An Overview of Unbalance Compensation Techniques using Power Electronic Converters for Active Distribution Systems with Renewable Generation

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Abstract:

In many residential and commercial low voltage (LV) networks, three-phase four-wire distribution systems are used to accommodate single- and three-phase customer loads and renewable energy sources (RES). Unequal distribution of both linear and nonlinear loads, along with the increasing penetration of RES units in distribution networks can increase the neutral current severely and also cause associated voltage unbalance problems, such as neutral to ground voltage rise, neutral voltage shift and harmonics at the point of common coupling (PCC) where grid, loads and converter are linked together. A high neutral current can cause electrical safety concerns at customer points. It also demands a costly neutral conductor with higher current ratio to avoid damages of the conductor and the distribution transformer. Therefore, reducing the neutral current using a control-based compensation method is desirable without increasing the size of the neutral conductor. This paper presents a comprehensive review for reduction of neutral current on different state of the art techniques utilised for power electronic converters having direct and indirect control over unbalance components to compensate for various unbalance effects, such as high neutral current, phase unbalance, and neutral shift, in three-phase four-wire (3P-4W) LV networks. Relevant international standards and analytical results for unbalanced real LV networks, and load data are also presented. This review provides a clear picture of state of art neutral compensation techniques to identify the challenges and future directions for researchers and engineers working with various RESs in both residential and commercial 3P-4W LV networks.

Highlights:

- To present a review on reduction of neutral current on different state of the art unbalance compensation techniques.
- Power electronics based compensation techniques are presented to compensate the neutral current.
- Different international standards and analytical results are thoroughly analysed.
- Future directions are put forward which will be useful for engineers working with renewable energy.

Keywords: Unbalance compensation, international standards, neutral current, three-phase four-wire network, low voltage network.

Word count: 10,494

List of Abbreviations:
LV- Low Voltage
RES- Renewable Energy Source
PCC- Point of Common Coupling
3P-4W- Three-phase Four-wire
IT- Information technology
DT- Distribution Transformer
LED- Light Emitting Diode
PV- Photovoltaic
DNO- Distribution Network Operator
NGV- Neutral to Ground Voltage
VUF- Voltage Unbalance Factor
CUF- Current Unbalance Factor
APF- Active Power Filter
STATOM- Static Synchronous Compensator
UPS- Uninterruptible Power Supply

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1. Introduction

The advancement in information technology (IT) is making the world step into the digital domain, with computer technology and electronic devices dominating in almost every sector. Most of the electronic devices in residential and commercial areas are single-phase (1P) loads, such as the adjustable speed motor drive used in air conditioners, switch mode power supplies, LED (light emitting diode) lights, electronic ballasts, photocopy machines etc. Three-phase four-wire (3P-4W) low voltage (LV) distribution systems are commonly used to supply both three- and single- phase loads utilizing the delta-wye configured distribution transformer (DT). The neutral line, which is supplied from the terminal of a DT, is used as a reference point for single-phase loads and is generally grounded at multiple network locations to ease the installation of both three- and single-phase loads. The traditional power system network with different electricity customer connections is shown in Fig. 1.

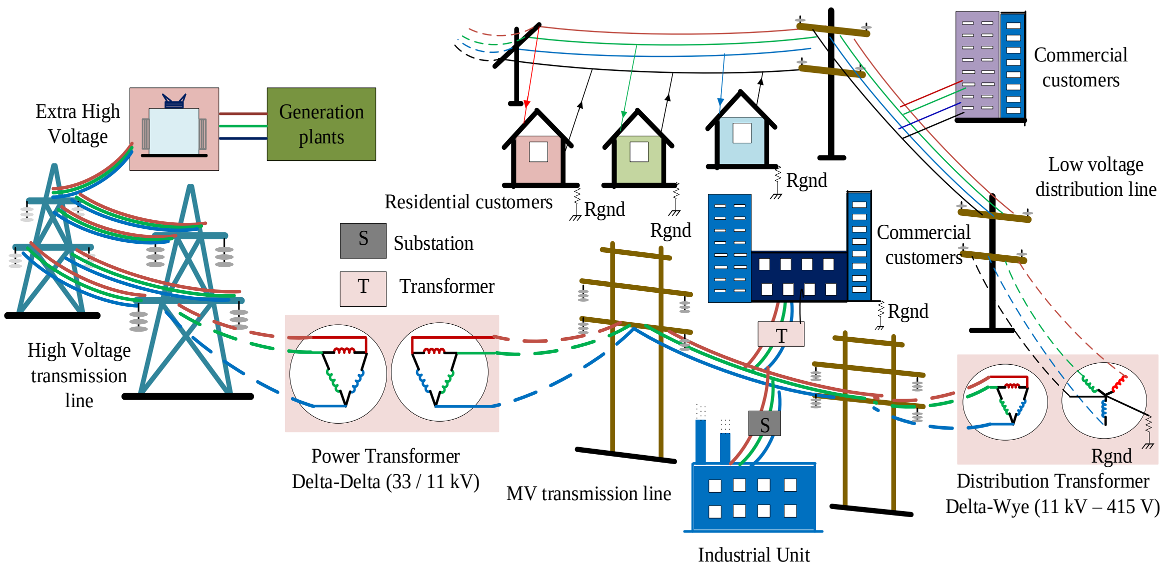

Fig. 1 Traditional power system network with load distribution

It can be seen from Fig. 1 that the low voltage (LV) side consists of both three- and single-phase loads which can cause an unbalance load distribution in the network. Some commercial loads, such as university buildings and shopping malls, generally get their supplies of electricity from a delta-wye step down transformer, whereas commercial buildings in downtown areas are generally connected directly to the 3P-4W LV network. The neutral conductor connected to the delta-star terminal of a DT is mainly designed to carry currents generated from system abnormalities, such as single-line to ground faults and leakage currents. However, the increasing application of power electronic loads which exhibit nonlinear characteristics can generate a lot of harmonic content, especially third harmonics, and can cause poor power quality [1]. For a rectifier type non-linear load which includes a diode bridge at low current, the maximum neutral current is 173% of the line current [2]. In addition, the generation of the zero sequence current component is related to the unbalanced distribution of continuously changing linear single-phase loads, and also flows through the neutral transmission line and causes overloading in the neutral conductor. Even with a balanced distribution of loads in all the phases, excessive neutral current can be generated with loads, such as computer or switched mode power regulators, in 3P-4W networks [3].

The survey conducted by Liebert customer service engineers in 146 computer sites across the United States revealed that around 22.6% of the sites had a neutral current excess of 100% of the phase currents [4]. This is also verified by the results from the published white paper based on a commercial building by the computer and business equipment manufacturers association (CBEMA) [5]. The LV network can also face an unbalance condition due to asymmetrical transformer winding impedances, open wye-delta transformers, blown fuses of three-phase capacitor banks, and unbalance effects from upstream networks. Additionally, unbalance allocation of single-phase active power sources, such as photovoltaic (PV) systems, battery storage, electric vehicles etc., in the distribution network can cause phase unbalances along with voltage rise at the point of common coupling (PCC) and ground to neutral voltage rise. According to a survey in 2013, 9.6% of all customers with electricity connections within Australia are using rooftop PV installations of the single-phase type [6]. The increasing penetration of RESs into the LV network can make the unbalance scenario get worse with unplanned allocation of single-phase RES and loads in the inherently unbalanced distribution network [7].

To compensate for sudden unbalances in the electrical distribution network, different countries use different grounding systems, such as an isolated neutral in Italy, Switzerland, and Finland; multiple neutral grounding along with connection of the utility neutral to the customer grounding in USA, Australia, and Greece; solid neutral grounding in the UK, resistance neutral grounding in France, reactance grounding in Belgium, Spain, Portugal, and Netherlands; and via a 'Petersen' coil in Germany [8]. Because of the increase in unbalance conditions, the existing grounding system is facing new concerns about the proper operation of electrical equipment and providing safety to customers. An over-current protection circuit in the neutral wire can be used to reduce the harmful effects of high neutral currents, however, the national electrical code does not allow it to be installed at the PCC. Proper control over the zero-sequence current and voltage quantities are possible with additional compensation devices installed at the secondary side of the DT. Additionally, it is recommended to compensate the load-generated excess neutral current at the PCC to keep the DT neutral point at virtually zero potential [9]. The neutral compensation methods are mainly categorised into two categories as: passive compensation, and active compensation.

The working principle of the passive compensation methods is to absorb the zero-sequence current flowing through the neutral conductor and improve the output current harmonics. Popularly used passive-compensation devices consist of the application of passive filter combinations [10-12], synchronous machine [13], magnetic transformer configurations [14] and the combination of transformer and three-phase voltage source integration [15-17]. The installation of passive compensation device is quite simple, however, it needs to be installed close to the customer connection point to work effectively. Additionally, passive compensators quite bulky and expensive, and only provide indirect control over the unbalanced quantities.

Alternatively, the active compensation method utilises power electronics converters to cancel the neutral current using controlled power electronic switching devices. Active compensators provide a better control option but incur additional cost due to the switching devices. Moreover, all power electronics converters are not necessarily work as active unbalance compensators. Some converters use power electronics switching devices, however, to provide indirect control over the unbalance contents.

