# THE DROOP METHOD BEYOND SIMPLY PARALLELING UPS SYSTEMS

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## Introduction

This white paper presents the basic methods for controlling uninterruptible power supply (UPS) systems connected in parallel, especially the evolution of methods based on the so-called droop control. UPSs protect electrical and electronic devices from power supply problems, such as temporary outages, micro-cuts, voltage surges, and frequency variations. The power sizing of a UPS (kVA) must be carried out based on estimating the maximum power consumption of the devices to be protected, including future expansion. This estimation should be carried out as precisely as possible in order to reduce installation costs, but also taking into account those future expansions.

Among others, a paradigmatic example where this situation is especially difficult to estimate is a data center, a system of multiple servers such as Google, Microsoft, Facebook, etc. The same data center may have very small initial power requirements, for instance 50 kVA, but this can increase by up to a factor of 20 or more (becoming one MVA). When the difference between initial installation and future estimation is large, a scalable sizing system where UPSs can be added in parallel to the initial installation without any major changes. To achieve good scalability with reliability, it is necessary to develop parallel UPS systems that go beyond simple centralized systems.

This white paper reviews the control systems used to achieve parallel UPS systems and compares the functionality and performance of each solution. The organization of this document is detailed as follows. In the following section, the advantages and disadvantages of paralleling voltage generators are briefly discussed. Then, the most commonly used methods for achieving current sharing are described. The following section explains the conventional droop method, and then the use of virtual impedance to improve robustness. Finally, the improvement of the functionalities of the droop control using a non-critical external control loops and low bandwidth communication. Although the description of the methods discussed here is of the generic application of paralleling alternating current (AC) sources, this document targets the specific characteristics of UPS systems.

## Advantages and disadvantages of paralleling voltage sources

The parallel connection of generators, with respect to a single generator, presents a number of well-known advantages in terms of scalability, performance and reliability, which are detailed below:

• Scalability since it is possible to add or remove modules or devices as the overall power requirements change. This means that the system in the initial phase of the project does not require oversizing and just needs to meet the initial requirements, with the certainty that power can be increased in later phases by simply adding more modules in parallel.

• High performance because the power supplied can be distributed between devices, enabling most of them to work at their optimum performance point, thereby improving overall performance and, more importantly, providing a wider range of powers supplied.

• Reliability since it easily enables modules or devices to be added in order to configure redundant systems in which the failure of a module can be automatically replaced by the redundant one without harming supply or functionalities.

Despite these advantages being well known, to parallel voltage sources has a difficulty inherent to the definition of voltage source, since they should ideally maintain the voltage regardless of the current supplied, in other words, they should present zero output impedance. In practice, when multiple voltage sources are connected in parallel, small voltage differences (and/or phase differences in AC) will produce large current differences. In the case they must also be completely synchronized and generate the same waveform without harmonic distortion to maintain frequency, phase, and amplitude.

Although it is true that, in practice, devices have a certain non-zero impedance, the problems of paralleling voltage sources increase with the functionalities of the device, in other words, a standalone device with high functionalities can be counterproductive when it comes to connecting several devices in parallel. In practice, output voltages will not be identical due to the tolerances of the voltage sensors and their associated conditioning electronics. Moreover, since they will not be equal in phase and amplitude, they will cause circulating currents between modules, resulting in a reduction of the overall efficiency of the system. Even some of the inverters may eventually act as rectifiers, absorbing energy that could compromise the DC link voltages of the UPSs.

From the abovementioned, and for practical purposes, it is clear that direct connection of voltage generators is not feasible without controlling their current distribution. Below is a description of the most common current distribution control methods that have been implemented, in part, thanks to advances in digital signal processors (DSP), which allow the implementation of complex algorithms at a reasonable price.

## Paralleling methods

There are three main types of paralleling technique that differ depending on the method of interconnection and relate to the concepts of centralised, distributed and decentralised control.

### Centralized

This first type is based on the concept of central control somewhere in the system, which monitors and records the other subsystems in real time and therefore needs high-speed and real-time communication between the central node and the subsystems.

