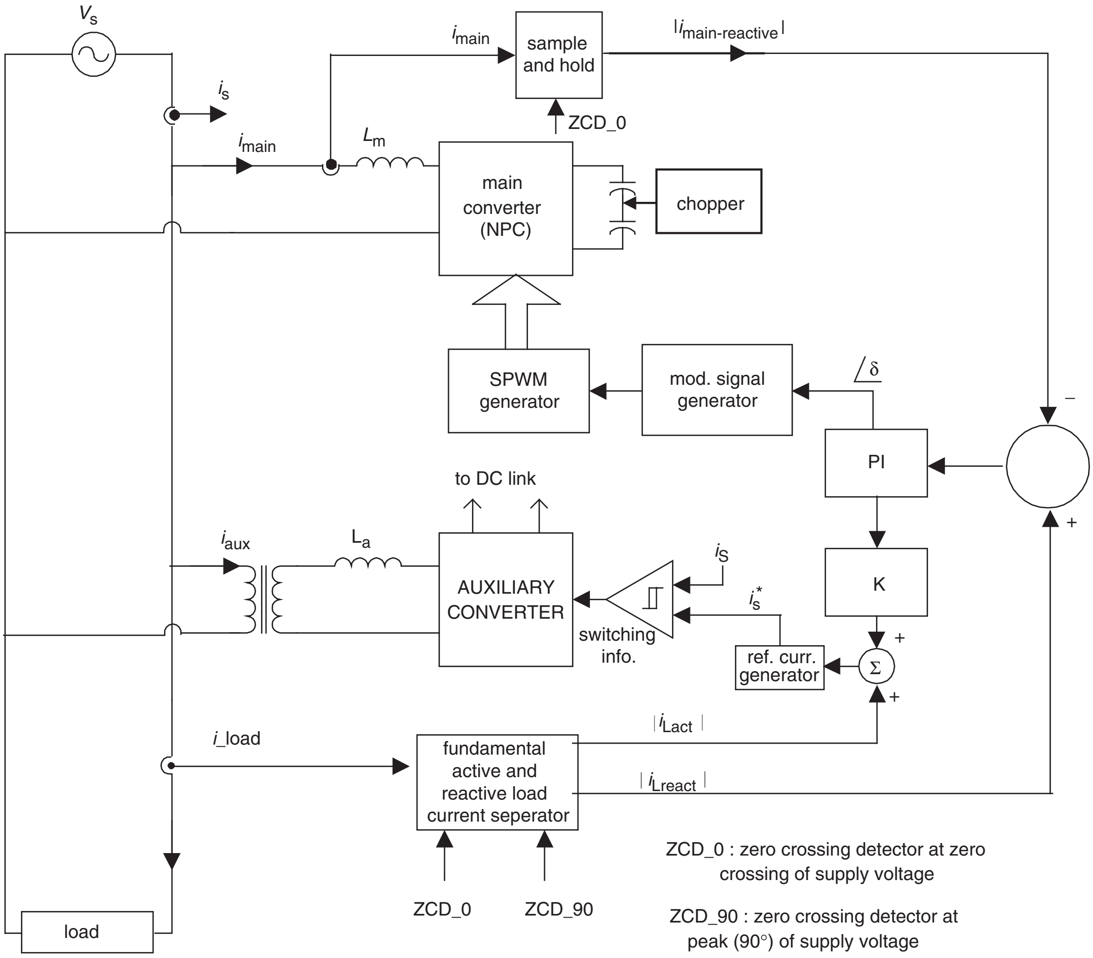

Fig. 4 *Combined control block diagram of proposed compensator scheme of NPC active power filter*

reported in the literature [5] that to keep the converter's 5th and 7th harmonics low, and the overall THD at a minimum, the converter firing angle should be $\alpha = 15°$, which has been chosen in the present investigation.

The auxiliary converter is a current-controlled VSI. The difference between the actual supply current and the reference utility current is processed through a hysteresis controller. The hysteresis window is selected in such a manner that the THD of the utility current remains within the IEEE-519 specified limit of 5%. This limit has been chosen considering the worst case I_{sc}/I_L ratio at the PCC. The output of the controller acts as switching information to the auxiliary converter.