Compared to the passive compensators, power electronics based active compensators exhibit better and more reliable results in neutral current compensation process, which are not systematically available in existing literature. This review paper presents rigorous and up-to-date reviews of different compensation methods of power electronics converters, and associated unbalance issues from both load and RES distributions. Several case studies are conducted to compare the performance of different compensation techniques under different operating conditions. Different international standards and actual load profiles from residential and commercial networks are presented to demonstrate the unbalance effects in real 3P-4W LV networks. This will help to design new compensators to overcome the unbalance effects according to the standards and validate the feasibility of different control topologies with diverse loads and RESs in real LV networks. The rest of the paper is organised as follows: in Section 2, the challenges associated with the unbalanced distribution network are highlighted; different international standards for unbalanced compensation are outlined in Section 3; power electronics converter based unbalance compensators for 3P-4W networks are summarised in Section 4; a comparative simulation analysis between passive and active unbalance compensators is presented in Section 5; constructive future directions are provided in Section 6; and the paper is concluded in Section 7, describing the key findings from this paper.

2. Challenges with 3P-4W unbalanced distribution network

An uneven distribution of loads is a common phenomenon in 3P-4W LV networks. Even with a balanced utility supply, non-uniform single-phase load distributions can cause various unbalance phenomena. There are many concerning issues arising from an unbalanced distribution system, as follows:

i. Overloading the neutral conductor: Generally, the neutral conductor is designed with the same capacity as the phase conductors, however, during unbalance situations, as high as three-fold phase current can flow through the neutral conductor causing severe overloading [4].
ii. Over-sizing the three-phase generator due to a higher current requirement from each phase [18].
iii. Over-heating the distribution transformer can increase losses and reduce the overall system's efficiency. The zero sequence harmonic current flows via the fuel tank wall and the steel components of the DT which generates heat, causes winding insulation failure and reduces equipment lifetime [9], [13].
iv. Reducing voltage quality at the supply side and increasing harmonics [19].
v. Increasing fire and electrical safety concerns for customers [20].

vi. Introducing power line communication interference [21].

vii. Increasing line losses ($I_N^2R_{line}$) due to higher neutral current. Therefore, in some countries the neutral current is restricted. For instance, in Korea, the neutral current is restricted to be less than 20% of a normal phase current in overhead transmission lines [21].

viii. Introducing prolonged and abnormal vibration in rotary machines, such as induction motors [22].

ix. Mal-functioning of sensitive equipment such as medical equipment, process control plants, and telecommunication equipment [23].

x. Producing mal-operation of protection relays [24].

xi. Unstable control operation from power electronics converters [25].

xii. Rising neutral to ground voltage (NGV): The NGV can occur in an ineffectively grounded system because of the asymmetry in the distributed parameters and resonance between the Petersen coil and distributed capacitances. The NGV also acts as common mode noise to sensitive electronics equipment [26, 27].

xiii. Causing neutral shift: With a finite neutral impedance in a distribution network, the neutral shift voltage is the product of the neutral impedance and the neutral current flowing in the neutral conductor. The neutral shift can cause premature failure of adjustable speed induction motors and synchronous motors [28, 29].

xiv. Producing common mode voltage which can cause electromagnetic interference emissions and induced voltage problems and bearing currents. A constant common mode voltage can cause variety of problems such as reliability and lifetime of operating machines [30, 31].

xv. Causing phase unbalance: The phase unbalance could result in lower order torque pulsations in electromechanical systems, such as generators, leading to increased mechanical losses and instability [32, 33].

3. Different standards for unbalanced distribution systems

Different countries have their own electricity connection standards which are generally provided by their distribution network operators (DNOs). Any electrical equipment connected to the distribution network needs to follow specific power quality standards. Stringent standards are followed with the loads and RES units which require power electronics converters to transfer power to/from the grid. Nonlinear loads have the characteristic of drawing non-sinusoidal currents (harmonic currents) even from a sinusoidal supply voltage, causing poor power quality at the supply voltage side. The European Union Industry and Commerce pays around €10 billion per annum because of losses due to poor power quality in their distribution network [34]. To interact with the power quality issues, two types of voltages are defined in the IEC 038 standard [35]:

i. Line to line supply voltage or line to neutral supply voltage at PCC,

ii. Utility voltage at the plug or terminal of electrical equipment.

It is the responsibility of customers to maintain good power quality at their utility voltage connection point and the DNOs are responsible for the supply side voltage. Degradation in the customer end voltage can also happen because of a disturbance on the supply side or by any other user equipment connected at the utility side. Therefore, there are several definitions available to evaluate the unbalance factor (UF) at the PCC [3]. Considering the positive and negative sequence components of the voltage and current quantities, the UF can be expressed as:

$$UF = \frac{|G_{neg.seq.}|}{|G_{pos.seq.}|} \tag{1}$$

where G can be voltage or current quantities. Most international standards use the above expression to define the UF in their network. However, for a 3P-4W network, the UF needs to be expressed considering the zero sequence components as shown in the following expression [26], [29]:

$$UF = \frac{\sqrt{|G_{neg.seq.}^2| + |G_{zero.seq.}^2|}}{|G_{pos.seq.}|} \tag{2}$$

Despite the variations in the UF expressions, different countries strictly maintain specific voltage unbalance factor (VUF) to estimate the condition in which the 3P voltages deviate in amplitude and/or phase. According to the power community, the VUF is the ratio of negative (or zero) sequence and positive sequence [24, 36]. Table 1 summarises different ratio of VUF in different countries [37].

Table 1 Voltage unbalance factor standards from different countries

Country	*VUF (%)*	*Standard codes*
USA	Less than 3 2 1	- ANSI C84.1 - IEC [38] - NEMA-MG-1 [39]
England and Wales	1 (under planned outage)	- CIGRE working group C4.07 recommend 2% for HV-LV - 1.5% for EHV - 3% for predominantly single-phase load connections
Scotland	2	GB grid code
Germany	2	At transmission and distribution levels
Australia	2	For short duration 3% [40]
France	2	RTE at transmission level
South Africa	2	For HV-LV. 3% VUF is also considered in special cases
Hydro Quebec, Canada	1 2	- Based on 2 hrs average data on transmission level - for MV and LV network
New Zealand	1	Electricity Governance Rules 2003, Part C Common Quality
Brazil	2	At all voltage levels

It is shown in Table 1 that the ANSI C84.1 standard recommends the maximum VUF to be less than 3%, however, in most of the states in the USA, the VUF is restricted to max. 2.5% [41]. The ANSI/IEEE standards 141-1993 and 241-1990 suggest that computer loads will behave abnormally if the VUF is higher than 2.5%. Some motor manufacturers require a current unbalance factor (CUF) of less than 5% to validate their warranty, whereas NEMA MG1 requires 1% VUF which generates around 6-10% CUF [38]. The effects of voltage unbalance on certain types of motors can be found in Australian Standard AS 1359.31. The National Electricity Code Australia (NECA) and National Electricity Regulator (NER) mainly set the voltage and current unbalance limits within the Australia electricity network. The permissible voltage unbalance factors within the Australian electricity network are shown in Table 2.

Table 2 VUF at specific voltage level within Australia [40]

Voltage level	VUF considered based on expression 1			
	No contingency (%)	Credible contingency event (%)	General (%)	Once per hr (%)
>100 kV	0.5	0.7	1	2
10 kV to 100 kV	1.3	1.3	2	2.5
< 10 kV	2	2	2.5	3

According to one of the largest local power distribution companies in Australia, Ausgrid, NSW, the customer should use special relay circuits to trip the equipment generating unbalance current, and it is the responsibility of the customers to make their load balanced to ensure that the NGV does not go above 10 V [42]. In situations where the taps are connected to metallic water pipes, a special neutral displacement protection relay needs to be installed to reduce the NGV rise during faults [38]. In some cases, such as computer equipment manufacturers, it is recommended to maintain less than 0.5 V NGV [4], [7]. In phase unbalance conditions, it is recommended by the Australian standard for energy systems connected to grid tied inverters, AS477, that the imbalance between the phases must be maintained at less than 20 A [42, 43]. Therefore, customers need to be responsible for maintaining proper voltage levels and power quality at their connection points if the full benefit from modern electronics based appliances and RES installations are utilised. Thus, this review paper is focused on decentralised unbalance compensation methods to provide an extensive insight for customers and DNOs to maintain the power quality and voltage level at the PCC.

4. Power electronics converter based unbalance compensation topologies

In this section, power electronics converter topologies which are assigned to participate in active unbalance compensation process are thoroughly reviewed. There are many significant research studies being undertaken on unbalance compensation methods in 3P-4W distribution networks. Increasing the capacity of the neutral conductor is the easiest solution, however, not an economical and robust one [4]. Instead of using neutral compensation devices, the network unbalances can also be mitigated using phase balancing [44] and phase swapping [45] techniques. The authors in [46] review commonly used neutral current compensation methods in a 3P-4W network, however, there is a lack of specific guidelines for the operation, i.e. standards. Interruptible power supplies (UPS) and active power filter (APF) topologies can be installed on a 3P-4W distribution system to supply both single- and three-phase loads. An extensive review on APF is presented in [47]. One of the popularly used dynamic voltage regulation devices is the static synchronous compensator (STATCOM) which uses a power electronics converter to control its operation. Different STATCOM configurations and operational functionalities for both three- and four-leg configurations are presented in [48]. However, issues with RES unbalanced allocation is not considered for 3P-4W networks. The consideration of RES plays an important role in 3P-4W networks for different unbalance conditions. From the future roadmap of the RESs in the power generation and distribution sectors, it can be seen that customer loads and small-scale RES units are mainly installed in commercial and residential distribution networks. Therefore, the unbalance compensation methods are presented mainly for the 3P-4W LV distribution networks. Generally, power electronic converter based unbalance compensators are categorised by single-phase and three-phase converters which are reviewed in detail in the following subsections.