The basic centralized system is based on a single control that sends the same control signal to all modules alike. The problem with this control scheme is that the equalization of currents depends on the parameters of the devices' power stages, being as similar as possible, which is not always possible given the dispersion of the output filter values.

To solve this problem, master/slave schemes are often proposed (see Figure 1), in which the master module acts as a voltage source, setting frequency, phase and amplitude, sending the value of its output current as a current reference ($i^*$) for each of the slave modules (see Figure 2).

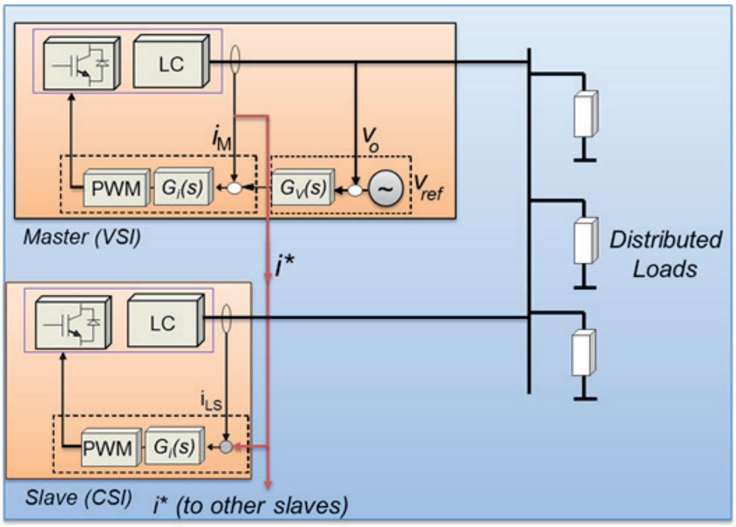


*Fig. 1. Master/slave control: an inverter acts as a voltage source and the others as current sources that copy the output current of the master*

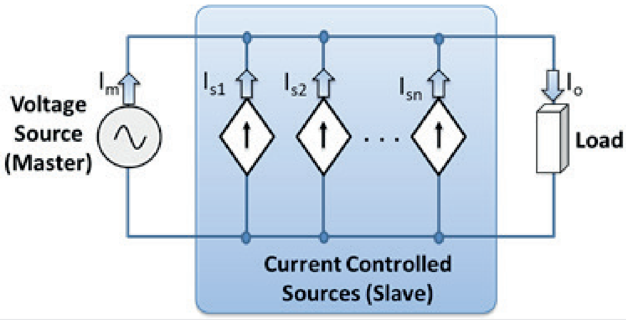


*Fig. 2. Equivalent master/slave strategy circuit*

This scheme provides very good functionalities since, by acting as a single monolithic system, it maintains individual functionalities, but suffers from two problems. On the one hand, loss of robustness due to communications and/or master module drop. On the other hand, poor scalability due to critical dependence on communications that must be real-time and high-speed.

The first problem with the master/(multi)slave scheme is that, unlike a slave failure, a master failure will produce the shutdown of the whole system. In order to avoid this dependence of the system on the master, a rotating master management system can be designed, where all of the elements can adopt one of the three functionalities: master, normal-slave and reserve-master/slave (see Figure 3).

In the event of a master drop, the reserve-master/slave takes command by allocating the voltage references. The next normal-slave becomes the reserve-master/slave. This system needs ring communications because all elements must be sure of their function in the system.

