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## Parallel Operation of Inverters and Active Power Filters in Distributed Generation System: A Review

Shafiuzzaman Khan Khadem

*Technological University Dublin, skkhadem@gmail.com*

Malabika Basu

*Technological University Dublin, mbasu@tudublin.ie*

Michael Conlon

*Technological University Dublin, michael.conlon@tudublin.ie*

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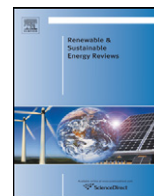
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# Parallel operation of inverters and active power filters in distributed generation system—A review

S.K. Khadem\*, M. Basu, M.F. Conlon

School of Electrical Engineering Systems, Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland

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### ABSTRACT

In this paper a technical review of parallel operation of power electronics inverters for load sharing conditions in distributed generation (DG) network is presented. Emphasis is given to parallel operation of Active Power Filters (APFs) as they are widely used to mitigate load current disturbances into DG networks. Discussions on recent advances in control strategies as applied to APFs are presented.

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### 1. Introduction

New control, operation and management strategies are being developed to connect the increasing number of distributed

generation devices into the grid or microgrid in order to maintain or improve the power quality of the distribution system. Therefore, control of DG inverters is essential not only to supply the active power but also to manage of reactive power. Parallel operation of multiple inverters with low capacity has been introduced instead of the high capacity single units, to add flexibility and reliability in operation.

Increasing numbers of harmonic or sensitive loads are leading to more Active Power Filter (APF) application. Similarly, parallel

\* Corresponding author. Tel.: +353 1 402 2814; fax: +353 1 4024992.  
E-mail addresses: [skkhadem@gmail.com](mailto:skkhadem@gmail.com) (S.K. Khadem), [mbasu@dit.ie](mailto:mbasu@dit.ie) (M. Basu), [michael.conlon@dit.ie](mailto:michael.conlon@dit.ie) (M.F. Conlon).

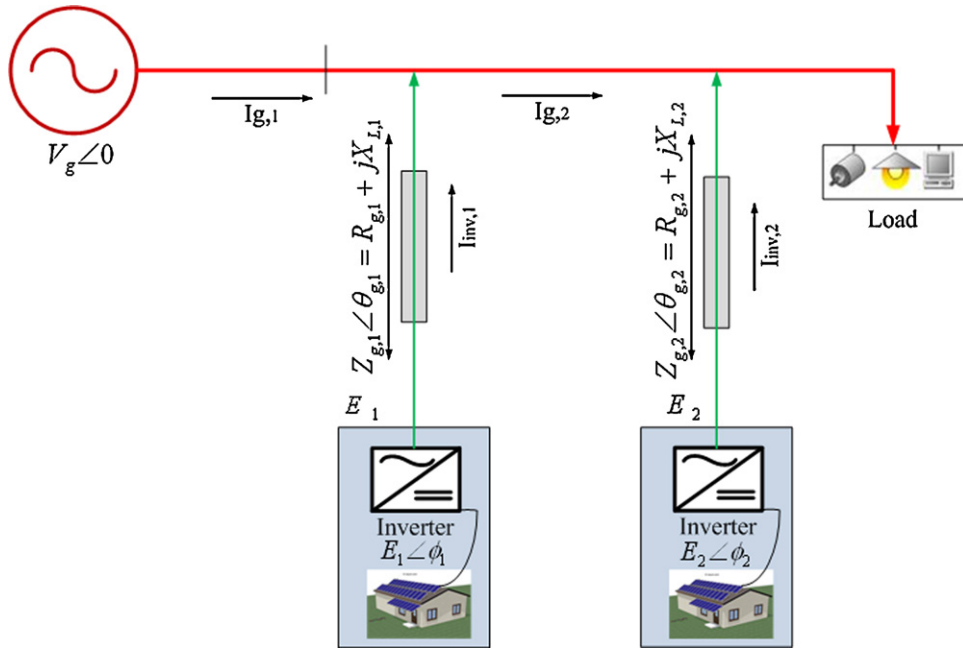


Fig. 1. Equivalent circuit of parallel inverter connected to the grid.

operation of APFs and their control strategies are being given more emphasis for compensating high levels of harmonic and reactive current in the distribution network.

In this paper, these new trends in parallel control of inverters and APFs to cope up with increasing capacity are discussed. The paper is organized as follows: In Section 2, the principle of parallel operation of inverters with their possible problems is discussed. Active load sharing and a droop control method for parallel operation of inverters is presented in brief in Section 3. It is found that droop control is very suitable for both DG and off-grid conditions. Section 4 deals with the working principle of the droop control method. Section 5 presents a discussion on the application of parallel inverters in DG or in a microgrid. Control strategies for parallel operation of APF are presented broadly in Section 6. Finally, concluding remarks are made in Section 7.

## 2. Principle of parallel operation of inverter

Balance between generated and consumed real ( $P$ ) and reactive ( $Q$ ) power indicates the stable operation of a power system. Therefore, implementing effective control over  $P$  and  $Q$  is very important from the operational and control points of view. The real ( $P_1$ ) and reactive ( $Q_1$ ) power transferred from the inverter to the common bus or grid can be calculated as described in [1] and from the following diagram, as shown in Fig. 1;

$$P_1 = \left[ \left( \frac{E_1 V_g \cos \phi_1}{Z_{g,1}} - \frac{V_g^2}{Z_{g,1}} \right) \cos \theta_{g,1} + \frac{E_1 V_g}{Z_{g,1}} \sin \phi_1 \sin \theta_{g,1} \right] \quad (1)$$

$$Q_1 = \left[ \left( \frac{E_1 V_g \cos \phi_1}{Z_{g,1}} - \frac{V_g^2}{Z_{g,1}} \right) \sin \theta_{g,1} - \frac{E_1 V_g}{Z_{g,1}} \sin \phi_1 \cos \theta_{g,1} \right] \quad (2)$$

Here  $E_1$  and  $V_g$  represent the inverter output voltage and grid voltage, respectively. For only real power transfer,  $V_g$  and  $E$  should have the same amplitude with a phase angle difference. Different amplitude of voltage with the same phase will give a reactive power circulation. When both of the magnitude and phase angle differ between the two voltage sources, it causes real and reactive power flow. Control of frequency dynamically controls the power angle and hence, the real power flow. As the output impedance of the

inverter is very low, a small change in  $\phi_1$  (phase difference between the inverter and grid voltage) could result a very large imbalance in the active power flow [2]. For parallel operation, the output voltage of all inverters must be kept strictly in phase in order to guarantee equality of the output active power for the corresponding inverters. Reactive currents can still circulate between inverters, as shown in Fig. 2, if their output voltage magnitudes differ from each other and this can overload the inverters unnecessarily.

To suppress the circulating current and prevent the dc-link over-voltage, an isolation transformer can be used as a passive control measure, as shown in Fig. 3(a) [3–5], but then the size of the transformer for high power application could be a problem. Some active methods, such as zero-sequence current control loop, coordinate control, and space vector modulation control are also described in [6–8] respectively. A simple protective control algorithm, as shown in Fig. 3(b), has also been proposed in [9] where the regeneration protection concept based on the rising dc-link voltage is considered. If  $V_{dc}$  is greater than  $V_{dc,ref}$ , the converter stops delivering power from the battery/dc side. Here a proportional controller detects the error signal of the dc-link voltage.

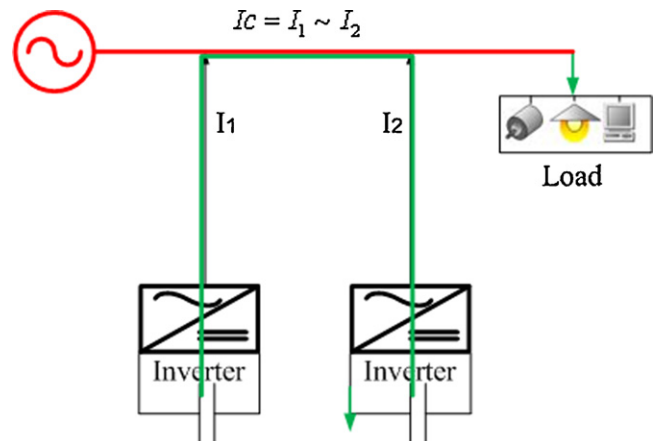


Fig. 2. Circulating current flow between the parallel inverters.