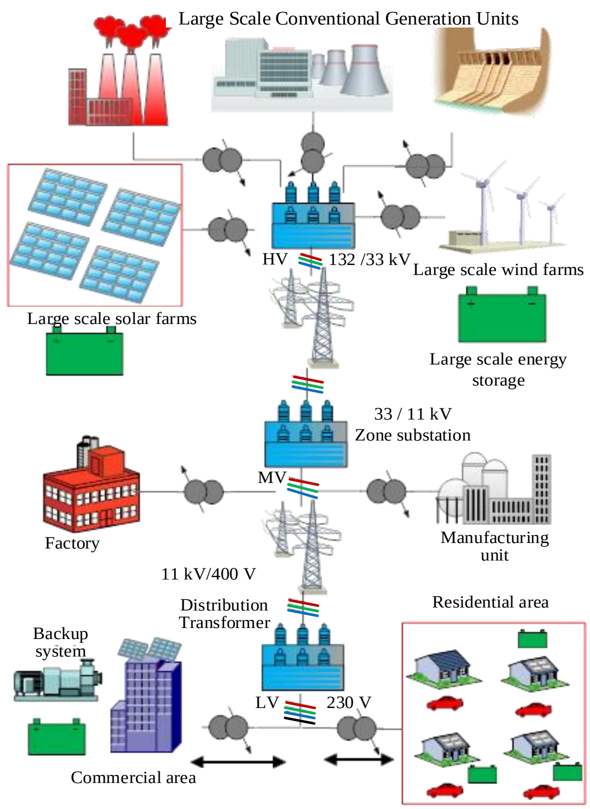

Fig. 2 RES integration into power system network

4.1 Single-phase converter topologies

Popularly used passive compensation methods, comprised of various magnetic core transformers, are required to be installed close to the customer connection point, however, it suffers from unreliable performance during unbalances in the supply side. Therefore, an additional single-phase power electronics converter is generally installed on the fourth wire with the magnetic core transformers to provide direct control over the neutral current. This type of 1P converter can also act as an APF to filter harmonic content in the neutral wire. The connections of a 1P converter with different transformer configurations and corresponding neutral compensation controls are shown in Figures 3 and 4 from (a)-(d) [49-52]. The hybrid filter presented in [49] is utilised to compensate for the harmonics on the neutral current while not affecting the fundamental frequency components. The zig-zag transformer (ZT), placed in parallel with the loads and the 1P converter, is connected in series with the neutral line via a bypass switch which operates in the case of converter failure as shown in Fig. 3 (a). The series connection of the converter allows only the fundamental currents to flow and the controller ensures a lower DC voltage requirement. The harmonic compensation at the neutral line using the 1P converter also reduces the overloading of the ZT. The control diagram for this method is shown in Fig. 4 (a). A similar capacity reduction operation is presented in [50], where an additional three-leg converter is used with the delta side of the ZT as shown in Fig. 3 (b). The presented filter topology provides six times the capacity requirement for neutral current compensation of the previous method. Three- and single-phase converters are used to compensate the nonzero- (positive- and negative- sequence components) and zero sequence current harmonics respectively as shown in Fig. 4 (b). Excessive neutral current elimination is presented with a star/delta transformer and a two-switch 1P APF configuration in [51] and shown in Fig. 3(c). The proposed method, with closed-loop operation of the 1P converter virtually, eliminates the transformer overheating issue. The harmonic compensation control from Fig. 3(c) is shown in Fig. 4 (c). The harmonic content in the neutral current from the voltage (capacitive) and current (inductive) source/loads are compensated using a combination of 1P converter and ZT as shown in Fig. 3 (d) [52]. The rectifier at the DC side of the inverter is removed using a DC bus voltage regulator as shown in Fig. 4 (d). This provides a lower volt-ampere requirement and provides better harmonic compensation in the neutral line. In Figures 3, 4 and 5, LPF and BPF stand for low-pass and band-pass filters, I_L represents the load-side current, I_g is the grid-side current, I_{Ln} represents the load-side neutral current, I_{fn} is the transformer-side neutral current, I_{sn} is the converter-side neutral current, V_{dc} is the dc-link voltage, V_g represents the grid voltage, V_f is the converter's output voltage, L_g and R_g are the grid impedance respectively, L_{gn} and R_{gn} are the impedance of the neutral line respectively, L_f and C_f are the impedance of the harmonic filter respectively, C_{dc} is the dc-link capacitor, K_{amp} is the amplifying gain, K_c and K_I are the gains of the controllers, αβ and dq represent the stationary and rotational reference frames of the neutral current respectively.

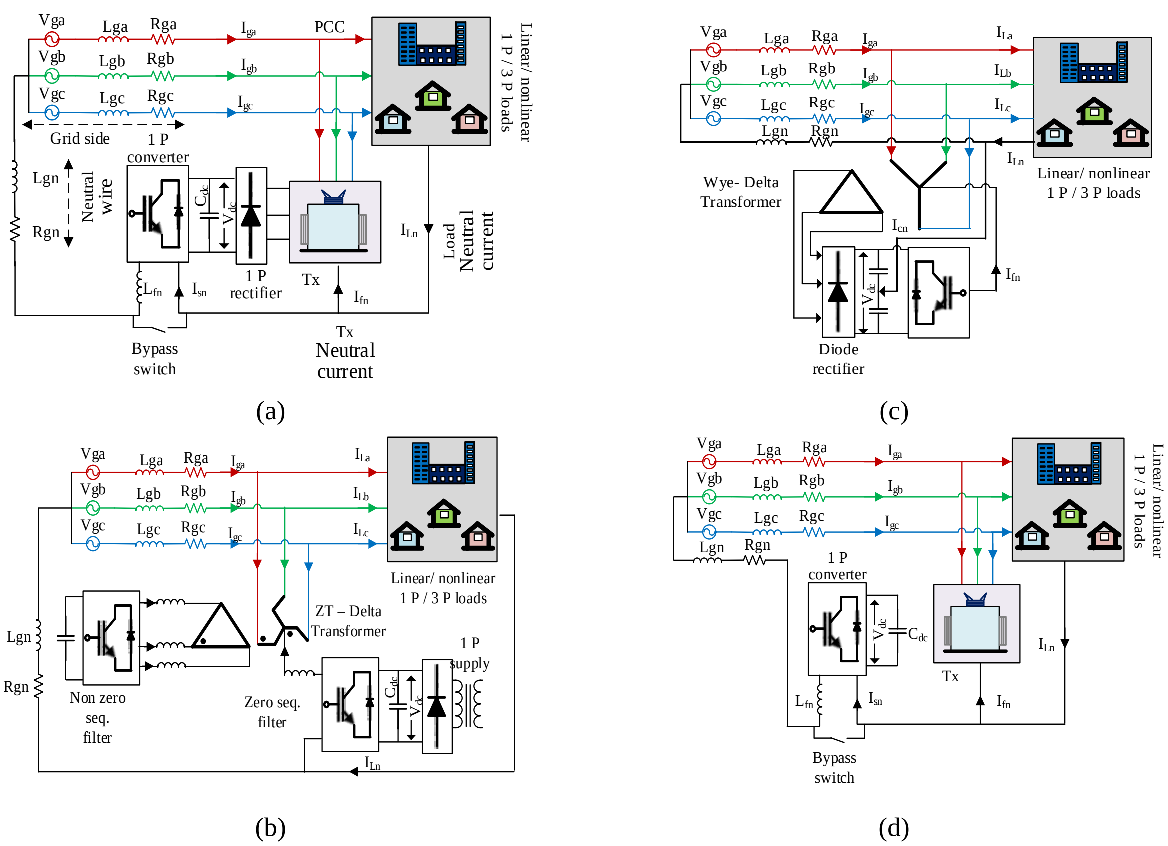

Fig. 3 Single-phase (1P) converter and transformer connections from (a) [49], (b) [50], (c) [51], and (d) [52]

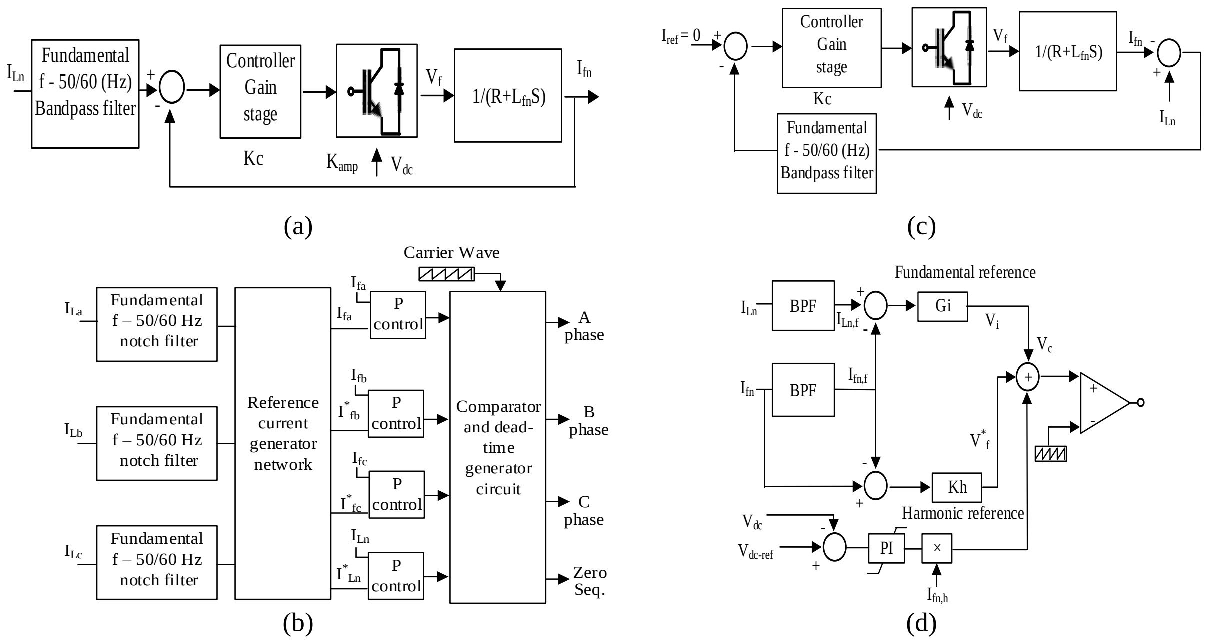

Fig. 4 Control diagrams of 1P APF from (a) [49], (b) [50], (c) [51], and [52]