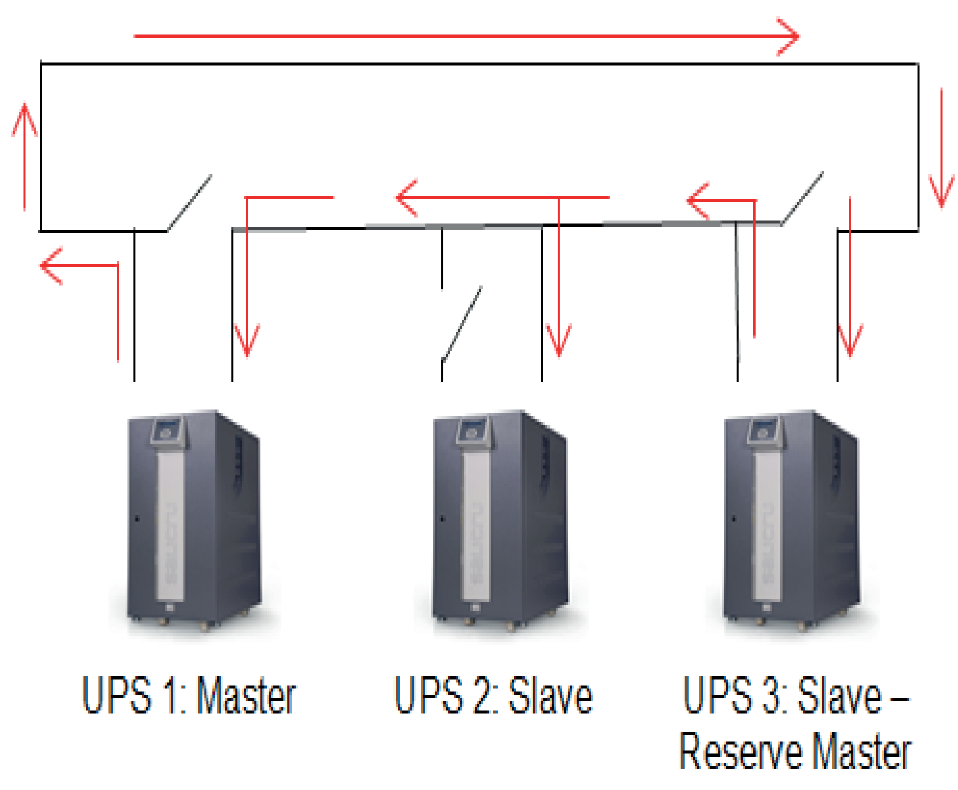


*Fig. 3. To avoid dependence on a single element, master assignment can (and must) rotate between elements while one slave always remains as the reserve master ready to take control*

Distributed

The second type is based on the concept of distributed control, in which each element makes its contribution according to its local measures, using the communications to agree with the rest of the individuals in the system.

This kind of solution consists of averaging the currents (see Figure 4) or powers (see Figure 5) of each module by adjusting the current/reference powers of each of them. In the case of instantaneous currents, it becomes difficult because it requires communications with a large bandwidth. However, by using active and reactive powers, it is possible to use reduced bandwidth communications since active and reactive powers can be averaged in each network cycle without any loss of functionality.