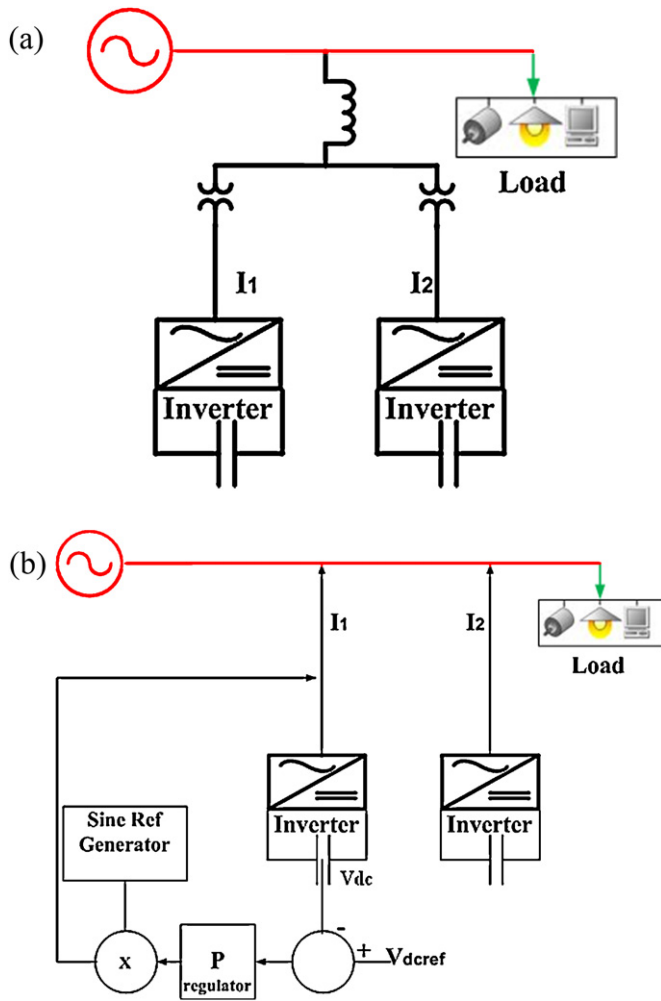


Fig. 3. (a) passive control using isolation transformer; (b) Regenerative control structure to avoid dc-link overvoltage/to prevent circulating current.

### 3. Control strategies in parallel operation of inverters

In distributed generation (DG) systems, either connected to or off the grid, there may be more than one inverter acting in parallel. Therefore, distributed uninterruptible power supply (UPS) systems as well as the parallel operation of voltage source inverters with other inverters or with the grid, are sensitive to disturbances from the load or other sources and can easily be damaged by over-current. Hence, careful attention should be given to system design and the control of parallel operation of inverters. Several control methods are proposed and discussed in [3,10–22]. When two or more inverters operate in parallel, the following features must be achieved: (1) amplitude, frequency and phase synchronization among the output voltages of inverters, (2) proper current distribution according to the capacities, (3) flexibility and (4) hot-swap feature at any time [14].

Some of the outcomes of recent research on parallel operation of inverters are given below. The conventional control strategies for the parallel-connected inverters can be classified into two types: active load sharing/current distribution and droop control.

#### 3.1. Active load sharing/current distribution

The objective of the active current distribution control is to generate a reference current for each parallel-connected inverter and this can be subdivided into;

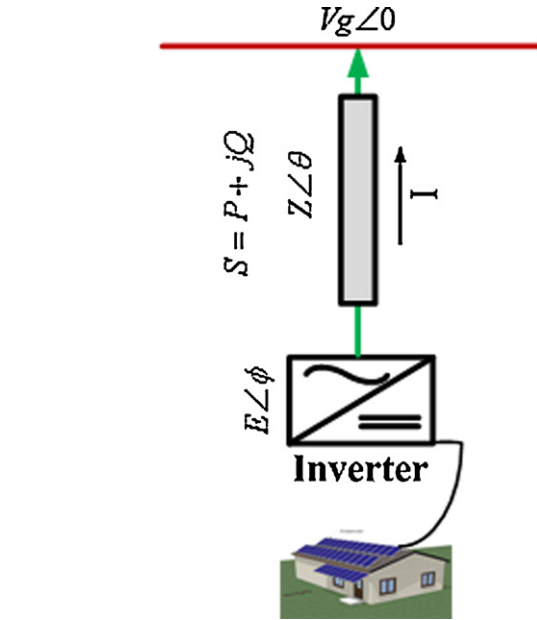


Fig. 4. Inverter connected to the grid.

- (i) central limit control (CLC);
- (ii) master–slave control (MSC);
- (iii) average current sharing (ACS)/distributed logical control (DLC);
- (iv) circular chain control (3C).

In CLC mode, all the modules should have the same configuration and each module tracks the average current to achieve an equal current distribution [14]. Perfect and equal current distribution can be achieved by using DSP-based control for the voltage and current controller and by tracking the averaged inductor current of the inverters. Thus the system stability and robustness can be improved [15].

In the MSC method, one inverter is specified as the master, and all others are as the slaves. The master inverter supplies a reference current to the slave inverters. Thus the master module is responsible for the output voltage regulation [16]. In such a system, if the master module fails, the system will shut down. This is a major drawback. This can be partially overcome by introducing a separate current-controlled PWM inverter unit to generate the distributing current independent for the slave inverters. Hence, precise current division between the inverters are very important. This strategy is easy to implement in the parallel operation of UPS [11]. In other cases, another module can take the role of master in the event of a main master unit failure. The control scheme can be of dedicated, rotary or high-crest current type [17].

In the MSC and CLC methods, the output currents of all parallel-connected inverters must be collected, and the number of parallel-connected inverters must be pre-known. If one of the parallel-connected inverters fails, the parallel-connected system will fail. This problem can be overcome by the DLC mode where redundancy is also achievable.

In the ACS/DLC mode, an individual control circuit is used for each inverter. The current control mode is used to control its output current and to trace the same average reference current. When a defect is found in any module, others can still operate in parallel [18–20]. It can also be used as a power-sharing technique where each inverter controls the active and reactive power flow in order to match the average active power of the system [21].

In the 3C mode, the successive module tracks the current of the previous module to achieve an equal current distribution, and the

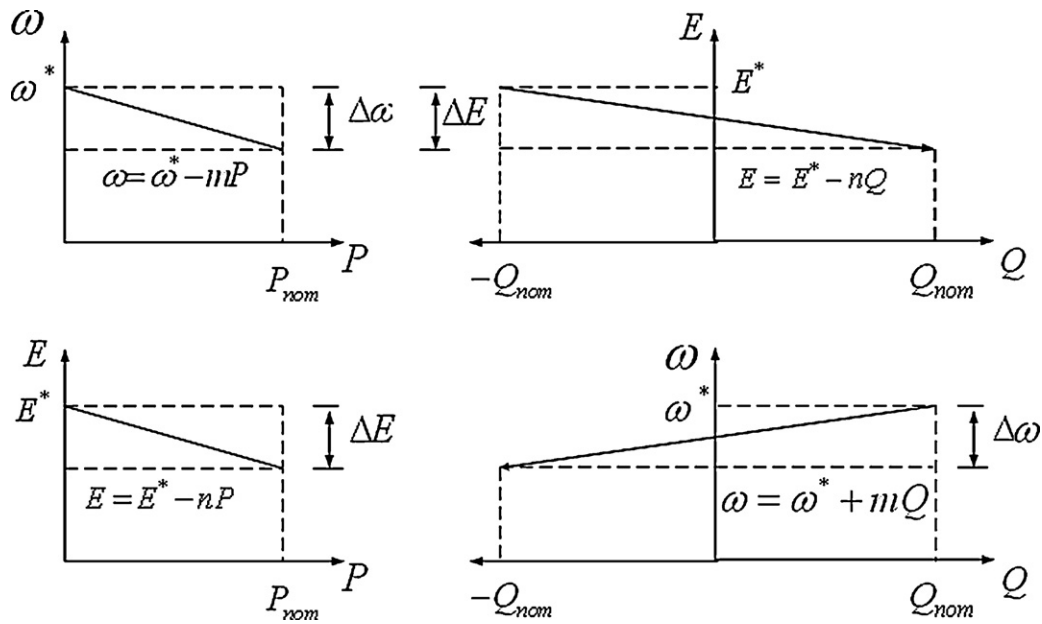


Fig. 5. Static droop characteristics P- $\omega$  and Q-E.