The 1P converter is also used to provide an active grounding system for a 10 kVA three-phase system in [53]. The converter is used to overcome the neutral to ground voltage rise issue due to asymmetry in the parameters of the distribution system. In [54], the 1P series APF coupled with a matching transformer (MT) is used with the neutral conductor to mitigate either the third harmonic content of voltage or the neutral current, and the system is shown in Fig. 5 (a). The APF is designed to behave as an inductor for the neutral current components. The sensed neutral current is transformed to synchronously rotating frame (SRF), *dq* components utilizing the third harmonic phase angle from the neutral point voltage, and normalised to compensate the output neutral current in addition to the DC bus voltage regulation as shown in Fig. 5 (b).

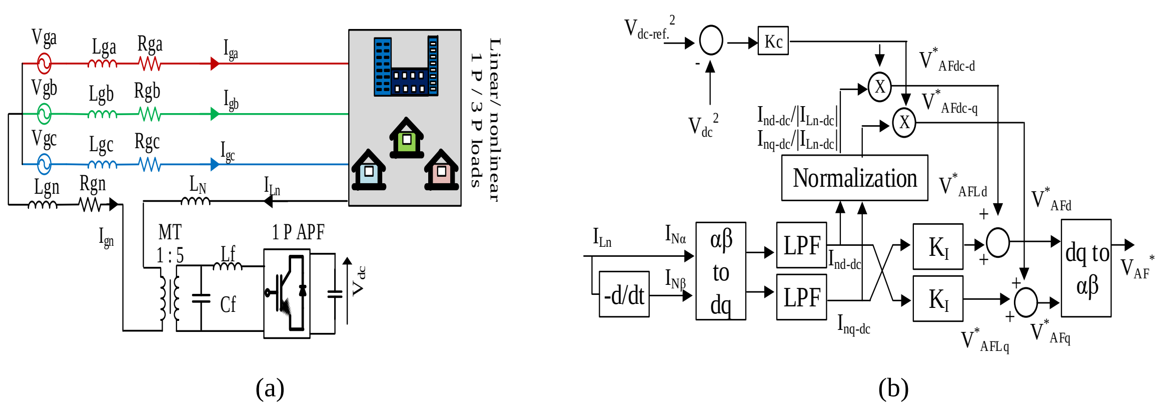

Fig. 5 Single-phase APF: (a) connection with MT, and (b) control block diagram [54]

The technical specifications of the experimental prototypes for the single-phase power electronics unbalance compensators are shown in Table 3. The single-phase compensator provides simplicity in controls, however, requires a magnetic core transformer connection for grid connection which increases the cost and makes the system bulky. Therefore, this type of topology is only suitable for commercial and industrial level customers.

Table 3 Technical specifications of the single-phase APF

Specification	[49]	[50]	[51]	[52]	[54]
Unit rating (kVA)	-	3	6	50	3
Voltage $_{L-N}$ (V)	120 V	150 V	120 V	220 V_{L-L}	100 V

and frequency (Hz)	60 Hz	60 Hz	60 Hz		50 Hz
Modulation	SPWM	Asynchronous PWM	PWM	PWM	PWM
Switching frequency f_{sw} (kHz)	20	8	20	20	10
DC bus voltage (V_{DC})	-	150 V for 3P 25 V for 1P	80 V	30 V	150 V
Transformer	ZT	ZT-delta	Delta-wye	ZT	MT
Rectifier at DC side	Yes	Yes	Yes	No	No
Neutral inductor (mH)	2	1.3	1.21	2	0.86
Harmonic compensation	Zero seq.	Pos. Neg. and Zero seq.	Zero seq.	Zero seq.	Zero seq.
DC voltage regulation	No	No	No	Yes	Yes
Neutral current reference	Sensed	Calculated	Sensed	Sensed	Sensed

4.2 Three-phase converter topologies

4.2.1 Three-phase three-leg split DC-link capacitor converter

Among the different three-phase (3P) unbalance compensator topologies, the split-DC link capacitor configuration is one of the commonly used topologies in 3P-4W electricity networks. The fourth wire from the 3P-4W distribution system is connected at the middle point of the two DC-link capacitors as shown in Fig. 6 (a). The harmonic currents can flow through either of the capacitors and get absorbed, providing indirect control over the neutral current. This configuration provides a simple solution for a four-wire system with minimum switching device requirements. The shunt split-DC APF is used to compensate the harmonics and zero sequence current components using the constant power and sinusoidal current supply methods under unbalanced voltage conditions in [55]. An additional DC voltage regulator is used to regulate the DC voltage difference to zero between the two capacitors and to supply the active power required for the converter losses. Utilizing the three-dimensional (3D) space vector modulation method with the symmetrical components of the PCC voltage, the grid feeding operation under an unbalance situation is presented in [56]. The authors in [57] present the operation of a power redistribution device (PRD) using the split-DC configuration to compensate for the harmonic content and neutral current using a model based controller. The proposed method is considered to operate in a decentralised approach which can also reduce the tuning complexity of the passive filters. Special control focus is given to the homopolar, i.e. zero sequence, current and voltage components. A passivity based controller is applied in the split-DC converter with three control objectives, i.e. current tracking, voltage regulation and homopolar current compensation, in [58]. A performance comparison of different control strategies with split-DC converter is presented in detail in [59]. The distributed STATCOM (D-STATCOM) operation for a non-stiff distribution system is presented with the split-DC configuration in [60]. An extra capacitor is used in series with the interacting inductor which reduces the DC link voltage requirement and switching losses. The series APF, with the capacitor midpoint converter, is used to compensate for the voltage unbalances, such as sag and swell cases, and the hybrid combination with a resonant LC filter is used to compensate the zero-sequence harmonic as shown in Fig. 6 (b) [61-64]. An improved modulation strategy with state vector pulse width modulation (PWM) is presented with both balanced and unbalanced voltage sag situations in a dynamic voltage restorer (DVR) operation in [65]. The presented modulation method considers three voltage space vectors and analyses its performance with respect to total harmonic distortion, weighted total harmonic distortion, neutral line ripple and switching loss. The construction of the DVR is similar to the hybrid series APF construction as shown in Fig. 6 (b) except for the passive filter section.

The split-DC converter provides a simple method of controlling the neutral current, however, it requires a high value of DC link capacitors as well as an additional voltage balancing controller at the DC midpoint. To reduce the complexity in the controls, the single DC capacitor configurations are presented in the next subsection.

4.2.2 Three-phase three-leg single DC-link capacitor converter

The single DC-link capacitor converters do not require additional control loops to make zero potential difference at the DC mid-point. Utilising this configuration in addition to a small value, AC capacitor provides a similar split-DC APF performance to the 3P-4W system [66]. The AC capacitor is connected between the negative DC bus and the grid neutral connection as shown in Fig. 6 (c). The proposed system eliminates the complexity of DC voltage regulation at the capacitor midpoint compared to using a hysteresis band controller and instantaneous symmetrical compensation theory. The size of the AC capacitor used in this configuration depends on the amount of neutral current needing to be compensated. Therefore, a comparatively large capacitor needs to be installed for higher neutral current compensation. Providing a similar indirect neutral control option to a single DC link capacitor, the authors in [67] propose a hybrid power filter for the 3P-4W system. The utility side neutral line can be connected directly to the positive or the negative terminal of the DC bus as shown in Fig. 6 (d). This improves the passive filter performance and reduces the manufacturing cost. Additionally, the series connected passive filter at the AC side helps to reduce the requirement for a higher DC bus voltage. A comparative analysis of different capacitor configured 3P-4W APF operations is shown in Table 4.

