Real and Reactive Power Sharing

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1. Introduction

When two ac power sources operate in parallel, the following conditions are met:

- Their voltage magnitudes are equal if one neglects voltage drops in the interconnecting cable.
- The voltage frequencies are equal.
- The voltage phase angles are equal if one neglects voltage drops in the interconnecting cable.

For dc power sources, the voltage magnitudes are equal (neglecting voltage drops in the interconnecting cable).

When operating in parallel, the amount of power (both real and reactive) each source provides is determined by one of the following power modes:

- Swing source characteristic
- Operator or control system input
- A droop characteristic
- Cross-current compensation signals
- Exchange of control signals among paralleled sources

Sources operating in parallel may not all employ the same power mode. Indeed, only one source in a group of paralleled sources should operate with a swing source characteristic.

In most systems, each paralleled source provides an equal percentage of its rated power. In other words, if the total load is 6 MW and we have three generator sets paralleled, then each generator set provides 2 MW.

Sharing power as an equal percentage may not always be the most economical. The overall power system control may operate the plant where sources operate with unequal sharing to minimize overall fuel consumption.

In ac systems, the method for sharing reactive power may differ from the method for sharing real power. It may be possible for synchronous motors and power electronic converter loads to be serve as controlled sources of reactive power while being loads for real power; these loads may be configured to have a leading power factor which can offset some or all of the lagging power factor from the rest of the system.

For additional details, see EDQP SD-311 or Doerry (2020).

2. Power modes

2.1. Swing source characteristic

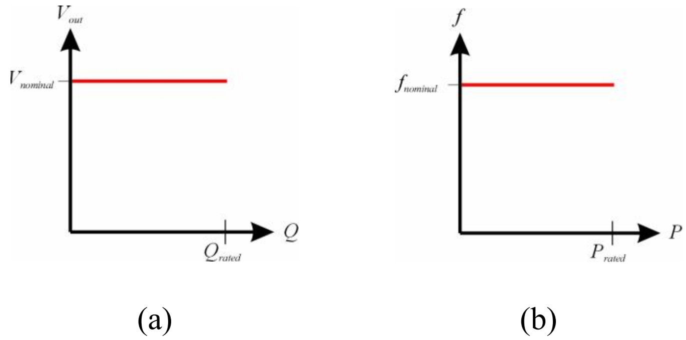


Figure 1: AC swing source characteristic (a) voltage (b) frequency

As shown in Figure 1, an ac swing source regulates the voltage and/or frequency to the nominal value. It provides the amount of power (either real or reactive) consumed by the loads less the amount of power provided by other sources. The control system must ensure that the other sources do not provide more real power than the load consumes; and that the other sources provide sufficient power such that the amount of power provided by the swing source is no more than its rating.

Regulating the frequency to the nominal value is also called "isochronous mode."

Within a set of paralleled generator sets, no more than one should be configured as a swing source. If two or more swing sources are in parallel, then the amount of real and reactive power provided by each is indeterminate. Often, one source will attempt to provide all the power, overload, and trip offline. This can continue until all sources have tripped offline. In other cases, power may oscillate between two or more sources, causing significant wear on prime movers.

When a ship's generator set is paralleled to shore power, the shore power connection behaves as a swing source. Usually, the ship's generator set is operated in droop mode to enable a safe and stable interconnection.

A dc swing source regulates the output voltage to the nominal voltage; the voltage is not impacted by the amount of power provided. Otherwise, its behavior and use are the same as for ac swing sources.