3.2 Control of DC link voltage and chopper control

In the present control scheme, the DC link voltage is not compared with a pre-specified reference. It automatically charges up or down according to the reactive power requirement of the load. A chopper circuit is used to keep the two capacitors charged to equal voltage. Whenever one capacitor overcharges with respect to the other, a circulating current flows from one capacitor to the other through an inductor of 10 mH, so that the two capacitors are brought back to equal voltage. The chopping frequency is 5 kHz.

4 Simulation study

Detailed simulation studies were carried out with a SABER simulator to observe the performance of the combined compensators with the proposed control law. For the start-up process, the main converter was switched on, and after the current had reached steady state, auxiliary converter was made on.

4.1 Steady-state response for linear load

A three-phase star-connected 100 kVA linear load was considered in a 400 V three-phase three-wire system with load current of 145.8 A and 0.634 lagging power factor. When the main converter current reached steady state, the auxiliary converter was turned on. Figure 5 shows the supply voltage and current, which are found to be nearly in

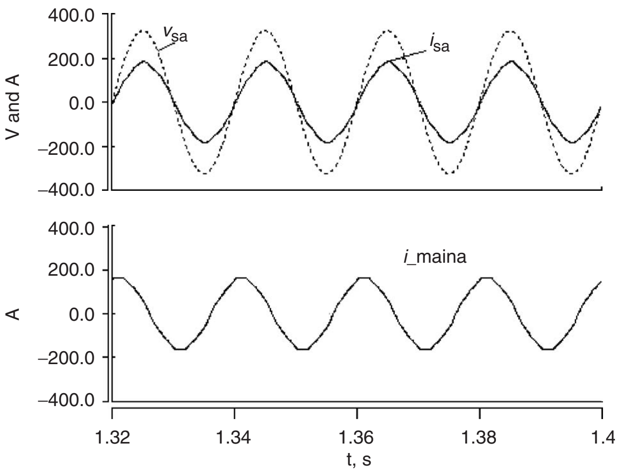

Fig. 5 *Steady-state voltage and current waveform of phase A in NPC active power filter supplying linear load, when auxiliary converts is not connected*

v_{sa} = phase A supply voltage, i_{sa} = phase A supply current

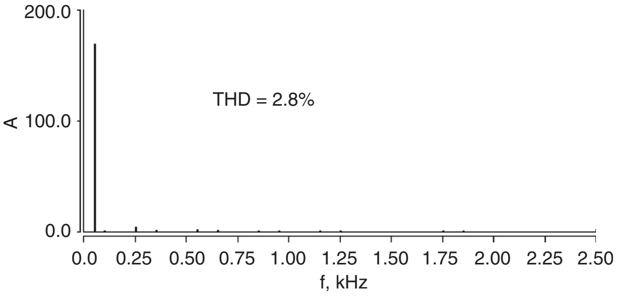

Fig. 6 *Harmonic spectra of supply current of phase A for NPC active power filter scheme, supplying linear load, when auxiliary converter is not connected*

phase with each other (0.996 power factor). Figure 6 shows that, with only the NPC converter working, the utility current THD is only 2.8%, which is well within the permissible limit of the IEEE-519 standard specification.

4.2 Dynamic response for linear load

The dynamic response of the converter was studied when the load current was changed from 145.8 A, 0.64 power factor lag to 170 A, 0.368 power factor lag, and brought back to its previous value. Figures 7 and 8 show the NPC converter performance under dynamic load change. As soon as the load current changed, though the converter current started changing according to requirement, the power factor deviated from unity for two cycles as the NPC converter was not directly current controlled. When the load current was increased, the source current became a little lagging (0.89 lag in the simulation). When the load current was brought back to its previous value, the source current became leading (typically 0.98, in the simulation). The transient changes in the DC link voltage are shown in Figs. 9 and 10, where with increase in load current the DC link voltage was also increased from 1300 to 1670 V, and came back to its previous value when the load current was restored to the previous value. The ripple in the DC link voltage was 7%.