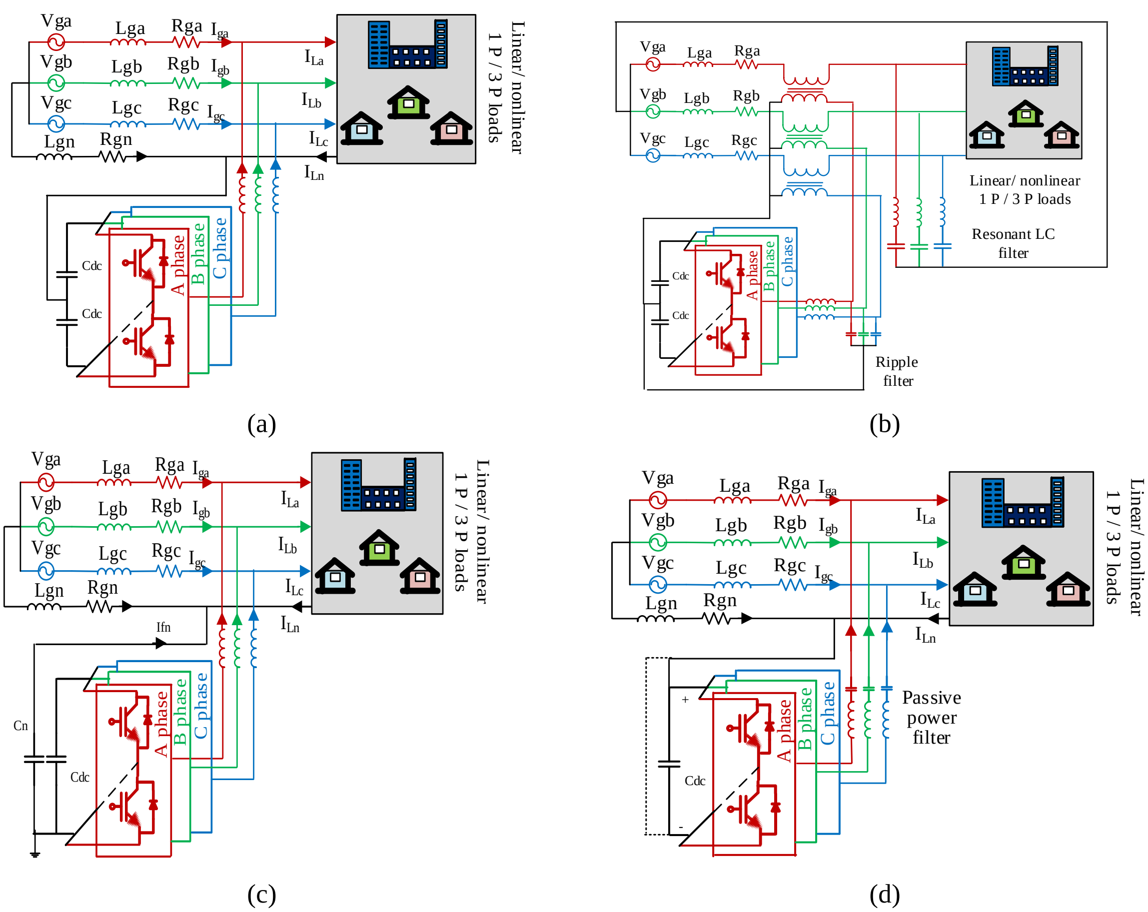

Fig. 6 3P-4W converter configurations from (a) [55], (b) [61-64], (c) [66], and (d) [67]

Table 4 Comparative analysis of different capacitor-configured four-wire APF operations

Ref.	Capacitor connection	Connection	Controller	Modulation method	Unit Capacity kVA	Grid supply	V_{DC} C_{DC}	f_{sw} kHz	Filter
[55]	Split DC	Shunt APF	Hysteresis	PWM	-	230 V, 50 Hz	600 V, 3 mF	13	L-2.5 mH C-30 μF
[56]	Split DC	Shunt APF	PI	3D-SVM	10	- 50 Hz	650 V -	10	L-3 mH C-10 μF
[57]	Split DC	Shunt PRD	Digitally controlled	-	17.86	185 V 60 Hz	720 V 14.1 mF	20	L- 740 μH
[58]	Split DC	Shunt APF	Model based & Passivity based	-	2	110 V 60 Hz	340 V 2200 μF	18	L- 5 mH

[60]	Split DC	Shunt DSTATCOM	State feedback	Hysteresis Band	15 simulation	100 V 50 Hz	115 V 50 µF	-	L- 26 mH C_{Series}- 65 µF
[62]	Split DC	Series hybrid APF	PI	PWM	-	-	-	5	LC -
[63] [64]	Split DC	Series hybrid APF	PI	Hysteresis Band	-	100 V 50 Hz	100 V 2200 µF	20	L- 13.5 mH C- 50 µF
[65]	Split DC	Series DVR	-	3D-SVM	9	415 V 50 Hz	100 V -	2.4	L- 50 µH C- 2556 µF L_n 500 µH
[66]	Single DC & small AC capacitor	Shunt DSTATCOM	PI	Hysteresis Band	10	50 V 50 Hz	220 V 3300 µF C_N 100 µF	13	L- 10 mH
[67]	Single DC & DC bus +/- connection	Shunt hybrid APF	PI	PWM	-	220 V 60 Hz	130 V 2200 µF	20	L- 19 mH C_{seris} - 41 µF

A similar indirect control over neutral and harmonic content in the neutral wire can also be achieved using a triple single-phase H-bridge configuration, which can provide independent control over each phase and reduce the neutral current using the same configuration, as discussed in the next subsection.

4.2.3 Three single-phase H-bridge (3-HB) converter

The three single-phase H-bridge connection with a single DC link capacitor allows the unbalance compensator to have independent control over all three phases along with indirect control over the zero sequence components as shown in Fig. 7 (a). Control over each phase quantity is possible by controlling each H-bridge as a single-phase unit. Hence, even during fault conditions, such as single- or double-phase faults, it is possible to keep the other phases operating without affecting the DC link capacitor. However, due to the requirement for more switching devices, i.e. 12 switches, it is mainly suitable for high power applications. The 3-HB configuration can be used for both shunt APF [68, 69] and series DVR operations [70, 71]. For shunt APF operation, an equal current synchronous detection (CSD) method is proposed for the 3-HB configuration in [68]. The CSD operates on a per-phase basis by calculating the unbalance voltage and current relationships and sharing the compensation information with other phases. The compensation method ensures equal sharing of real power, line current and load resistance among the three phases. For network balancing operation, the 3-HB converter is controlled using the single-phase p-q theory to achieve a significant reduction in the current unbalance factor, from 40% to 4.76 % [69]. Additionally, the 3-HB APF converter can also be operated in both independent phase control and load unbalance compensation methods. The 3-HB system is designed to work as a dynamic voltage restorer (DVR) using synchronous reference frame (SRF) theory, which extracts the fundamental positive sequence component of two phase voltages to control the PCC voltage [70]. Different configurations, control techniques and modulation processes of a DVR system can be found in [71].

The three-phase three-leg converters, such as split-DC, single-DC and 3-HB, provide simple connection and control methods for multi-functions, however, cannot provide direct control over unbalance components. In most cases, indirect control cannot perform a satisfactory operation to meet the appropriate standards during unbalanced grid supply conditions. Therefore three-phase four-leg power electronics converter topologies with active compensation are presented in the next subsection.

4.2.4 Three-phase four-leg converter (4L)

An established way to provide the neutral point for a 3P-4W system is to add an additional fourth leg (half-bridge) to the conventional three-phase three-leg inverter. The three-phase four-leg topology provides an additional degree of freedom for controlling the neutral current in addition to active and reactive power compensation. The configuration of the four-leg inverter is shown in Fig. 7 (b). The four-leg APF topology was introduced in the early 1980s and has been attracting attention in many application sectors, such as an aircraft variable power supply [72], a power supply for data and IT centres [73], electric vehicle applications [74], multiple AC induction motor control [75], fault tolerance improvement for a permanent-magnet synchronous machine (PMSM) [76], APF [77-80], D-STATCOM

[81-83], DVR to provide voltage support to sensitive loads during voltage imbalances [84, 85], an RES installation with the grid [86-92], stand-alone operation with RES units [93, 94], leakage current elimination from PV installations [95], unified power quality conditioning operation [96-98], matrix converters which can operate under high temperature and pressure [99, 100], medical equipment, and military applications. An extensive review on topologies for a four-leg inverter with multifunctional operations are presented for the grid connected mode in [101] and for the autonomous microgrids in [102]. Various linear and nonlinear advanced control strategies are presented in many studies and are applied to the four-leg inverter, focused on compensation operation for unbalance components and neutral current [103-108]. Different modulation methods, such as pulse width modulation (PWM), sine pulse width modulation (SPWM), 3D space vector etc., are utilized in the literature to provide neutral current and unbalance compensation using novel control methods [109-115]. Most of 3P-4L converters are designed to operate as a voltage source inverter (VSI) where the converter behaves like a voltage source connected in parallel at the PCC. Alternatively, the current source inverter (CSI) utilizes a large DC link inductor instead of a capacitor, and a DC current source connected in series at the DC side to provide the compensation operation, as shown in Fig. 7 (c). The CSI topology provides a higher AC output voltage and requires less DC voltage than the VSI topology [116]. The four-leg CSI topology is used with a bi-directional Z-source converter to reduce the common mode voltage along with the unbalance compensation operation in [116, 117]. However, VSI is preferable for industrial application over CSI due to the faster dynamic response, higher reliability and better efficiency.

In general, the four-leg inverter topology provides superior control over the neutral current, however, the requirement for an additional switching module to operate as the fourth leg and the associated switching losses are the main problems with its extended application. Improper control over the neutral current can cause a high common mode voltage and can cause malfunctions in sensitive electronic appliances. To reduce the common mode voltage at the DC side, a different topology is generally used, combining both the split DC-link and fourth leg in a single three-phase four-leg converter system as discussed in the next subsection.