2.2. Operator or control system input

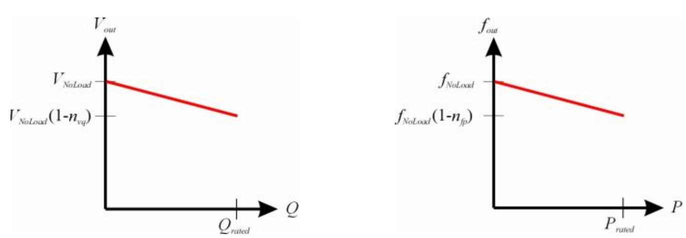
Power converters operating as grid-following converters, do not attempt to regulate voltage or frequency, but instead sense the voltage magnitude, phase angle and frequency at their interface and inject an appropriate amount of current of the proper frequency and phase in order to provide a specified amount of real and reactive power. Grid-following converters are controlled current sources. The amount of real and reactive power injected into the power system is determined by the operator, the power management control system, or by the component itself.

It is not unusual for waste heat recovery systems that provide electrical output, photo-voltaic systems, and other niche energy sources to have interfacing power electronic converters to maximize power production to inject into the power system. The power injected is based on internal controls of the source, and is not a function of the properties of the electrical interface.

The power management control system may command a source that is not normally grid following (such as a generator set) to provide a specific power output in order to minimize overall fuel consumption.

Grid following converters require at least one grid forming source to be paralleled to it to provide the voltage waveform they need to produce the correct current waveform. Some grid following converters are capable of switching modes should they detect loss of a grid-forming source; other grid following converters will simply shut down.

2.3. Droop characteristic



(a) (b)

Figure 2: AC droop characteristic (a) voltage (b) frequency

For ac generator sets employing droop, the typical convention is to have the voltage regulated to a value that is a function of the reactive power, and the frequency regulated to a value that is a function of the real power as depicted in Figure 2. The equations for the voltage and frequency of generator set *i* are given by equations [1] and [2].

$$V_{out\_i} = V_{NoLoad\_i} - n_{vq\_i}\left(\frac{Q_i}{Q_{rated\_i}}\right)V_{NoLoad\_i} \qquad [1]$$

$$f_i = f_{NoLoad\_i} - n_{fp\_i}\left(\frac{P_i}{P_{rated\_i}}\right)f_{NoLoad\_i} \qquad [2]$$

Restating:

$$Q_i = \left(1 - \frac{V_{out\_i}}{V_{NoLoad\_i}}\right)\left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right) \quad [3]$$

$$P_i = \left(1 - \frac{f_i}{f_{NoLoad\_i}}\right)\left(\frac{P_{rated\_i}}{n_{fp\_i}}\right) \quad [4]$$

The total power (both real and reactive) for all *m* online generator sets is the sum of the power provided by each generator set. The frequency and voltage for all generator sets are the same (*f* and *V)*.

$$Q = \sum_i^m \left(1 - \frac{V}{V_{NoLoad\_i}}\right)\left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right) \quad [5]$$

$$P = \sum_i^m \left(1 - \frac{f}{f_{NoLoad\_i}}\right)\left(\frac{P_{rated\_i}}{n_{fp\_i}}\right) \quad [6]$$

Restating:

$$Q = \sum_i^m \left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right) - \sum_i^m \left(\frac{1}{V_{NoLoad\_i}}\right)\left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right) V \quad [7]$$

$$V = \frac{\sum_i^m \left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right)}{\sum_i^m \left(\frac{1}{V_{NoLoad\_i}}\right)\left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right)} - \frac{Q}{\sum_i^m \left(\frac{1}{V_{NoLoad\_i}}\right)\left(\frac{Q_{rated\_i}}{n_{vq\_i}}\right)} \quad [8]$$

The equation for frequency is similar:

$$f = \frac{\sum_i^m \left(\frac{P_{rated\_i}}{n_{fp\_i}}\right)}{\sum_i^m \left(\frac{1}{f_{NoLoad\_i}}\right)\left(\frac{P_{rated\_i}}{n_{fp\_i}}\right)} - \frac{P}{\sum_i^m \left(\frac{1}{f_{NoLoad\_i}}\right)\left(\frac{P_{rated\_i}}{n_{fp\_i}}\right)} \quad [9]$$