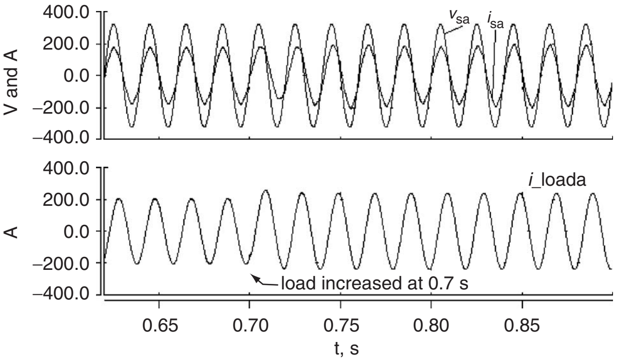

Fig. 7 *Dynamic response of NPC active power filter scheme when linear load current is increased from 145.8 to 170 A*
v_{sa} = phase A supply voltage, i_{sa} = phase A supply current, *i*_loada = phase A load current

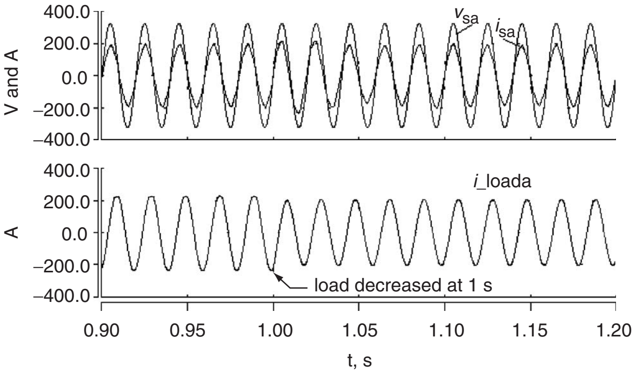

Fig. 8 *Dynamic response of NPC active power filter scheme when linear load current is decreased from 170 to 145.8 A*
v_{sa} = phase A supply voltage, i_{sa} = phase A supply current, *i*_loada = phase A load current

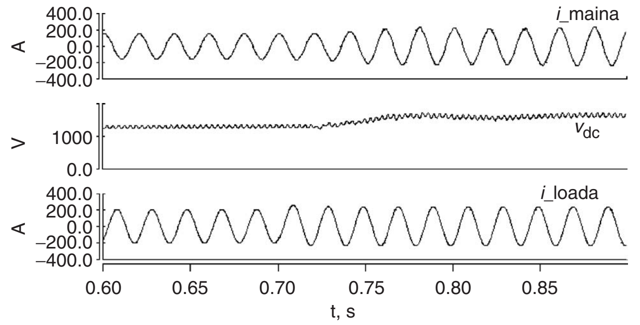

Fig. 9 *Dynamic response of NPC active power filter scheme when linear load current is increased from 145.8 to 170 A*
V_{dc} = DC link voltage, *i*_loada = phase A load current, *i*_maina = phase A main converter current

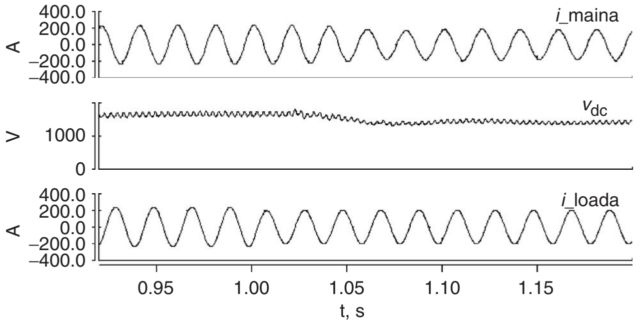

Fig. 10 *Dynamic response of NPC-active power filter scheme when linear load current is decreased from 145.8–170 A*
V_{dc} = DC link voltage, *i*_loada = phase A load current, *i*_maina = phase A main converter current

4.3 Steady-state performance for non-linear load

A phase-controlled rectifier, which consumes around 100 kVA, used as a non-linear load having both large reactive power and harmonics in the input current. Figure 11 shows the supply voltage, supply current and load current of phase A. The load current had a displacement factor of 0.66 (lag). The load current RMS was 148 A. The load current THD was 15.1% (with 5th and the 7th as dominant harmonics, as seen in Fig. 12). Initially the auxiliary converter was not switched on. The main converter supplied the fundamental reactive current to the load. But the main converter cannot compensate for the current harmonics, and the supply current THD was found to be 17.19% (dominant harmonics were found to be 5th (15.7%) and 7th (7.6%)). As the auxiliary converter was switched on, the supply current was confined within a hysteresis band, and then the utility current THD reduced to 4.4% (Fig. 13),