**Table 1**  
Output impedance impact over power flow controllability [26].

Output impedance ( $Z$ )	$Z = jX$ (inductive: $\theta = 90^\circ$ )	$Z = R$ (resistive: $\theta = 0^\circ$ )
Active power ( $P$ )	$P = \frac{EV}{X} \sin \phi \cong \frac{EV}{X} \phi$	$P = \frac{EV \cos \phi - V^2}{R} \cong \frac{V}{R}(E - V)$
Reactive power ( $Q$ )	$Q = \frac{EV \cos \phi - V^2}{X} \cong \frac{V}{X}(E - V)$	$Q = \frac{EV}{R} \sin \phi \cong -\frac{EV}{R} \phi$
Frequency droop ( $\omega$ )	$\omega = \omega^* - mP$	$\omega = \omega^* + mQ$
Amplitude droop ( $E$ )	$E = E^* - nQ$	$E = E^* - nP$
$m$	$\Delta\omega/P_{nom}$	$\Delta\omega/2Q_{nom}$
$n$	$\Delta E/2Q_{nom}$	$\Delta E/P_{nom}$

first module tracks the last one to form a circular chain connection. The output voltage and current of each inverter can also be varied and internally controlled to achieve a fast dynamic response [13]. A coordinated control strategy for different load sharing controls can be implemented to eliminate the circulating currents due to unbalance of parallel inverters [22].

### 3.2. Droop control

The droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as wireless control (WC) with no interconnection between the inverters. In this case, the inverters are controlled in such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities [23].

This technique is then improved for non-linear load where harmonic components can be shared properly [24]. The impact of line impedance on reactive power sharing in the conventional frequency/voltage droop concept is further enhanced in [25] to make the controller ideally suited for distributed ac power supply systems.

### 3.3. Outcomes

A detailed review and performance comparison of these control strategies has been presented in [26] which shows that within active load sharing control schemes, current-sharing control is good for output voltage regulation and harmonic current control. However it requires high speed communications. Active power sharing requires low bandwidth communication for active and reactive power sharing, but the harmonic power sharing is poor and therefore sharing non-linear loads with a high crest factor is a

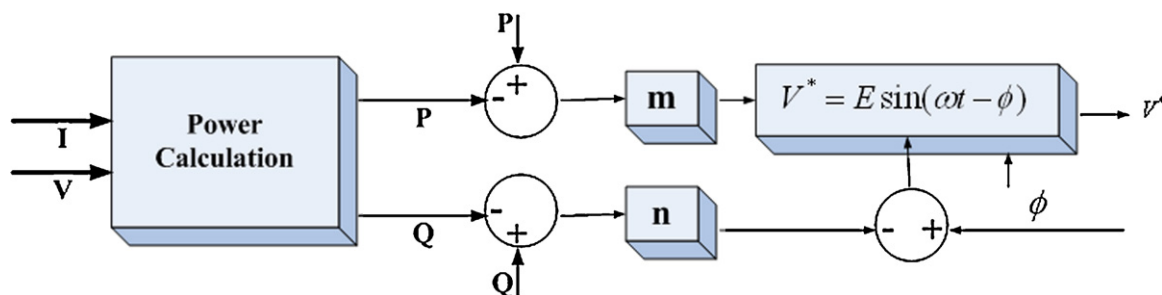


Fig. 6. A simple block diagram of P/Q droop controller.

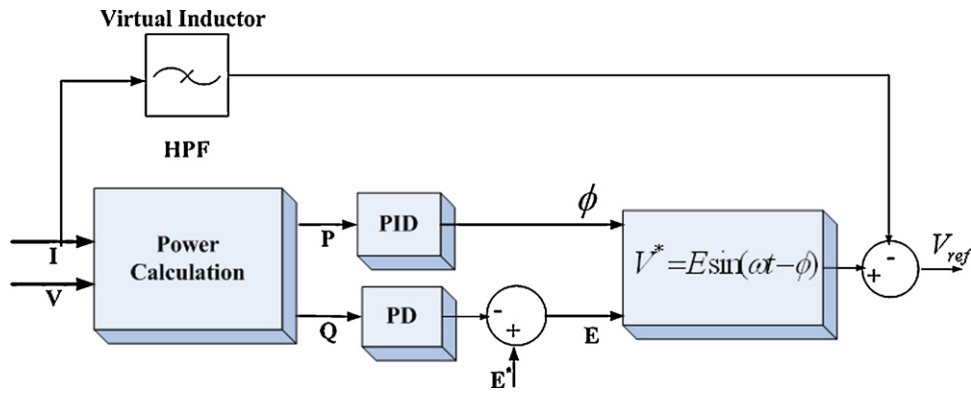


Fig. 7. PD and PID based conventional droop control to improve the transient performance.

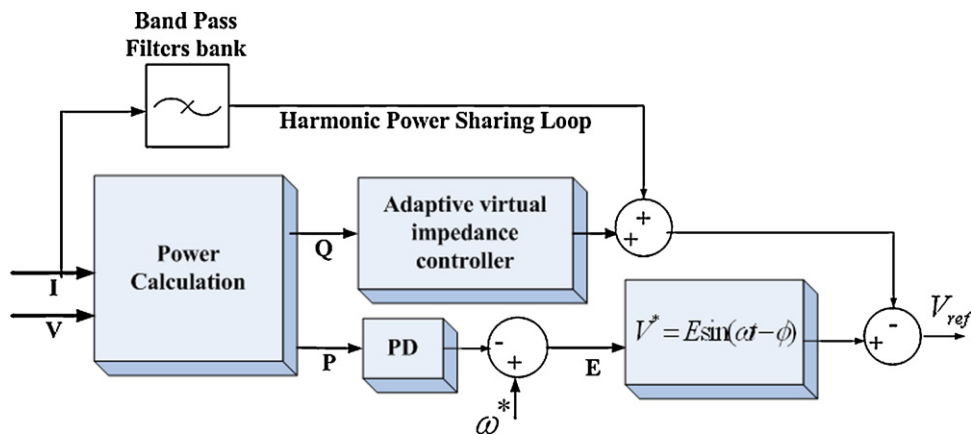


Fig. 8. Adaptive Virtual Impedance controller in droop control scheme.

problem. Active synchronization is also a major problem for both the schemes.

Within the active load sharing scheme, the centralized and the master–slave controller need a main inverter module to be set as the central control unit and this would lower the system reliability. Modularity and redundancy are very low for both of the controllers. The average current sharing/distributed logic controller, for which there is no central controller and thus has higher modularity, requires a current sharing control loop to manage the transient and stability problems. The circular current control strate-

gies require more communication between each of the inverters as well as a circular path for current distribution. This is suitable when forming an ac power ring.

In general, while the active current distribution control method is perfect for well balanced current distribution, the inter-communication process of the generated reference current of parallel-connected inverters can be subject to interference, and thus the system reliability will be degraded. In addition, the communication of the reference current among the parallel-connected inverters is difficult in some applications such as a distributed generation system.

On the other hand, droop control or the wireless control with no interconnection of lines could be more useful for either active load sharing or for a distributed generation network connected to the grid or off-grid. Some improvement in control has also been achieved to overcome its limitations such as poor transient response. Hot-swap operation is another benefit of using the droop control method. Low sensitivity to line impedance unbalances and harmonic power sharing capability are the other advantages of a droop controller.