Hence the composite functions for the paralleled set of generator sets are also droop equations. If all of the generator sets are identical and have identical no load values, rated values, and droop coefficients, the equations may be simplified to [10] and [11].

$$V = V_{NoLoad} - \frac{n_{vq}}{m}\left(\frac{Q}{Q_{rated}}\right) V_{NoLoad} \quad [10]$$

$$f = f_{NoLoad\_i} - \frac{n_{fp}}{m}\left(\frac{P}{P_{rated}}\right) f_{NoLoad} \quad [11]$$

For paralleled identical generator sets, the droop equation for the paralleled set is the droop equation for a single generator set with the droop coefficient divided by the number of paralleled generator sets.

One of the down sides of using droop for power sharing is that the bus voltage and frequency are usually below their nominal values. This can be corrected by raising the no load values of all the generator sets so that at the operating point, the bus voltage and frequency are at their nominal values. Adjusting the no load values can be automated using a master bus controller. A master bus controller (Figure 3) employs an outer control loop that regulates the bus voltage and frequency by adjusting the voltage and frequency set points (no load values) for all the paralleled generator sets. For stability purposes, the master bus controller typically employs a PI controller using time constants that are more than one magnitude slower than the time constants used in the generator set voltage regulator and speed governor.

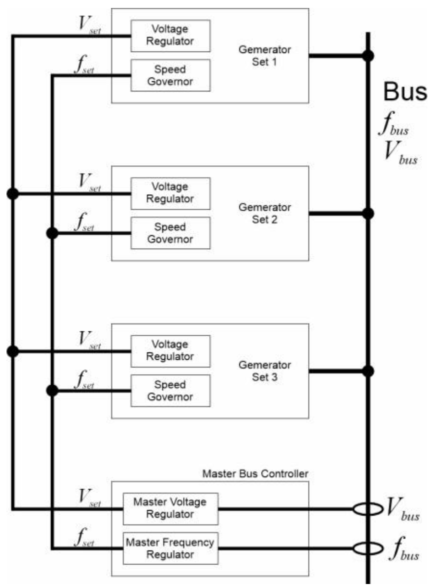


Figure 3: Master bus controller

If one of the paralleled generator sets is configured as a swing source, then the voltage and frequency are fixed. The amount of real and reactive power provided by each generator set with droop is given by equations [3] and [4]. The swing source provides the difference between the power demand of the loads and the power provided by the droop generator sets. The power provided by individual generators can be adjusted by increasing or decreasing the corresponding no load value (f_{NoLoad_i} for P, and V_{NoLoad_i} for Q).

Power electronic inverters may implement droop through a control method called virtual synchronous generator (VSG). A virtual synchronous generator emulates a physical synchronous generator by incorporating a model of a synchronous generator into the controls of the power electronics. Typically, real power is controlled by the (virtual) power angle which is the phase difference between the terminal voltage phase and the phase of an internal (virtual) voltage simulating the voltage behind the synchronous reactance of a synchronous generator. Reactive power is controlled by the magnitude of the (virtual) voltage simulating the voltage behind the synchronous reactance.

Power electronic rectifiers and dc-dc converters may employ droop directly; the voltage linearly decreases as the power increases. An alternate approach is to implement a virtual resistor where the voltage linearly decreases as the current increases.