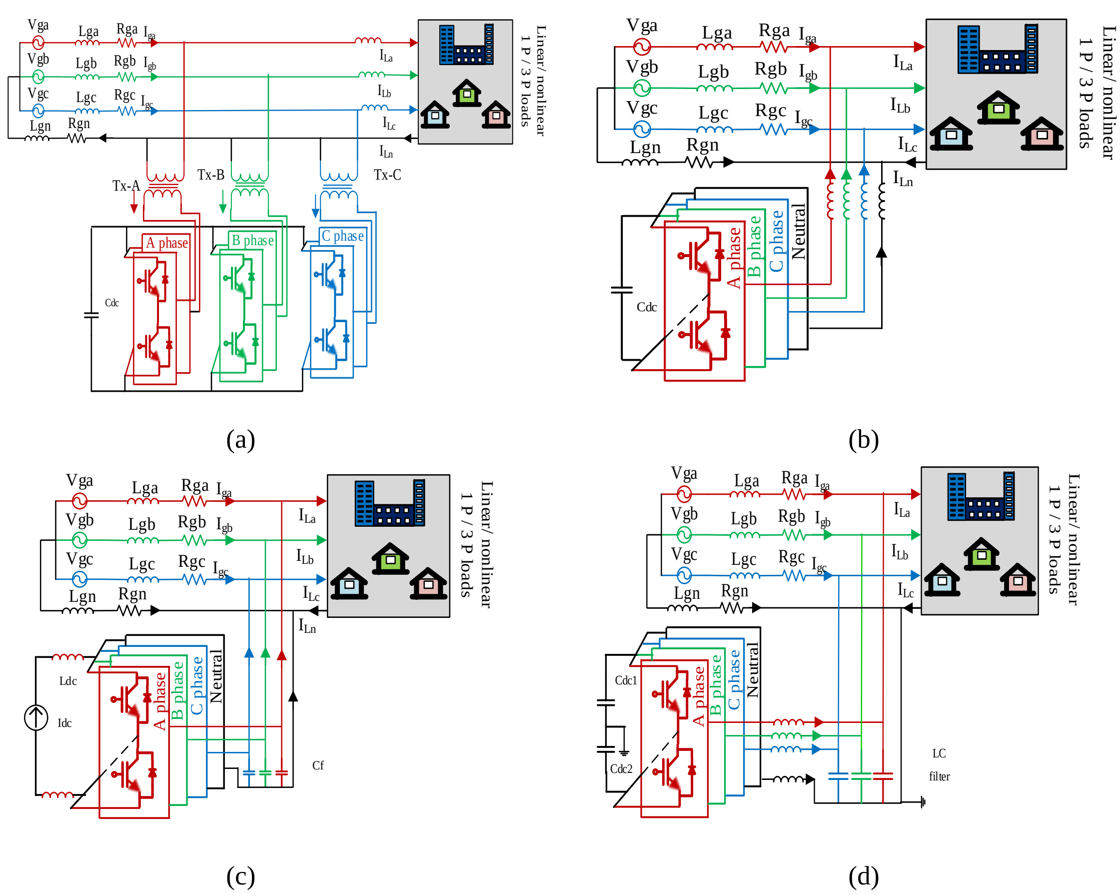

Fig. 7 Three-phase four-leg converter configurations: (a) 3-HB (b) VSI, (c) CSI, and (d) active split DC-link

4.2.5 Three-phase four-leg converter with active split-DC bus (2C)

The combination of the fourth leg and the split-DC capacitor topology is called active split-DC three-phase four-leg VSI as shown in Fig. 7 (d). This topology is used to eliminate the common mode voltage (CMV) created by the continuous modulation operation. Common mode current can cause malfunctions of sensitive devices, such as in aircraft, industrial appliances, motor drives etc. The split DC-link combination is utilized to maintain the common mode to ground voltage at zero potential all the time. The addition of the fourth leg with the split-DC link reduces the switching frequency component in the common mode voltage and actively regulates the CMV to zero [118]. Utilizing this topology, an APF operation is proposed in [119] where the three-phase current quantities are controlled using the split-DC configuration and the fourth leg is controlled to balance the DC capacitor voltages. The proposed constant frequency current control method reduces the size of the DC-link capacitor and eliminates the current ripple problem with a variable switching frequency system. Utilising the H^{∞} controller, the authors in [120, 121] propose a fast acting voltage balancing method at the DC bus in the presence of a high neutral current. The proposed controller provides a high-bandwidth operation which performs better than the dissipative DC voltage balancing method and reduces the size of the DC capacitor. The dual control mode proposed in [121] forces the neutral current to flow via the neutral inductor and improves the stabilisation of the neutral point voltage. The voltage and current controllers are designed to be decoupled in the frequency domain and operated in a parallel mode to outperform classic controllers. The authors in [122] present two relations: (i) load neutral point voltage (LNPV) to the switching states and (ii) the ratio of the neutral inductor to the phase inductors, and propose a modified switching strategy with 16 switching states (four groups) to eliminate the LNPV effectively. Different filter topologies, such as symmetrical and asymmetrical, and modulation techniques, such as triangular and sinusoidal third-harmonic injection, are compared to the control of the fourth leg in [123]. The authors have demonstrated that the connection of the split-DC capacitor and neutral conductor can create an oscillation in the output voltage due to discontinuous modulating signals. In addition, the pure sinusoidal third harmonic injection modulation can provide reduced oscillating output compared to the triangular third-harmonic injection method for nonlinear loads.

The three-phase active split DC-link four-leg inverter is mainly used to stabilize the neutral wire voltage; however, it is most desirable in high power applications which can compensate for the extra cost due to the larger capacitors and the fourth leg switching module. Various three-phase unbalance compensation topologies are compared in Table 5. A different type of neutral compensation method with battery charge and discharge operation via a power electronics converter is discussed in the next subsection.

Table 5 Comparison of 4L, 2C and 3-HB configurations [18, 124]

Parameter	Capacitor mid-point (2C)	Four-leg (4L)	3-HB
V_{DC}	Highest (2.8 × Vrms)	Medium (2.4 ×Vrms)	Lowest (1.4 × Vrms)
C_{DC}	Highest 2 C_{DC}	Low 1 C_{DC}	Lowest 1 C_{DC}
I_{rms} through C_{DC}	Highest	Medium	Lowest
Energy stored (C_{DC})	Highest	Low	Lowest
Neutral current	Full neutral current through C_{DC}	Direct control by the fourth leg	Indirect control by phase balancing/ harmonic compensation
Additional sensor	Extra DC bus voltage	Extra neutral current for the fourth leg	None
No. of switches	6	8	12
Switching device power	Low	Highest	Low
Switching device rating	High voltage	Unequal rating for the fourth leg	Equal rating
Isolation transformer	No	No	Yes
Modulation	Sine PWM	3D-SVM and/or *dq0*	Single phase

Size/weight	Medium	Low	High
APF control	Indirect	Indirect	Indirect
CUF	Highest	Lowest	Low
Neutral current mitigation	Degrade performance with unbalanced DC voltage	Better than 2C and 3HB	Better than 2C
Cost	Lowest	Higher than 2C	Highest
Application sector	Low or medium power application	Low or medium power application	Medium to high power application
RES integration	Not common	Common	Not common

4.3 Unbalance compensation via battery energy storage

Proper modelling of a three-phase four-wire system is necessary to evaluate the effect on a multi-grounded system of the unequal allocation of RESs and their injected powers into the network. The authors in [26] present a 3P-4W power flow model considering the neutral wire admittance, and analyse the effects of a single-phase PV power injection into the neutral current and neutral to ground voltage. The aforementioned issue with unbalanced PV allocation is mitigated using community energy storage (CES) in [125] and distributed energy storage (DES) in [7]. The application of the CES and the DES is shown in Fig. 8.

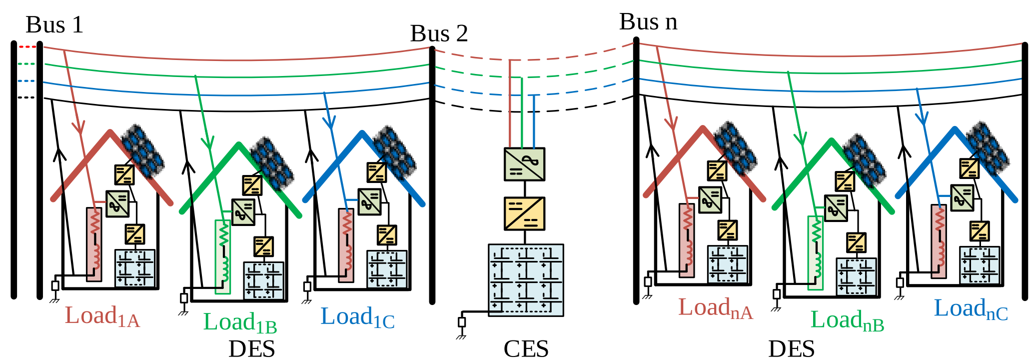

Fig. 8 CES and DES connection diagram

In both of the papers, the authors designed a charge/discharge algorithm to mitigate the unbalance issues by continuously adjusting the power exchange from the energy storage unit. A significant reduction of the neutral current and neutral to ground voltage is presented, however, harmonic characteristics are not considered in the design process. Also, no comparative results are presented to distinguish the improvement from the neutral compensation operation compared to other power electronics based methods.

5. Comparative analysis for unbalanced systems

This section demonstrates the generation and compensation effects of the neutral current using typical residential and commercial loads with parameters collected from Energex, a local DNO, and Griffith University, Australia respectively. Both types of load data are used in PSCAD/EMTDC software with a 44-bus distribution network model designed by Energex, Australia as shown in Fig. 9. Details about the network can be found in [126].