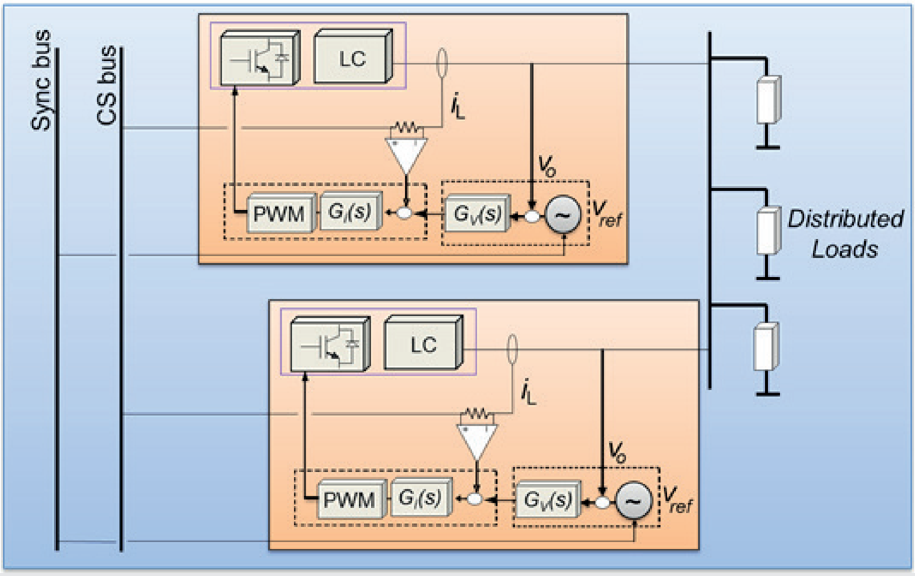


*Fig. 4. Average current control*

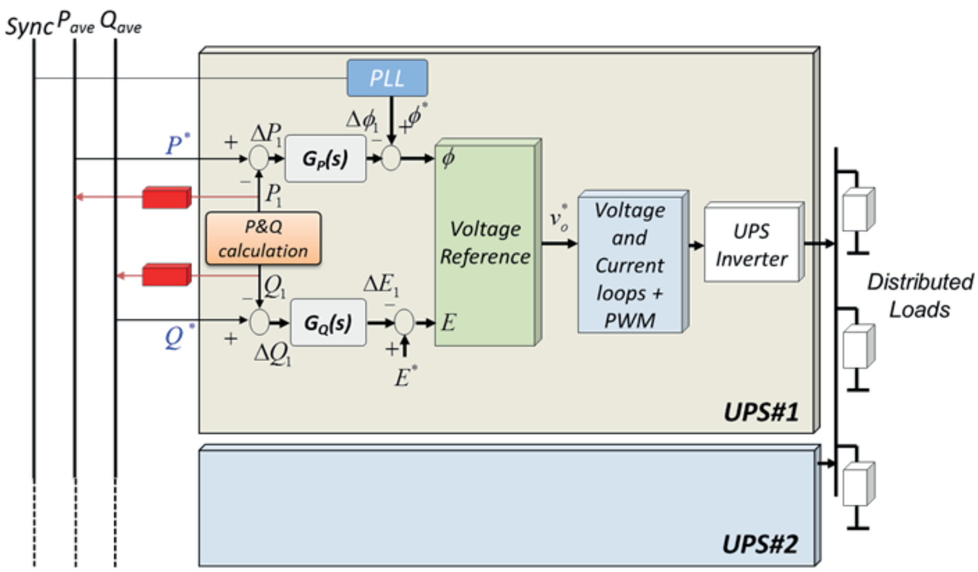


*Fig. 5. Average power control*

Alternatively, a circular current control (CCC) can be implemented (see Figure 6) in order for the reference currents to be sent to the adjacent module. The failure of a single module entails bypassing the information to the immediately preceding module. Implementation of this method depends on the power architecture, being advisable in secure rings that supply critical loads. Moreover, the use of communications in the form of a daisy chain is recommended for this type of structure.

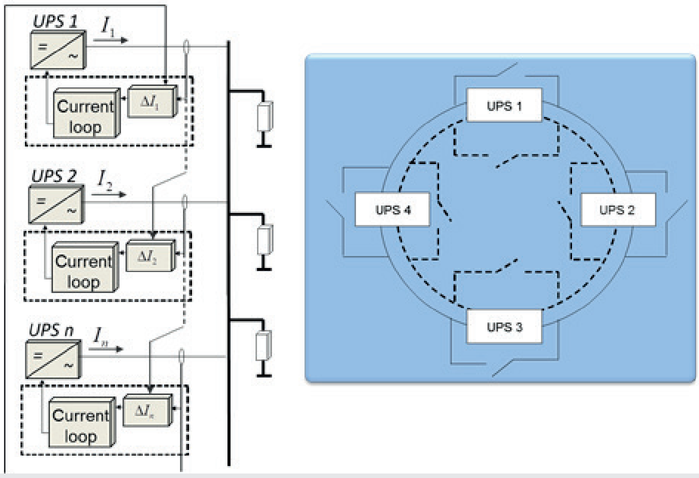


*Fig. 6. Current chain control (CCC) for secure power and communications rings on daisy chain*

## Decentralized

The third type is based on the concept of decentralized control, in which each element makes its contribution based exclusively on its local measures (without communications) but configured in such a way that individual behavior generates synergies in a natural way when connecting to the group. This is achieved with certain relaxation of the regulation of the control objectives and an individual design that is in good agreement with the group.