#### 4. Working principle of droop control method

The idea of the droop control method in the parallel operation of an inverter or APF is to control the system without interconnection between each other. Inverters can be placed in different locations within the microgrid or the DG system. In that case, the droop control method is very effective for inverters where active and reactive power flow predominantly depends on power angle/frequency and the output voltage amplitude of the inverters. Here, inverters are generally operated in the voltage-mode control and the phase and

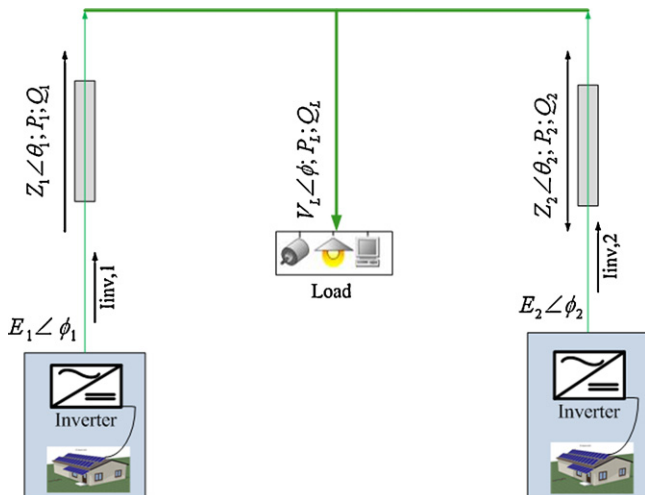


Fig. 9. Power sharing through droop control method.

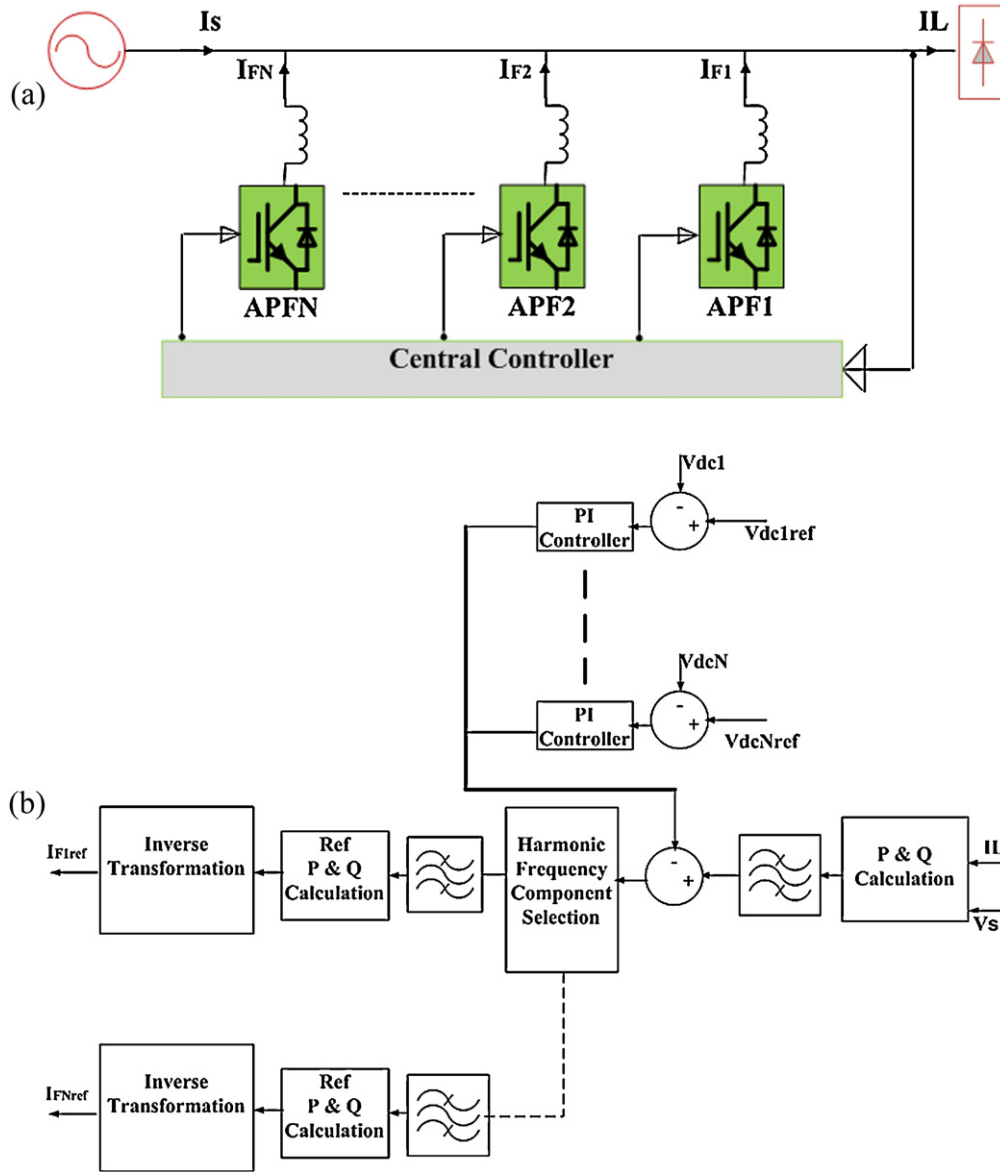


Fig. 10. (a) Centre Mode Control Technique; (b) Reference Current Generation technique for Frequency Splitting Control.

amplitude of the output voltage of the inverters are the control parameters. The controller is defined in such a way that the amplitude and frequency of the reference voltage signal follow a droop as the load current increases.

An inverter connected to the common bus through a decoupling impedance is shown in Fig. 4. Usually the inverter output impedance is highly inductive, and hence the active and reactive powers drawn to the bus can be expressed from Eqs. (1) and (2) as [1];

$$P = \frac{EV}{X} \sin \phi \quad (3)$$

$$Q = \frac{EV \cos \phi - V^2}{X} \quad (4)$$

where  $X$  is the output reactance of an inverter,  $\phi$  is the phase angle between the output voltage of the inverter and the voltage of the common bus,  $E$  and  $V$  are the amplitude of the output voltage of the inverter and the grid/load voltage, respectively. From the above equations, it is found that the active power is predominately dependent on the power angle  $\phi$ , while the reactive power mostly

depends on the output-voltage amplitude  $E$ . Consequently, parallel operation of inverters in wireless-control mode uses the conventional droop method, which introduces the following droops in the amplitude  $E$  and the angular frequency  $\omega$  of the inverter output voltage [23];

$$\omega = \omega^* - m(P_{0i} - P_i) \quad (5)$$

$$E = E^* - n(Q_{0i} - Q_i) \quad (6)$$

$\omega^*$  and  $E^*$  are the output voltage angular frequency and amplitude at no load, and  $m$  and  $n$  are the droop coefficients for the frequency and amplitude, respectively.  $P_{0i}$ ,  $P_i$  and  $Q_{0i}$ ,  $Q_i$  represent the power rating and actual power output for active and reactive power, respectively. If droop coefficients are increased, then good power sharing is achieved at the expense of degrading the voltage regulation, which can be acceptable if the frequency and amplitude deviations ( $\Delta\omega$  and  $\Delta E$ ), as shown in Fig. 5, are typically 2% and 5%, respectively [27].

The droop control law is determined by the output impedance angle  $\theta$ , as shown in Table 1. Fig. 5 also shows the droop control functions depending on the output impedance. Here  $m$  and  $n$ , the