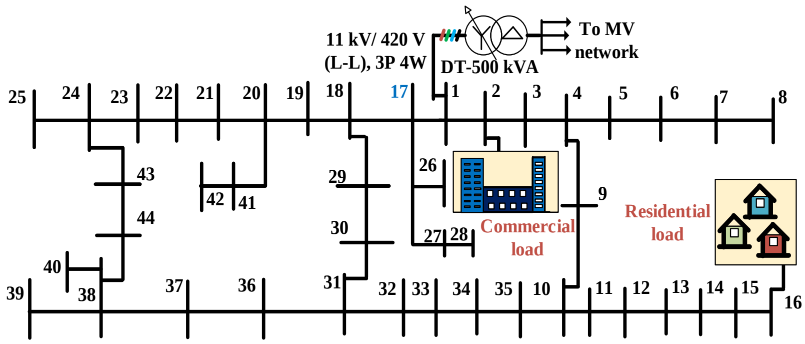

Fig. 9 44-bus Energex 3P-4W network

The residential and commercial load characteristics (active and reactive power) are shown in Fig. 10 over a 24-hour period with a 1 second resolution and a 5 ms simulation time step. The residential customer data is considered to the farthest point (420 m) from the DT, however, the commercial load is considered close to the DT (50 m) to represent actual network characteristics. The comparative analysis is presented focusing on five unbalance effects: (i) neutral current, (ii) phase unbalance, (iii) unbalance factor, (iv) NGV rise, and (v) neutral shift.

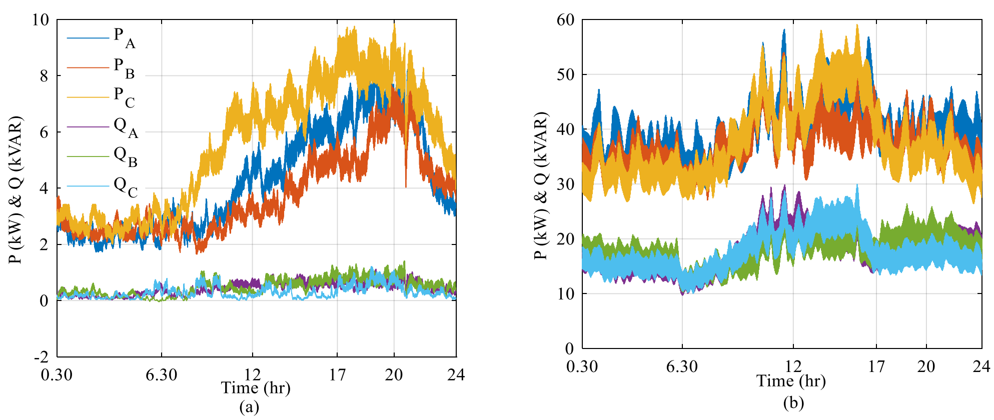

Fig. 10 (a) Residential, and (b) Commercial load profiles

The neutral current effect is shown in Fig. 11, and it is evident that the peak load demand occurs from 17- 21 hr and 10-17 hr for residential and commercial customers, respectively. The residential load profile shows more unbalance than the commercial load and causes a significant neutral current. It is noted for the LV distribution network that, even without the additional load connection, there are some neutral current flows via the fourth wire as shown in Fig. 11 (a) and (b) as Case (a). The neutral current from both the residential and commercial loads are shown as Case (b) in Fig. 11. The neutral compensation from passive and active compensation devices are shown in Case (c) and Case (d) respectively. The zig-zag transformer (ZT) and four-leg D-STATCOM are designed and used to apply passive and active neutral compensation at the PCC. The 3P-4L D-STATCOM is designed to operate with 14 kVA capacity and the ZT with 3 kVA for residential and 10 kVA for commercial loads. Details about the control methods are presented in [92]. It can be seen from Fig. 11 that the load generated neutral current on both of the load profiles can be significantly improved using the active compensation method. As the commercial load is connected quite close to the DT, installing additional neutral compensation devices would not be required. However, getting an additional feature from four-leg smart inverters with RES installations can definitely benefit the load profiles, as can be seen from Fig. 11.

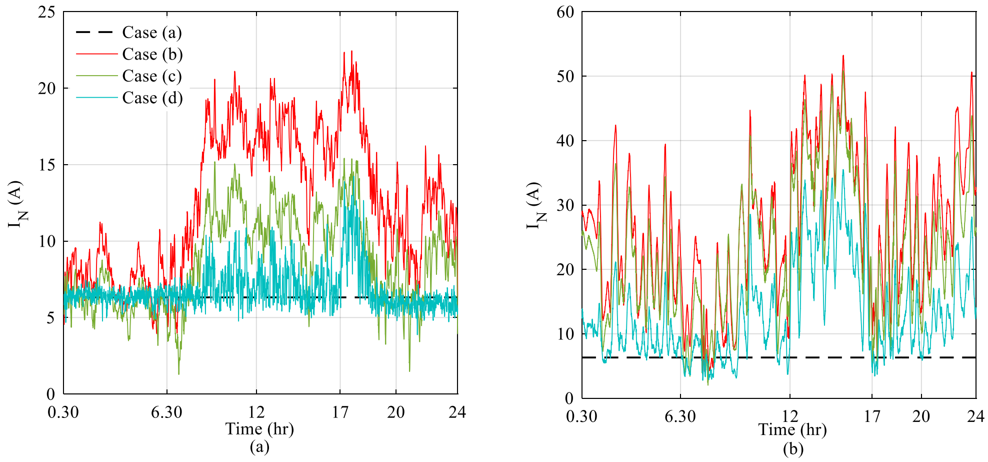

Fig. 11 Neutral current compensation for (a) residential, and (b) commercial loads

Phase unbalance is another reason for a high neutral current. Therefore, balancing the phases can reduce the neutral current effectively, as demonstrated using the battery discharge operation in [26], [125]. Alternatively, compensating the neutral current can also improve the phase unbalances as shown in Fig. 12 from 20-21 hr. In Fig. 13, only the phase currents from residential loads are shown due to their more dynamic characteristics than the commercial loads. The phase balancing operation is compared between passive and active neutral compensation in Fig. 13, and it is evident that active neutral compensation provides a better phase balancing operation. The active compensator redistributes the neutral current among the phases, which results in better phase balancing and a reduction in the CUF. According to [127], the voltage negative sequence unbalance has to be less than 3% for average 10-30 minute intervals and can exceed once in 1-hour periods. Therefore, the VUF and CUF performance with both compensators considering the zero sequence component is shown in Fig. 13 (a) and (b) respectively. It can be seen that active compensation can keep the VUF less than 3% and can improve the CUF by more than 5% around the 20-21 hr period compared to the other method [92].

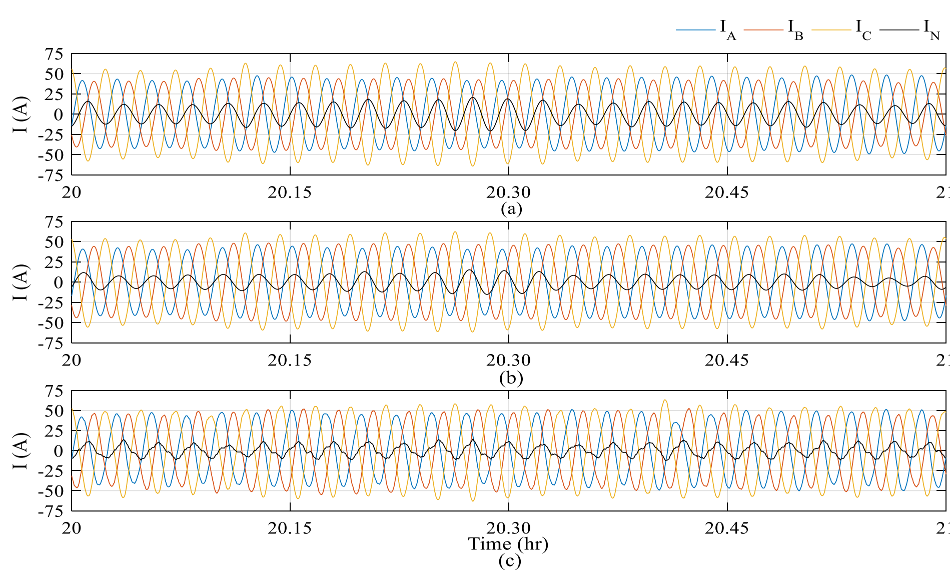

Fig. 12 Load currents (a) without compensation, (b) with passive, and (c) with active compensation

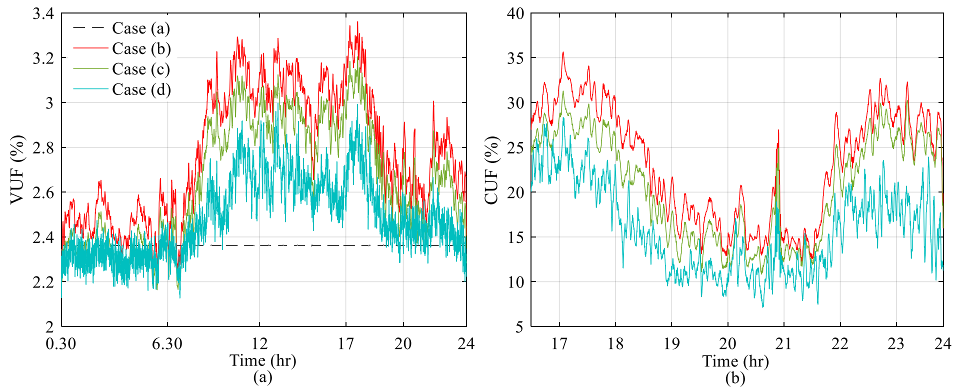

Fig. 13 (a) VUF, and (b) CUF for residential customer at PCC

Another important concern with the unbalanced distribution system is the neutral to ground voltage rise issue as discussed in Section 3 and shown in Fig. 14. It can be seen from Fig. 14 that an unbalanced load distribution in the residential area can cause up to a 2.6 V NGV rise at around 17 hr. Both compensation methods can reduce the NGV rise by more than 1 V, however, the active method compensates by 1.8 V more than the passive method at 17 hr. The improvement in the NGV compensation also improves the neutral shift issue as shown in Fig. 14 (b). The voltage unbalances cause the neutral potential to rise and shifts the zero-neutral point further from the balanced condition as shown in Fig.14 (b) [128]. Compensating the neutral current results in a reduction of the NGV and moves the zero-neutral point close to the actual zero potential, resulting in a reduction in the VUF and better power quality.