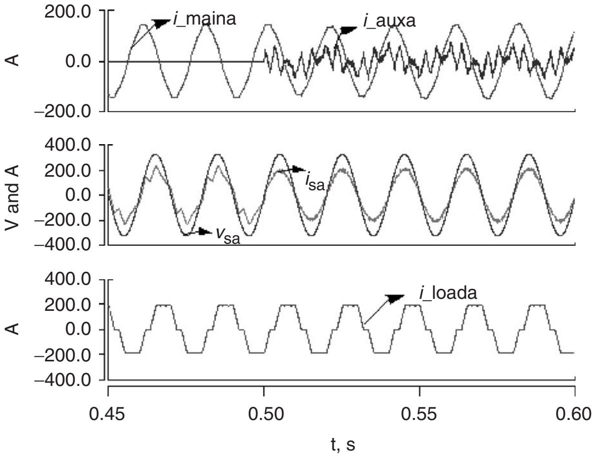

Fig. 11 *Steady-state voltage and current waveform of phase A in NPC active power filter with nonlinear load*
v_{sa} = phase A supply voltage, i_{sa} = phase A supply current, *i*_loada = phase A load current, *i*_maina = phase A NPC converter current, *i*_auxa = phase A auxiliary converter current

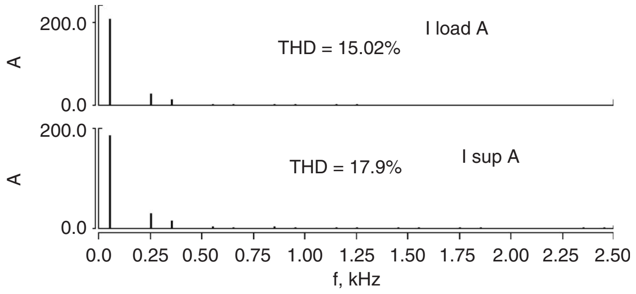

Fig. 12 *Harmonic spectra of NPC active power filter scheme for non-linear load compensation*
a Load current of phase A
b Supply current of phase A (without auxiliary converter)

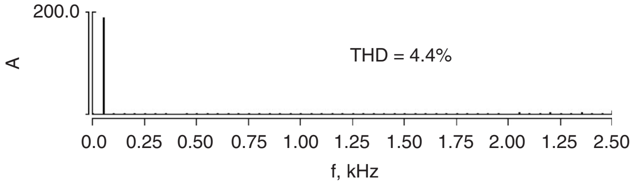

Fig. 13 *Harmonic spectra of supply current (phase A) with auxiliary converter on (non-linear load)*

and the supply power factor became nearly unity (0.996 power factor) [6].

4.4 Dynamic performance for non-linear load

The load kVA was increased from 100 to 120 kVA. Once the two converters locked the utility voltage and current to the unity power factor condition, the dynamic change in load was also mitigated at the same condition without change in power factor (Figs. 14 and 15). The transient reactive current demand of the load was taken care of by the fast-acting auxiliary converter. But as soon as the main converter current supplied the increased reactive power, the current of the auxiliary converter reduced. The corresponding increase in the DC link voltage was found to be 1300 to 1500 V. Figures 16 and 17 show load currents and converter currents for the dynamic load change.

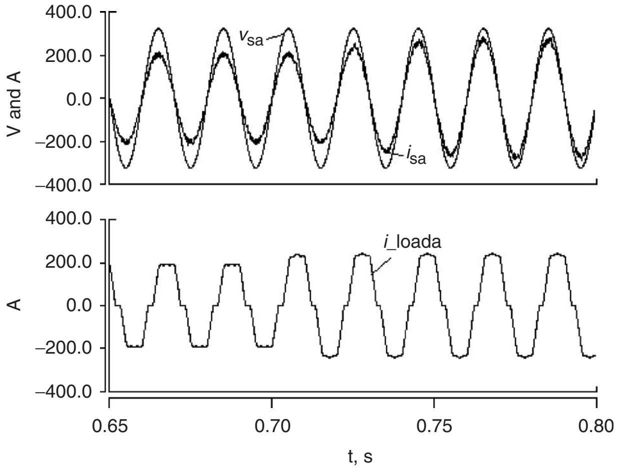

Fig. 14 *Dynamic response of utility current for NPC active power filter scheme when (non-linear) load current is increased from 145.8 to 170 A*
v_{sa} = phase A supply voltage, i_{sa} = phase A supply current, *i*_loada = phase A load current