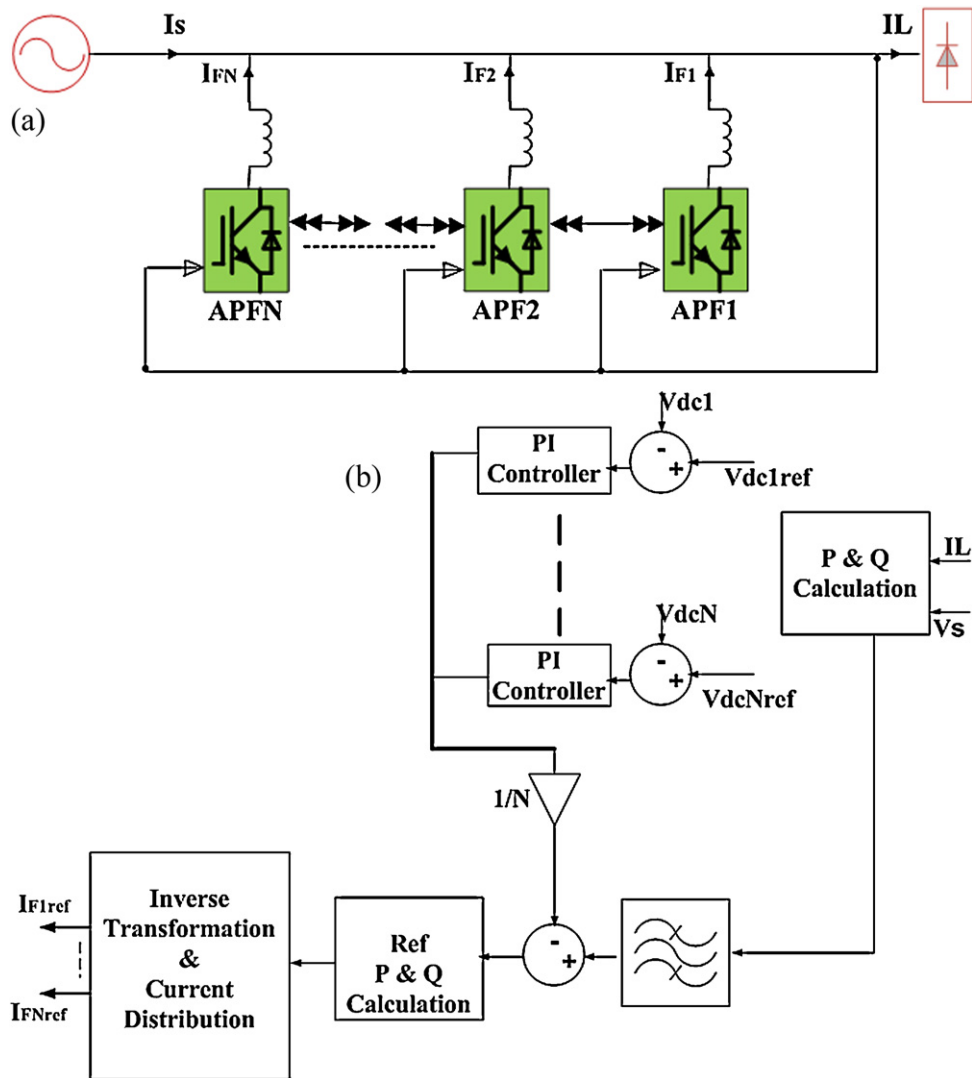


Fig. 11. (a) Distribute Control Technique; (b) Reference Current Generation technique for Power Splitting Control.

controller gains, are chosen as functions of the nominal values of  $P$  and  $Q$ , respectively. Fig. 6 shows a simple block diagram of a droop controller.

### 5. Parallel operation of inverters in DG or microgrid

Recent work on parallel operation of inverters in DG has concentrated on two applications: a) standalone AC system–Microgrid (island/off-grid mode) and b) grid-interconnection to the utility. In island mode of operation, a number of DGs supplies all the power needed by the load, like the parallel operation of the uninterruptible power supply (UPS) systems. In a grid-tie operation, each distributed energy source is connected in parallel to the utility, and directly provides power to the grid in order to cover increased power required by the loads.

Considering the parallel operation of DGs in any of the modes, voltage stability is a major concern. If appropriate controlling is not done, then the power system may become unstable under the heavy load condition and thus exhibiting voltage drops that can lead to a voltage collapse and resulting in a black-out. Again, when renewable energy sources are connected to the grid, the system should have the ability to dispatch the optimum energy as well as to control the power conversion system in (i) utility interactive grid-

tie inverter mode, (ii) off-grid inverter back-up mode, (iii) active rectifier mode and (iv) active power filter mode.

As the parallel operation of inverters for load sharing conditions and the application of DG in microgrids are increasing rapidly, control strategies of parallel inverters in microgrids are being given more attention. A countable number of researches have been done considering active load sharing condition [14–22] and droop control [23–29] or a combination of both [30–32]. Due to the advancement of digital signal processing techniques, some of these controlling methods have been applied to achieve voltage harmonics elimination and fast recovery performance on load transient in digital mode [31–35]. Transient response can also be improved by introducing proportional–integral–derivative (PID) terms [27], as shown in Fig. 7, or an adaptive output impedance controller [28], as shown in Fig. 8, into a conventional droop scheme. In addition, an instantaneous current control loop is also included to ensure correct sharing of harmonic components when supplying nonlinear loads.

The possible resonance due to long wiring cables having non-negligible inductance and resistance and its detrimental effect on system stability and performances should be considered during the design stage [36,37]. The line impedance ratio between the grid and inverter can be implemented to cancel voltage harmonic disturbances [27]. A grid impedance parameter estimation technique in





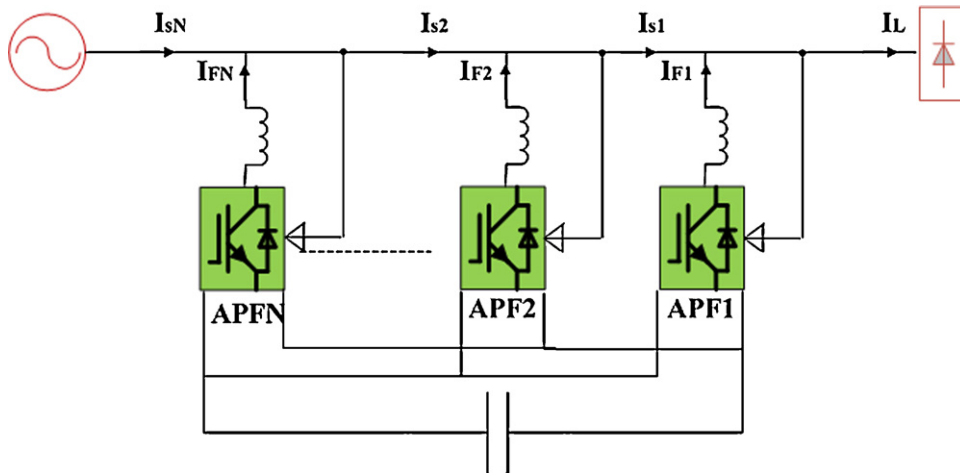


Fig. 13. Parallel inverters with common dc link capacitor.

limitation technique. In that case, APFs are connected in a cascade mode which shows the advantages of high flexibility, reliability due to no control interconnection and reduced power capacity demand of APFs. The disadvantage was that one APF treats other APFs on its load side as a part of its load. A third approach has been proposed in [45], which is based on power splitting. An overview of these techniques has been given below and present research outcomes along with the advantages and disadvantages of these techniques are also described.

6.1. Frequency splitting (FS)/centre mode control (CMC)

A central control unit is used to measure the total harmonic components and then each APF is assigned to compensate a specific harmonic component. Therefore it requires the minimum number of harmonic detection sensors, shown in Fig. 10(a). It can also be referred to as concentrated control. The technique for reference current generation has been presented in Fig. 10(b). If the sensing load current is  $i_L$  then the harmonic current will be,  $i_{Lh} = i_L - i_{L1}$  where  $i_{L1}$  is the fundamental component of the load current and  $h$  is the number of harmonic components. In this mode, if there are two APFs working in parallel and one is responsible for reactive power compensation, then the other one will compensate the harmonics [4,46].

The operational advantage is that the APF module which deals with the higher order harmonics should have the higher switching frequency. Since the harmonic current magnitude is inversely proportional to the harmonic order, the power rating is low. Thus it also helps to reduce the switching losses. The main disadvantage is that the APF modules are not identical and therefore replacement requires a similar one.

6.2. Power splitting (PS)/distributed control (DC)

In this case, compensating total harmonic current is equally distributed to the APFs and therefore identical modules are required. If there are  $N$  modules operate then the current reference of each module will be  $I_{FN} = i_{Lh}/N$ . Since it maintains interconnection between the inverters, number of sensors are also higher than the central control mode, as shown in Fig. 11(a). The reference current generation technique has been depicted in Fig. 11(b). The main advantage is its easy maintenance and installation.

It is clear that in both central and distributed control system, the reference current of each APF are resulting from the same  $P$  and  $Q$  calculating algorithm block and therefore all the APFs maintain an interconnection control. Hence a fault in any communication or malfunctioning of any APF can cause the system to halt.