In essence, we are talking about the droop method and, in the case of DC generators, it consists of adjusting the voltage to the output current. In the case of AC generators, it consists of adjusting output voltage and frequency to the active and reactive power supplied by the inverter.

The conventional droop method provides high reliability and scalability but at a cost of reduced functionalities:

- Slow dynamic response
- Inherent compromise between amplitude and frequency deviations and current/power distribution.
- It does not act on over the the distortion power, so it does not balance the harmonic currents in the case of supplying non-linear rectifier-type loads.
- High dependence on the output impedance of the inverter.

In addition, the impedance of the line is unknown so that it can result in discrepancies in the reactive power balance.

As will be seen below, conventional droop problems can be solved with subsequent refinements such as adding (non-critical) communications through the injection of high-frequency signals into the power lines or with explicit non-critical external communications. The signals can be given by a centralized or distributed superior controller. That way, this control method can be hybridized with the two above.

Examination of these refinements of the conventional droop method, in order to achieve a decentralized, scalable, robust and precise system, is the ultimate aim of this document and it is detailed below.

## Virtual synchronous generators: the frequency/amplitude droop method

The idea behind this method is to obtain voltage sources that emulate the behavior of synchronous generators, hence the concept is also known as virtual synchronous generators. In real synchronous generators, due to the inertias they include, when the power they require is increased, their frequency is reduced, and in turn decreasing the power angle. Due to this fundamental principle, parallel-connected generators naturally encounter a common point of operation and share the power required by the loads connected to the electrical system.

This principle has been used for decades to connect generators to the electricity mains without requiring an exchange of information between them. The electrical mains today, as we know, consist of multiple synchronous generators connected in parallel. This behavior, imperfect from the point of view of the voltage generator, but desirable from the point of view of practical parallel operation, is the one that has been sought for implementation in electronic power converters.

Unlike synchronous generators, UPSs, being generators based on power electronics, do not include any kind of inertia. Even so, it is possible for the output inverters of the UPSs to emulate these inertias through relaxation of frequency (ω) and amplitude regulation of the output voltage based on local active and reactive power measures.

That way, if a device has an initial tendency to overload, by allowing a voltage droop based on the current, the difference of this with the currents of other devices tends to be better distributed and therefore reduces circulating currents.

Figure 7 shows the effect of the frequency droop of large-scale power generators when the power demand (P) is increased, as has been described, to emulate the inertial characteristic of synchronous generators.

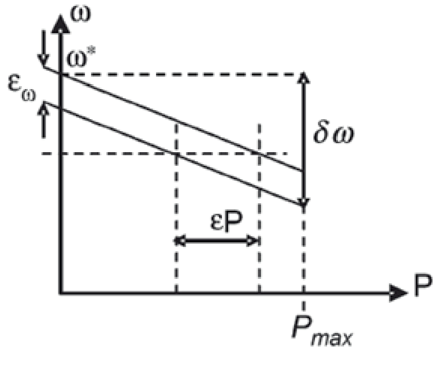


*Fig. 7. Effect on the distribution of powers between two devices due to relaxation in frequency regulation*

When two devices are connected in parallel with two different references (frequency error: εω), the frequency will be common (horizontal line) and the distributed powers will be deviated εP. Note that the frequency droop method brings powers closer but does not equalize them and that they will be closer when the droop δωis more pronounced. That is to say that power distribution accuracy is achieved at the cost of reducing accuracy in frequency regulation.

The use of frequency droop together with amplitude droop is related to active and reactive power, which enables a power control relationship to be established through frequency and amplitude (see Figure 8).