2.4. Cross-current compensation signals

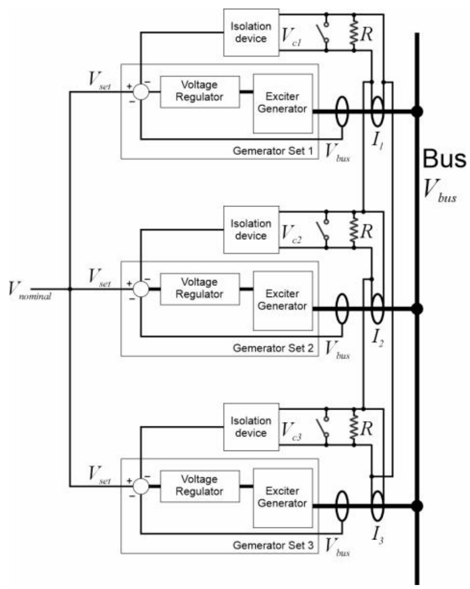


Figure 4: Cross-current compensation for reactive power sharing

Cross-current compensation is a technique used with voltage regulators to share reactive power equally while still regulating the bus voltage to the nominal value. As depicted in Figure 4, current transformers with burden resistors are interconnected; the voltage across the burden resistor is used to adjust the voltage setpoint of the voltage regulator. If all the paralleled generator sets provide the same current, the voltages across all the burden resistors are zero; if one generator set provides more current than the others, then the excess current will flow through the burden resistors, creating a positive voltage for the generator set with the higher current that is subtracted from the voltage setpoint; the voltages across the burden resistors for the other generators will be negative, resulting in a positive correction to the voltage setpoint. The net result is that the current is reduced for the generator set with an excess current and increased for the other generator sets.

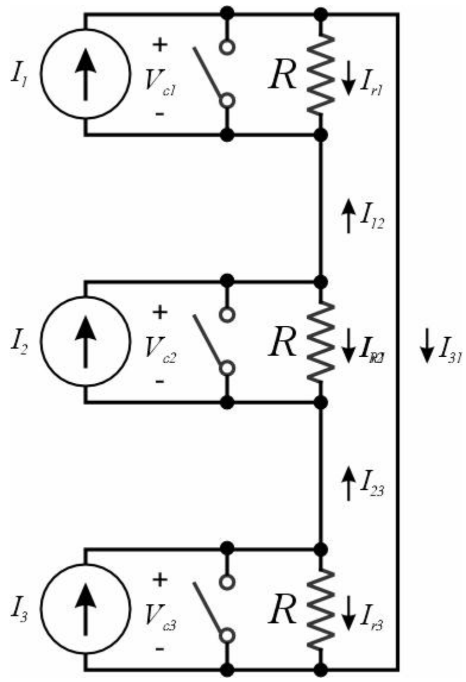


Figure 5: Cross-current compensation circuit

Figure 5 depicts the cross-current compensation portion of the circuit shown in Figure 4. The current sources reflect the output of the current transformers; the current source magnitude is proportional to the current supplied by the generator set. The equations for this circuit are given by [12] through [20].

$$V_{c1} = RI_{r1} \quad [12]$$

$$V_{c2} = RI_{r2} \quad [13]$$

$$V_{c3} = RI_{r3} \quad [14]$$

$$I_1 - I_{r1} - I_{31} = 0 \quad [15]$$

$$-I_1 + I_{r1} + I_{12} = 0 \quad [16]$$

$$I_2 - I_{r2} - I_{12} = 0 \quad [17]$$

$$-I_2 + I_{r2} + I_{23} = 0 \quad [18]$$

$$I_3 - I_{r3} - I_{23} = 0 \quad [19]$$

$$R(I_{r1} + I_{r2} + I_{r3}) = 0 \quad [20]$$

By adding [15] and [16] and [17] and [18] we can conclude:

$$I_{xy} = I_{12} = I_{23} = I_{31} \quad [21]$$

Restating [15], [17], and [19]:

$$I_{r1} = I_1 - I_{xy} \quad [22]$$

$$I_{r2} = I_2 - I_{xy} \quad [23]$$

$$I_{r3} = I_3 - I_{xy} \quad [24]$$

From [20], if we add [22],[23], and [24] we get [25].

$$I_{xy} = \frac{I_1+I_2+I_3}{3} \quad [25]$$

Restating [12],[13] and [14], the compensation signals to the voltage regulator are given by [26], [27], and [28].

$$V_{c1} = \frac{R}{3}(2I_1 - I_2 - I_3) \quad [26]$$

$$V_{c2} = \frac{R}{3}(-I_1 + 2I_2 - I_3) \quad [27]$$

$$V_{c3} = \frac{R}{3}(-I_1 - I_2 + 2I_3) \quad [28]$$

From [26], [27], and [28], we can clearly see that if the currents produced by the generator (I_1, I_2, and I_3) are all equal, then the compensation signals to the voltage regulator are all zero.