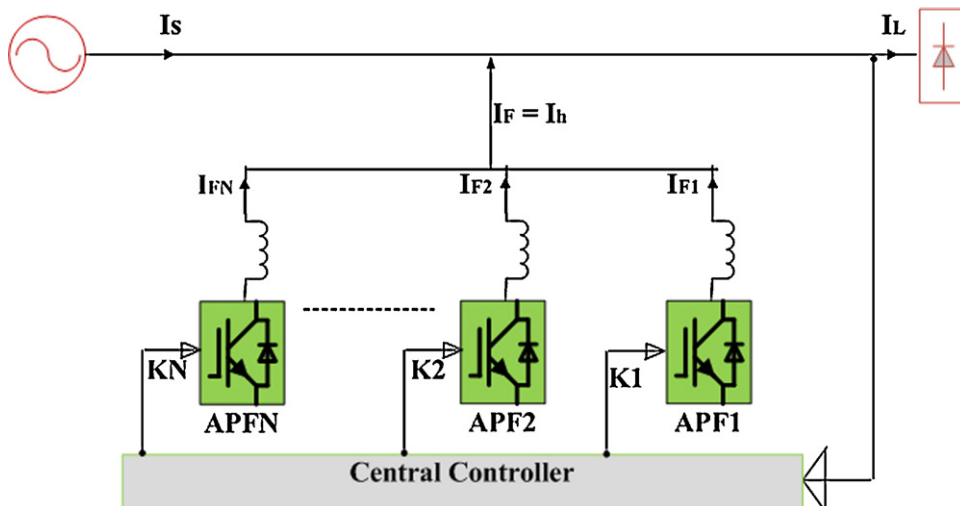


Fig. 14. Parallel operation of APF with a combination of central control and capacity limitation.

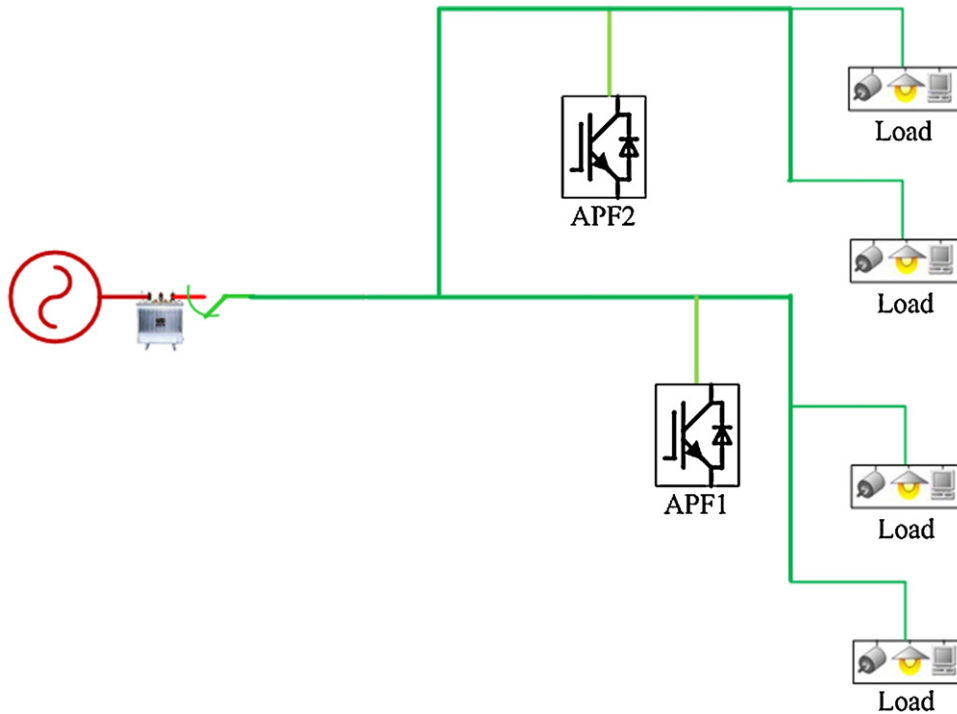


Fig. 15. Parallel operation of APFs with different feeder.

6.3. Master–slave control (MSC)/capacity limitation control (CLC)

In this mode, each APF compensates harmonic current according to its power rating. Each APF is independent and senses the current at the up/downstream of the node and therefore the maximum number of sensors is required, as shown in Fig. 12(a). Each APF only has to compensate the harmonic component left by the previous APF on its load side. Therefore generation of reference current for each APF requires separate  $P$  and  $Q$  calculation as shown in Fig. 12(b). The rating of each APF module is defined as;

$$P = \frac{\sqrt{3}}{2} V_{dc} I_{F \max} \quad (7)$$

In general, the APF near the load has higher capacity and the lowest bandwidth. As the APFs are not identical and work independently, power capacity enlargement is easier and the system reliability is also high. Also there is no central control and no information sharing between the APFs. Poor dynamic characteristics are the main disadvantages of this mode. But for steady-state conditions, CLC and PS show better performance than the FS [47]

A common dc link capacitor can be used for parallel inverters, shown in Fig. 13, to reduce the system cost [48], but it then raises the hardware design and control complexity due to the zero sequence current circulation between the inverters [49].

A new modular based APF controlled strategy with a combination of central control and master–slave mode has been proposed in [50] where each APF can operate independently and compensate the load harmonic current according to its own capacity-limitation. The output current of each APF is optimized in such a way that the APF with large capacity compensates more current and the one with small capacity compensates less current. In this way, the feasibility and security of modular APF has been guaranteed here. Fig. 14 shows the new control strategy where the total harmonic compensating current,  $I_F = I_{F1} + I_{F2} + \dots + I_{FN}$ . Here,

$$I_{F1} = K_1 I_F; I_{F2} = K_2 I_F; \dots; I_{FN} = K_N I_F \quad (8)$$

and

$$K_N = \frac{I_{rN}}{\sum_{j=1}^N I_{rj}} \frac{I_{rN}}{I_{FNref}} \quad (9)$$

where,  $I_r$  and  $I_{FNref}$  represent the rated current and the compensating current reference of the selected APF.

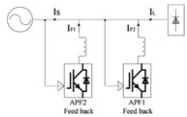
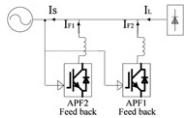
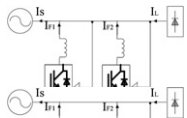
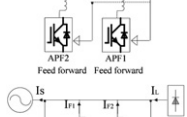
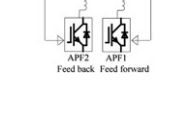
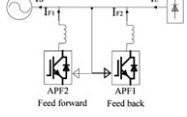
These control strategies are applicable only for the active load sharing mode when multiple APFs are placed close to each other either at the point of common coupling or close to a large capacity load. When these APFs are working in different feeders or deal with separate loads, as in Fig. 15, then no central control mechanism is needed even though they are apparently in parallel operation [51].

Depending on the placement of the harmonic current sensor, there could be two types of harmonic compensation loops for dual shunt APF in parallel mode; either feedforward or feedback [49,52,53]. In general, feedforward topology is extensively used for its stability and ease of installation where the controlling method is based on a current-controlled source. On the other hand, feedback control is better for stationary conditions but become unstable during certain grid conditions. A combination of both controllers for two parallel APF rather than a single unit shows a better compensating result for both low and high order harmonics and also stable grid operation [53].