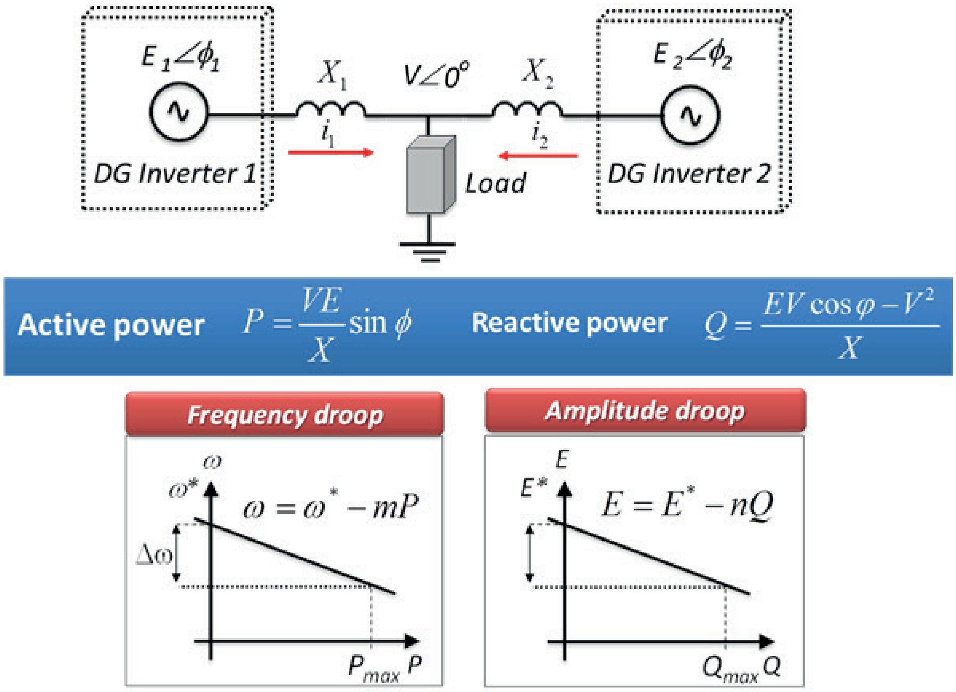


*Fig. 8. Frequency and amplitude droop for predominantly inductive lines*

Assumption of the output impedance inductive nature of the analysis above is valid in high-voltage lines or networks with synchronous generators, since its reactive component is very high. This, however, is not true for low-voltage lines, since they are mainly resistive, and much less so when using power electronics without output transformers, as is the case of most UPSs (see (Table 1).

| Type of line | R' Ω/km | X' Ω/km | $I_N$ A | $\frac{R'}{X'}$ |
|---|---|---|---|---|
| low voltage line | 0.642 | 0.083 | 142 | 7.7 |
| medium voltage line | 0.161 | 0.190 | 396 | 0.85 |
| high voltage line | 0.06 | 0.191 | 580 | 0.31 |

*Table 1. Typical line parameters*

## The concept of “virtual impedance”

The above analysis has been carried out under the assumption of dominant inductance in the power interconnection line but need not necessarily always be true. Failure to comply with this assumption in the actual impedance of the line has a considerably negative effect on the functioning of the drop method, especially in power distribution accuracy.

TABLE I
OUTPUT IMPEDANCE IMPACT OVER POWER FLOW CONTROLLABILITY

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

*Table 2. Impact of output impedance on transfer equations*

Table 2 shows the impact of the inductive or resistive nature of the input impedance on the relationship between power, phases, and amplitudes. In this table, it can be observed that active/reactive powers and phase/voltage relationships exchange their roles when the nature of the impedance change from pure inductive to pure resistive.

In order to ensure a fixed impedance in the inverter (whether inductive/resistive), an additional control loop is implemented to simulate an output impedance in the inverter for the system to ‘see’ the same impedance, normally designed to be much greater than the impedance of the line (see Figure 9).

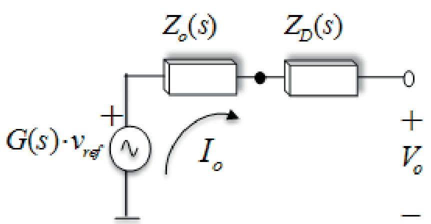


*Fig. 9. Equivalent impedance circuit in closed inverter loop*

In addition, the virtual impedance can also play an important role when it involves distributing current harmonics, since the harmonic impedance seen by the generator can be set individually (per harmonic) or in a specified frequency range. Always taking into account the inherent design compromise between distribution of harmonic currents and voltage harmonic distortion.