If the current provided by one generator set is higher than the others, that generator set will have a positive compensation signal which will reduce the voltage setpoint for the generator set; the other generator sets will have negative compensation signals that will increase the voltage setpoint for the generator sets. In this manner, the system will lead to equalizing the currents.

Cross-current compensation results in reactive power sharing because:

- The voltage is regulated to the nominal voltage by the voltage regulators.
- Because the voltage is regulated, ensuring the currents supplied by the generators are equal is equivalent to ensuring the apparent powers supplied by the generators are equal.
- Real power sharing is implemented by the speed governor and is assumed to be effective.

- Since the apparent powers are equal, and the real powers are equal, the reactive powers must also be equal.

If a generator set is not operational, or not paralleled with the other generators, the switch across its burden resistor and current transformer should be closed; the generator set's current transformer and resistor are eliminated from the circuit. Normally this switch is implemented with one or more auxiliary switches on the generator breaker and bus-tie breakers.

Theoretically, cross-current compensation can also be applied for paralleling dc sources. The challenge with dc systems is that current transformers are not compatible with dc currents; another current sensor is needed. DC current sensors typically have an analog voltage output; this voltage would need to be converted to a current for cross-current compensation to work with dc.

2.5. Exchange of control signals among paralleled sources

The increased use of digital controls has also made possible the exchange of data at high rates of speed between converters and generator sets. This data exchange can be used to implement real and reactive power sharing. To date, the protocols for this data exchange have been almost exclusively proprietary; the ability to integrate generator sets and converters that are not produced by the same company is not guaranteed. Furthermore, the availability of long-term logistic support for equipment employing the proprietary protocols may be a significant programmatic risk. The proprietary nature of the data exchange can also complicate modeling and simulation efforts.

The control signals may be communicated using separate networking cables (such as a Controller Area Network (CAN) bus), dedicated point-to-point cables, or power line communication (PLC). PLC is used in many residential photovoltaic systems.

3. Real and reactive power sharing among generator sets

Power systems that only employ generator sets generally use droop or cross-current compensation for voltage regulation and reactive power sharing when paralleled. Droop is generally used when paralleling with the grid (shore power).

Frequency regulation is typically accomplished using droop; a master frequency regulator may be employed to adjust the no load frequency of all paralleled generator sets so at the operating point, the system frequency is at its nominal value.

It is also possible for the generator sets to exchange load sharing information to adjust the amount of real power produced by the generator set to that needed to equally share across all the online generator sets.

4. Real and reactive power sharing among power electronic sources

Rectifiers and dc-dc converters may employ droop (voltage a function of power or current) to share power. A master controller can further regulate the bus voltage by providing feedback to each of the rectifiers / converters with the no load voltage to use in the droop equation. Alternately, the rectifiers and dc-dc converters can exchange control information to regulate voltage and implement power sharing.

Inverters and ac-ac converters may employ VSGs and droop to share real and reactive power. Alternately, the inverters / converters can exchange control information to regulate voltage and frequency, and implement power sharing.

5. Real and reactive power sharing among generator sets and power electronic sources

In systems where power electronic inverters / ac-ac converters and generator sets are paralleled, having the power electronic inverters / ac-ac converters implement VSGs is one option. Alternately, the generator sets and inverters / converters can exchange control information to regulate voltage and frequency, and implement power sharing.

6. References

EDQP SD-311 EDQP Study Paper Electrical Power Distribution

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