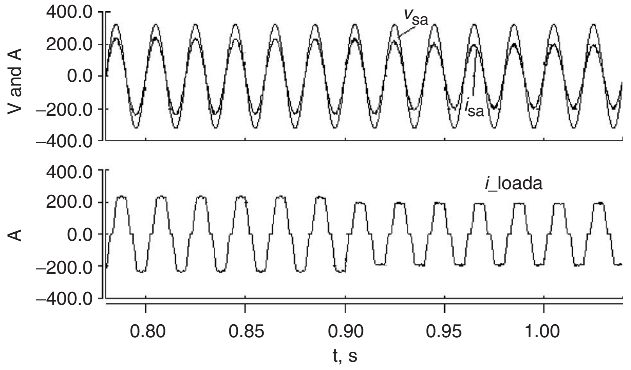

Fig. 15 *Dynamic response of source current for NPC-APF scheme when (non-linear) load current is decreased from 170 to 145.8 A*
*i*_loada = phase A load current, *i*_maina = phase A converter current, *i*_auxa = phase A auxiliary converter current

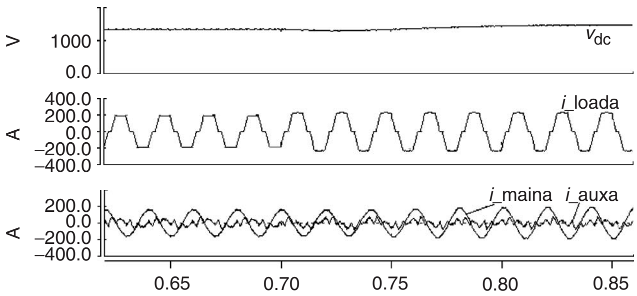

Fig. 16 *Dynamic response of dc link voltage, main and auxiliary converter currents for NPC active power filter when (non-linear) load current is increased from 145.8 to 170 A*
V_{dc} = DC link voltage, *i*_loada = phase A load current, *i*_maina = phase A main converter current, *i*_auxa = phase A auxiliary converter current

5 Conclusions

A new parallel converter topology and control strategy has been investigated and reported. This combination of parallel compensator has been shown to be useful for high power loads with large reactive power and harmonics, as the

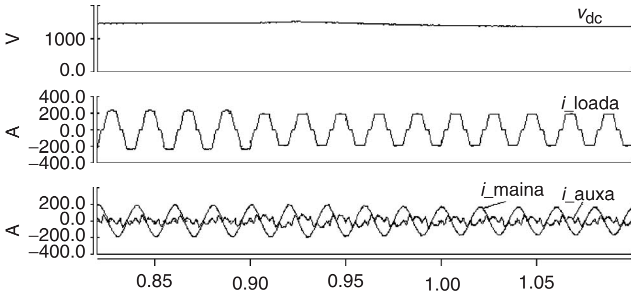

Fig. 17 *Dynamic response of DC link voltage, main and auxiliary converter currents for NPC active power filter scheme when (non-linear) load current is decreased from 170 to 145.8 A*
V_{dc} = DC link voltage, *i*_loada = phase A load current, *i*_maina = phase A main converter current, *i*_auxa = phase A auxiliary converter current

combination of high-power low-frequency devices and low-power high-frequency devices are utilised to their full capacity. For linear loads it has been observed that the NPC three-level converter combination provides reactive power support to the load, and its harmonic content in supply current is below 5%. There is therefore no further need to turn on the auxiliary converter. But during transient load change conditions, the input power factor deviates from unity, as the NPC converter is not directly current controlled. As the dynamic response is fast, within 2–3 cycles, the input power factor is restored to unity. The performance of the two-converter combinations is comparable for non-linear loads, having large harmonics. Thus, the combination of APF scheme proposed in this paper is found to be very effective for high-power load compensation.

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