A general control loop diagram with conventional droop, internal cascade control and virtual impedance is shown in Figure 10.

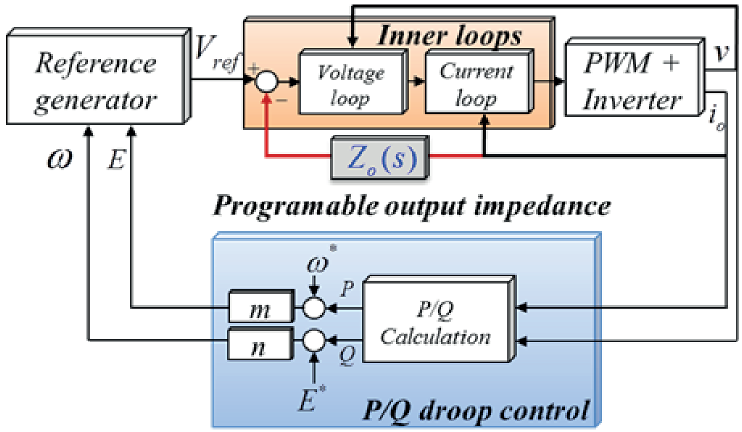


*Fig. 10. Complete loop diagram composed of cascade control with droop and virtual impedance*

## Secondary compensation loop

Without any other algorithm, the droop control with virtual impedance loop maintains the need to establish and assimilate a compromise between frequency and power distribution on the one hand and amplitude and phase regulation on the other. This system is completely free of communications and is totally autonomous. The price to pay is a drop in frequency and amplitude, which is a design parameter. However, with a non-critical, and not necessarily fast, communications system, an additional external compensation loop can be implemented to correct the drop in all control voltage setpoints (see Figure 11).

This loop only compensates for the percentage of design droop to obtain zero error in stationary state (see Figure 12). The system can be slow and use non-critical communication, as an interruption in communication will result in a small error (droop design parameter, usually close to +/- 1%, that is to say +/- 0.5Hz). The secondary loop can be implemented using a central or distributed controller along the local controllers of each of the UPSs.

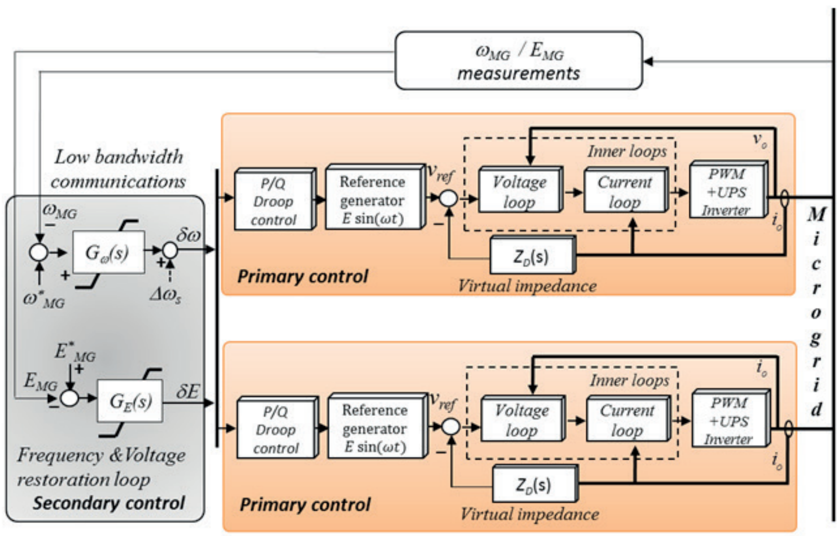


*Fig. 11. Implementation of centralized secondary control for restoration of output voltage frequency and amplitude*