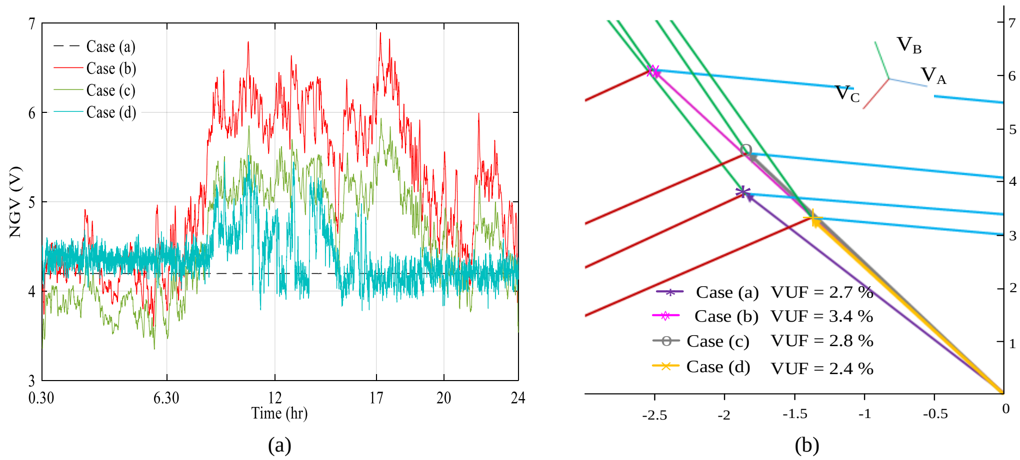

Fig. 14 (a) NGV at PCC, and (b) Neutral shift problem

From this comparative analysis, it can be concluded that the neutral compensation methods, especially the power electronics converter based ones, can significantly improve major unbalance issues, however, the final selection of the compensation device depends on the application, power level, and associated cost of the overall system [129].

6. Future research directions and discussion

The increasing amount of non-dispatchable RESs, together with growing and diverse linear and nonlinear loads and their asymmetric distribution among the three phases, ensure that converter-based active neutral compensation devices are inevitable for modern distribution networks. Thus far, this paper presents a thorough review of the configurations, control objectives, methodologies and parameters related to the existing power electronics converter based techniques appearing in the recent literature. In this section, future directions with discussion about the trend of active neutral compensation techniques are presented:

6.1 Harmonic considerations

With more interfacing of semiconductor-based renewable sources, energy storage systems and nonlinear loads, issues related to power quality and harmonics are an imperative research topic. Harmonics and unbalanced networks have already become a prime concern for the distribution operators, and the situation may be aggravated in the near future with a high demand for single-phase electric vehicle charging systems. There is a correlation between neutral current compensation and the harmonics in a system. As most of the unbalance compensators are not operated to their full capabilities, these devices can be utilized in a smart fashion using appropriate control to improve the harmonic content and the power quality. Auxiliary services, such as power factor correction, flicker mitigation and harmonic compensation, can be integrated with these devices along with the primary objective of voltage/current unbalance compensation.

6.2 Configuration of active neutral compensation techniques

This paper depicts some prevalent configurations of power electronics converter based techniques available in the recent literature. Even though the three-phase three-leg converter-based compensation techniques are predominantly deployed to tackle power quality issues due to their simple structure and control methods, single-phase APF and three-phase four-leg compensation techniques have the potential of improving neutral current compensation. Appropriate configurations of compensators also rely on their respective applications. Moreover, recently semiconductors, such as silicon carbide and gallium nitride based MOSFETs, are installed instead of IGBT switches, which improves the efficiency and the switching performance of the power electronics based compensators. However, the cost-performance trade-off is always an issue when deploying new semiconductor based devices with multiple switches. As a result, designing a cost effective and efficient configuration of an unbalanced compensator can be an interesting research topic.

6.3 Communication assisted control

The smart grid will be composed of several components connected to each other via low bandwidth communication networks. A high penetration of converter dominated renewable energy resources will ensure a high participation of semiconductor-based active neutral compensation devices. Due to the emergence of the concept of the internet of things (IoT), these devices are likely to be communicating with each other via either centralised or distributed communication links. Therefore, a wireless communication assisted control framework can be considered to enhance the reliability and efficiency of the overall compensation techniques [130]. For instance, distributed cooperative control, master-slave control, game theory-based cooperative control, distributed finite-time control etc. can be utilised to ensure reliable communication assisted control. However, there are cyber-physical security issues associated with these communication-based control frameworks which require novel techniques of identifying intruders and malicious data. All things considered, undoubtedly communication will play a vital role in unbalance compensation techniques and need further investigation.

6.4 Parallel operation

Multifunctional converters or active compensating devices are predominantly connected in parallel to share loads among themselves. Usually decentralised droop control is used to share power among multiple converters. Some modified droop control structures, such as harmonic droop and neutral current droop, are presented in the literature to share the harmonic content and neutral current. In order to share neutral current among several active compensating devices, decentralised, distributed and centralised control approaches can be adopted. Parallel connected converters can operate in a power control mode, DC bus voltage or AC bus voltage regulation mode. It is unlikely that all the parallel connected converters operate in the same control mode. The correlation and cooperation among multiple parallel connected converters operating in different modes to achieve a certain objective require extensive research. Moreover, the implications of these control structures in grid-tied and microgrid conditions need to be considered in future research.

6.5 Pulsed load management

A pulsed load can be harmful, particularly in industrial or commercial distribution networks. A pulsed load requires a large amount of power within a very short span of time (within some microseconds). If a large number of pulsed loads are turned on simultaneously that may create a devastating transient phenomenon in the system. Particularly, single-phase pulsed loads will generate a huge amount of neutral current for a short time, which may damage the distribution transformer and/or the converters connected to the grid. Active neutral compensators can play vital roles in mitigating this phenomenon. However, further research is needed on whether their pulse load withstanding capabilities can be improved using appropriate control methods, configurations or particular semiconductor-based devices.

6.6 Integration of transactive energy system

Apart from the technical considerations, power electronics based converters can play an important role from the economic standpoint. Passive neutral compensation devices can only contribute to one objective, on the other hand, active devices can be multifunctional. For instance, these devices can also be utilised to achieve economic objectives. Multiple active compensation devices connected in parallel can cooperatively share power among themselves using droop control or any other power sharing methods. This process can be made more optimized and economic if cost functions with necessary constraints can be integrated. Furthermore, these devices can provide several ancillary services to the grid which benefits both the owners and the grid operators. These devices can also contribute to shaping smart transactive building energy management systems. However, these economic issues need to be addressed appropriately when their large-scale deployment is considered.

6.7 Smart inverter with variable capacity operations

Generally, for three-phase three-wire balanced networks, the power electronics converter's total capacity is distributed for active and reactive power regulation [131, 132]. However, with 3P-4W unbalanced networks, the available capacity after active and reactive operations can be utilised for higher capacity unbalance compensation operations as presented by unbalanced power theory [133, 134]. Utilizing the capacity distribution concept, multifunctional power electronics compensators can prioritise their operation and achieve better compensation performance than fixed capacity compensators.

6.8 Participation in isolated power grid or microgrid

In the grid-tied mode, the grid operates as a slack bus and regulates both voltage and frequency, while multifunctional converters work as power regulators. However, during islanded conditions, multifunctional converters have to work primarily as voltage and frequency regulators. As a result, additional control objectives are added to achieve stability [135]. Therefore, off-grid active neutral compensation techniques are becoming recent research trends. Researchers can address a unified control or a configuration that can achieve all the requirements to achieve stable microgrid operation as well as the primary objective of compensating for the unbalanced conditions.

7. Conclusions

Neutral current is caused by unequal distributions of both linear and nonlinear loads as well as high penetration of RES units in distribution networks. While it is not compensated, it can cause voltage unbalance issues, harmonics generation, ground voltage rise and/or safety concerns at customer points. This paper reviews the relevant passive and active solutions and provides a comprehensive review on reduction of neutral current using different state of the art power electronics based active compensators. The challenges associated with the unbalanced three-phase four-wire networks are pointed out and relevant international standards are discussed in the initial sections of the paper. Later on, a comprehensive overview of the configurations and control strategies of converter-based unbalance compensation techniques are presented separately for both single- and three-phase systems. Passive unbalance compensation methods provide simple solutions, effective for small leakage current elimination. However, most of the passive compensators are bulky and expensive, and need to be installed close to the load centre. On the other hand, the active compensators (three- and single-phase) provide fast unbalance compensation without the requirement of additional magnetic transformers which reduce the costs. In addition, active unbalance compensators can be facilitated with different functions such as active power filtering and voltage regulation, along with unbalance compensation. However, the active compensators can cause high switching losses, and require proper control design to follow network connection standards. In order to validate the use of converter-based neutral compensation techniques, comparative case studies are presented to show the unbalanced scenario in the presence of real-time residential and commercial load profiles, and the post-compensation state of the network. The comparative case studies verify the superior performance of active unbalance compensation methods for different load conditions. However, depending on the load requirement, such as faster or slower compensation, and location in the connected network, i.e. closer to or further from distribution transformer, both passive and active can be an effective solution to network unbalance problems. As a final point, some promising research directions are set forth for further exploration in the field. It is expected that this paper will be a useful reference for researchers and engineers in both academia and industry.

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