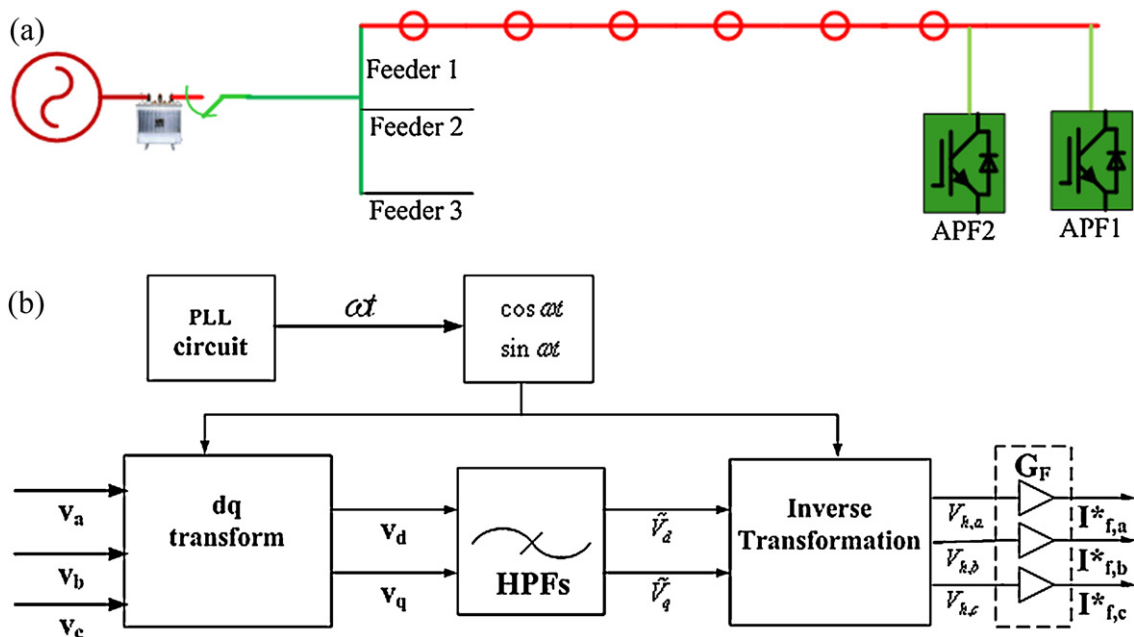
A comparative analysis with advantages and disadvantages of these techniques with topologies is presented in Table 2.

All the above approaches are for harmonic current compensation which is the primary function of parallel APF. This shunt APF can also be used as a compensator for voltage harmonics. Therefore, control of parallel APF for voltage harmonic compensation in a distribution line is another important issue. To detect the harmonic voltages, the active filter is characterized by behaving like a resistor for harmonic frequencies [54–56]. A cooperative controller based on voltage THD is proposed in [57] for parallel operation of multiple APF in a radial distribution feeder. A radial power distribution system with active power filter for voltage harmonic mitigation is shown in Fig. 16(a) whereas Fig. 16(b) shows a simple control method for the compensation. The real-time communications

**Table 2**  
Comparative analysis of parallel APFs controlling scheme with topologies.

Harmonic compensation loop	CS	Advantages	Disadvantages
	MSC	<ul style="list-style-type: none"> <li>i. Compensate damping resonance (due to grid and filtering capacitor at the load side)</li> <li>ii. Better transient response in steady state condition</li> <li>iii. Reliable and redundant</li> </ul>	<ul style="list-style-type: none"> <li>i. HDS – 4, thus increase the hardware complexity</li> <li>ii. Unstable for unknown grid condition</li> </ul>
	FS/PS	<ul style="list-style-type: none"> <li>i. HDS – 3, thus reduces the hardware design complexity</li> <li>ii. Reduce switching losses, if two inverters operate at different frequency</li> <li>iii. Good for load sharing between the filters</li> </ul>	<ul style="list-style-type: none"> <li>i. Design for reference current selection is critical; both inverters should be rated at same nominal power</li> <li>ii. Unstable for unknown grid condition</li> <li>iii. Requires identical replacement</li> </ul>
	MSC	<ul style="list-style-type: none"> <li>i. Does not depend on the voltage harmonic distortion</li> <li>ii. Good stability</li> </ul>	<ul style="list-style-type: none"> <li>i. HDS – 4, thus increase the hardware complexity</li> <li>ii. Load sharing between the filters is difficult</li> </ul>
	FS/PS	<ul style="list-style-type: none"> <li>i. HDS – 3, thus reduces the hardware design complexity</li> <li>ii. Easy maintenance and installation</li> <li>iii. Good for load sharing between the filters</li> </ul>	<ul style="list-style-type: none"> <li>i. Design for reference current selection is critical; both inverters should be rated at same nominal power</li> </ul>
	MSC	<ul style="list-style-type: none"> <li>i. Harmonic compensation is better than that of the above four configuration</li> </ul>	<ul style="list-style-type: none"> <li>i. HDS – 4, thus increase the hardware complexity</li> </ul>
	FS/PS/MSC	<ul style="list-style-type: none"> <li>i. Harmonic compensation is better than all other configurations</li> <li>ii. HDS – 3, thus reduces the hardware design complexity</li> <li>iii. Reduce the line current ripple if the inverters have the same switching frequency</li> </ul>	<ul style="list-style-type: none"> <li>i. Redundancy is possible in load sharing mode but may not be cost-effective</li> <li>ii. Higher rated power for APF2 is required for load sharing condition</li> </ul>

CS – controlling Scheme; HDS – harmonic detection sensor.



**Fig. 16.** (a) A radial power distribution system with active power filter; (b) a simple control circuit of the shunt APF as a voltage harmonic compensator.

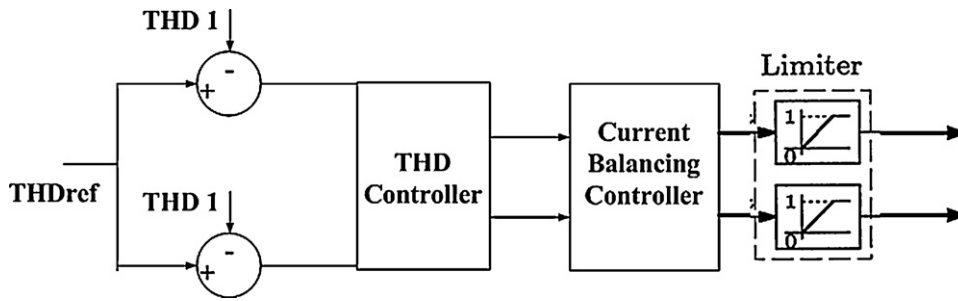


Fig. 17. Block diagram of cooperative control.

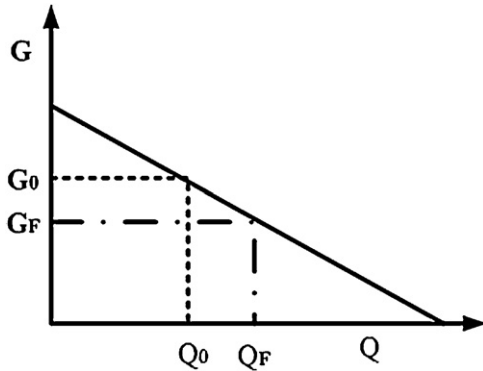


Fig. 18. Droop characteristics between G-Q.

compensating currents for the APFs. Thus the cooperative controller makes a significant contribution to reduce the required current rating of each active filter. Fig. 17 shows a block diagram of cooperative control to reduce the voltage THD.

### 6.5. Droop control for APF

As has already been mentioned, droop characteristics relate the output phase angle of inverter with active power and the output phase voltage with reactive power flow. The function of APF is to compensate harmonic load current. The APF can also be used to control voltage harmonics at the point of installation. Therefore, the droop control can be implemented for both purposes of APF. The basics of these controls are briefly described below.

#### 6.5.1. Voltage harmonics control

Using a high pass filter (HPF),  $V_h$  can be extracted from the supply voltage, shown in Fig. 16(b), and then  $I_{Fref}$  is generated. Final voltage command,  $V_F$  is calculated as [58], Eq. (11) and the PWM then generates the corresponding gating signals.

$$V_F = \frac{L_F}{\Delta T}(I_{Fref} - I_F) + V_s \quad (11)$$

where  $L_F$  is the interfacing inductor and  $\Delta T$  is the sampling period of the controller. A droop relationship between the  $G_F$  and the VA consumption,  $Q_F$  of the APF can be derived as;

$$G_F = G_0 + n_F(Q_F - Q_{F0}) \quad (12)$$

where  $G_0$  is the rated conductance,  $n_F$  is the slope of the droop equation and  $Q_{F0}$  is the rated capacity of the APF. The value of  $n_F$  is determined by the VA rating of the APF to ensure the sharing of filtering workload in proportion with the capacity of the each APF. The droop relation between the  $G$  and  $Q$  is also depicted in Fig. 18.

#### 6.5.2. Current harmonics control

To work as a harmonic current compensator, the APF current should deal with the node voltage,  $V_L$  or voltage at the point of

among the APF units are required to coordinate the operations, which is overcome by introducing droop control method [58,59].