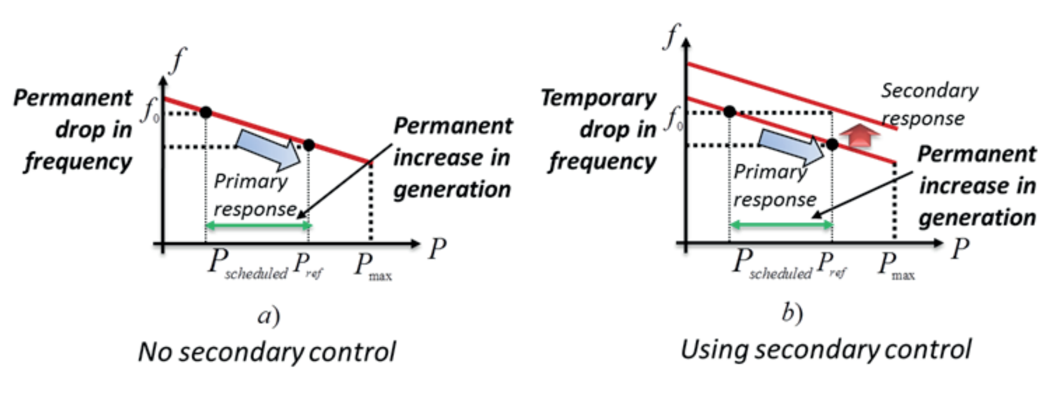


Fig. 12. Action of the secondary control loop to restore the frequency of the system

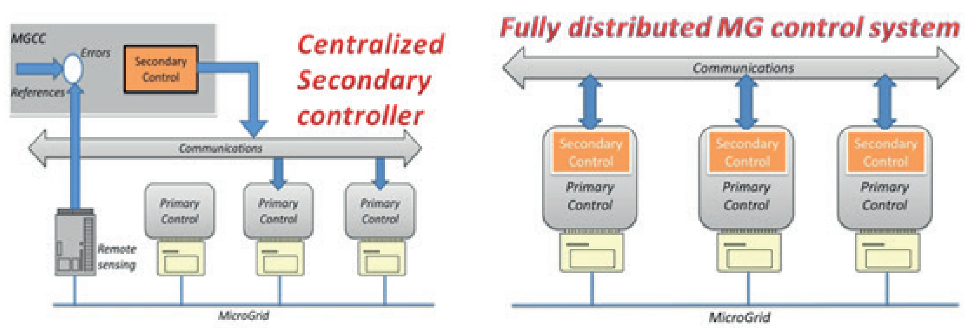


Fig. 13. Implementation of secondary control loop using a centralized and distributed controller

Although centralized control in the secondary loop is completely manageable and functional, it results in the loss of the concept of a decentralized system based on droop and the appropriateness of centralizing this second loop or not must be reassessed (see Figure 13).

## Conclusions

The most significant UPS control strategies in parallel: centralized, distributed, and decentralized, have been discussed.

The conventional centralized strategy has good functionalities but a heavy dependence on communications and reliability of the master, so that subsequent variants attempt reducing this dependence with rotating master and/ or information sharing (voting) strategies. However, critical dependence on communications cannot be easily solved, so that, in general, an increase in the number of nodes is detrimental to the initial advantages of paralleling: reliability, scalability and overall system performance.

The conventional distributed strategy solves this lack of reliability by allowing the interconnection of a large number of elements, but at the cost of loss of functionality which can be offset by the implementation of virtual impedance and non-critical external communications.

| Functionalities | Average current control | Average power control | Control of droop drop |
|---|---|---|---|
| Number of control signals | 1 synchronization + CS/2 PS bus | 1 synchronization + 2 PS bus | 0 or low bandwidth |
| Harmonic distortion of voltage | Low | High | Medium |
| Distribution of harmonic currents | Good | Limited | Limited |
| Dynamic | Quick | Slow | Slow |
| Compromise between regulation and current sharing | High | High | Poor |
| Modularity | Medium | Medium | High |
| Redundancy | Medium | Medium | High |

*Table 3. Active load sharing strategies vs. droop controllers*

| Control loop | Centralized control | Master/slave | Average power/ current | 3C |
|---|---|---|---|---|
| Centralized | ✓ | ✓ | = | = |
| Distributed | ✗ | ✗ | ✓ | ✓ |

*Table 4. Voltage loop for active current/power distribution strategies*

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