### 6.4. THD based cooperative control

The study in [55] shows that installation of an active or passive filter on a long-distance power distribution feeder may result in a “whack-a-mole effect” which is the magnification of voltage harmonics on the other buses where no filter is connected. This voltage harmonic distortion can be damped by introducing an active filter at the end of radial feeder [56,57]. The active filter detects voltage harmonics,  $V_h$  at the point of installation, and then injects a compensating current,  $I_F$  as follows:

$$I_F = G_F \cdot V_h \quad (10)$$

where  $G_F$  is the control gain/conductance of the active filter.

An automatic gain adjustment was also proposed in [56] to damp out harmonic propagation without considering the circuit parameters of the distribution feeder. The purpose of cooperative control is to reduce the values of voltage THD over balancing the compensating currents. At first, the THD controller is set to be lower than a specified value to reduce the THD at the installation bus of one active filter. Then the current controller generates equal com-

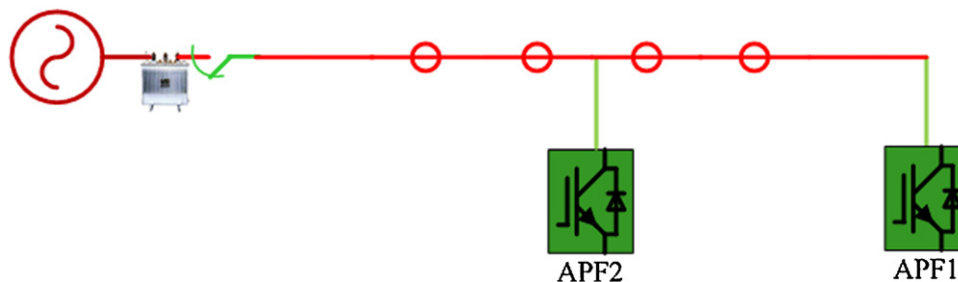


Fig. 19. Distributed APFs System.

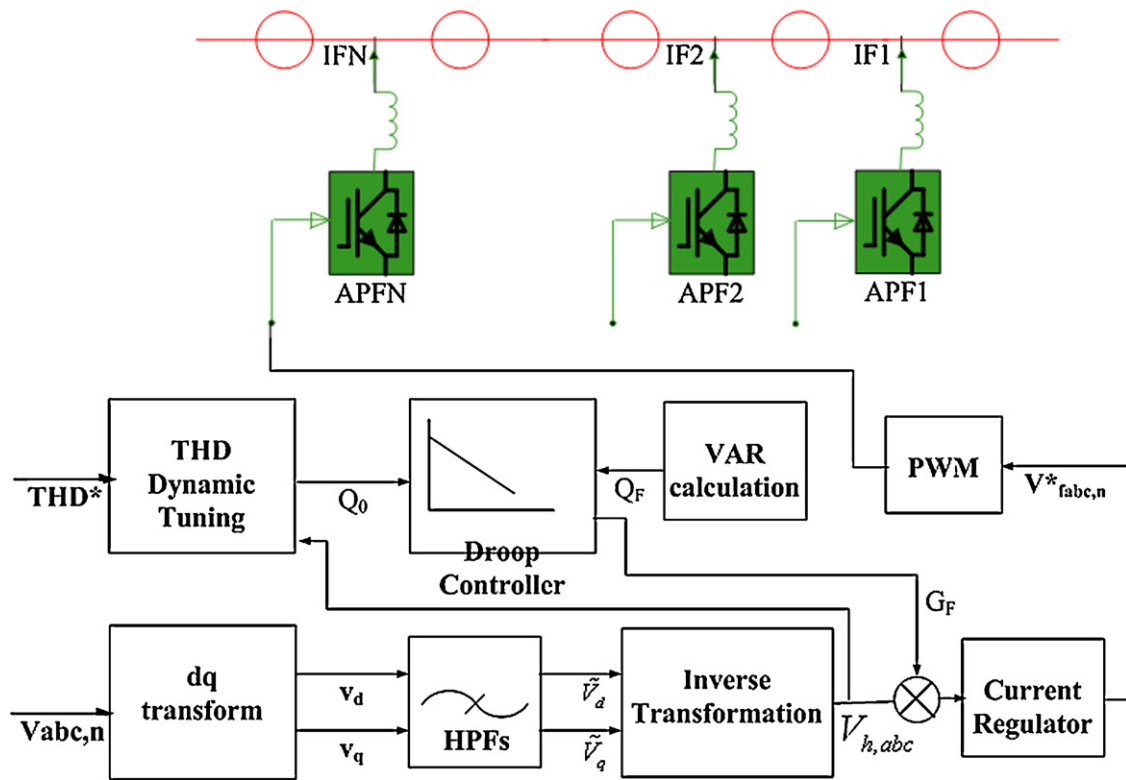


Fig. 20. A Dynamic tuning of THD for DAFS.

installation. In that case, the injected compensating current will be,

$$I_F = G_F \cdot V_L \quad (13)$$

The droop relation will be based on the conductance and non-fundamental power,  $Q_{hF}$  of the APF and this can be derived as [60];

$$G_F = G_0 + n_F(Q_{hF} - Q_{hF0}) \quad (14)$$

where  $Q_{hF0}$  is the rated non-fundamental power of the APF. Non-fundamental power can be calculated as;

$$Q_{hF} = \sqrt{Q_F^2 - Q_{1F}^2} \quad (15)$$

$$Q_F = V_F \cdot I_F \quad (16)$$

$V_F$  is the output phase voltage of APF.

### 6.5.3. Droop control for multiple parallel APF

When multiple APFs with different ratings are used to compensate the reactive and harmonic components in a distributed environment, then the control should be based on locally available information. In that case, the droop controller can be effectively used for harmonic voltage and current compensation which is similar to the adjustment of fundamental voltage amplitude and frequency. Here, the droop coefficient values have to be adjusted according to the following relationships [23,61];

$$n_1 \cdot Q_{10} = n_2 \cdot Q_{20} \dots = n_i \cdot Q_{i0} \quad (17)$$

The relation between the VA of the APF and rated capacity can also be expressed as [58];

$$\frac{Q_1}{Q_{10}} \approx \frac{Q_i}{Q_{i0}} \quad (18)$$

Using the droop characteristic to share the current of a certain harmonic frequency has also been presented in [61]. The main advantages of droop control for multiple parallel APFs is that it can

be used either when the APFs are in close proximity at the point of installation [56,57,60] or in distributed mode with no interconnection between each others [58].

APFs in distributed mode can be termed as distributed active filter system (DAFS). Fig. 19 shows the DAFS where multiples APFs are installed at different locations of the distribution line.

The filtering capacity of the APFs is further improved by introducing a dynamic tuning method in the DAFS [58], as shown in Fig. 20, where the voltage THD at the installation point of each APF is used to adjust dynamically the VA capacity and the slope of droop characteristic. Here, the APFs adjust their filtering capability in response to increasing or decreasing of nonlinear loads in the system to maintain the voltage distortion at the allowable level. A discrete frequency tuning active filter is also proposed in [59] to suppress power system harmonics effectively. Here, the APFs operate as a variable conductance for each individual harmonic frequency. Each harmonic conductance is then dynamically adjusted according to the corresponding harmonic voltage distortion of the APF.

## 7. Conclusion

In this paper, the control strategies of parallel operation of DG inverters are initially described. Techniques for harmonic voltage and current compensation using APFs in parallel mode are also reviewed. From the inverter control strategies it is found that active load sharing control techniques have some limitations. Due to intercommunication requirement between the inverters, control complexity is significant. Although active load sharing techniques for parallel operation of a fixed number of inverters can be better due to its robust control, expansion of capacity due to the additional load may not be easy. On the other hand, droop control seems better for most purposes. Research indicates that most efforts are being put into droop control techniques due to its capacity expansion flexibility, independent inverters and hot-swap facilities.

In the case of APFs in parallel operation, active harmonic load sharing techniques become more complicated due to the placement of harmonic current sensors or compensation topology. A comparative summary table has been prepared and it is found that a combination of feed-forward and feedback topology gives better results [53]. For multiple APFs, these controller designs will be more difficult. Therefore, research efforts have concentrated more on the droop control method. Implementing the basic ideas of droop control for parallel inverter operation, placement and controlling of APF has been advanced to distributed active filter systems which is very much suitable for distributed generation integration on a network or off-grid operation.

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