Generator Technologies

Application Guidance Notes: Technical Information from Cummins Generator Technologies

# AGN 087 – Power Factor

## DEFINITIONS

### What is Power Factor?

**Power factor** is a way of identifying the electrical relationship between the active **real power, also known as working power (kWe)**, required to do the job, and the consumed **apparent power (kVA)**. The difference being due to the electrical characteristics of the electrical load applied to the **a.c. generator** (alternator). In electrical engineering terms, the power factor of an a.c. power system is the ratio of the **real power (kWe)** flowing to the load to the **apparent power (kVA)** in the electrical circuit.

The nature of the load in an a.c. circuit will determine if the **current** drawn is in phase or out of phase with the generated **voltage**. The load again determines if that **current** waveform 'leads' the **voltage** waveform or 'lags' the **voltage** waveform. For normal industrial loads (e.g. motors) the **current** will lag the **voltage** by some time interval or phase angle. The optimum situation is where **current** and **voltage** are in phase. This makes the power factor unity (1.0) and hence the real power (**kW**) the same as the product of **voltage** and **current** (**kVA**). Conventionally, alternator **kVA** ratings are based on a lagging power factor of 0.8. In this case the **current** will lag the **voltage** by an amount that causes the real power level supplied (**kW**) to fall below the **kVA** level by a factor of 0.8 times.

### What Causes Power Factor?

**Power factor** basically is a measurement of the timing - phase angle difference - of the **current** waveform relative to the **voltage** waveform. The idea being to identify how effectively the supplied power **(kVA)** is working in relation to the real work being done **(kWe)**. The power is being used more effectively when the power factor is closer to unity.

It is possible for a load to demand a **current** that is almost totally out of phase with the generated **voltage.** Also, that **current** may be lagging the **voltage** (inductive or motor loads) or leading the **voltage** (capacitive loads). This, therefore, completes the range of power factors for alternators from zero p.f. lagging, through conventional 0.8 p.f lagging, to unity (1.0 p.f), to zero p.f. leading. One aspect of this is that even though only a small real power (**kW**) is demanded by the load, which is well within the machines capability, damage can easily result if the load is a very low power factor load demanding a very high **kVA** level.

## TECHNICAL DESCRIPTION

### Alternator Ratings and Current Carrying Capacity

Alternators are rated in line with industry standards and are designed to operate safely between 0.8pf lagging and 1.0pf (unity), because most electrical loads have these inductive power factor characteristics. This is an alternator's region of optimum working performance.

The Generating Set industry settled upon rating Generating Sets at 0.8pf lagging, because this enables a given Generating Set to have the highest possible output rating, therefore impress the Customer about what is being offered, from the smallest possible engine power - engines being the most costly part of a Generating Set.

It is however, true that most industrial electrical load does operate at a lagging pf, and so the adopted 0.8pf was chosen for valid reasons.

The stated power factor of a load will be used to calculate the load in terms of **kVA**. Once the **kVA** of load has been identified, there will be no change to this **kVA** level by simply relating **kVA** and different values of pf. and so no change to the current flowing within this connected load.

The formula for calculating **current** [I] in a three phase system is:

$$I = \frac{kVA}{\sqrt{3} \times V_{L-L}}$$

For instance: Alternator operating at 1000kVA, 400V $_{L-L}$, 3ph, 0.8pf.

$$\text{Current flowing} = \frac{1000,000}{\sqrt{3} \times 400} = 1443A \text{ per phase.}$$

Now consider the same kVA at unity pf. Alternator operating at 1000kVA, 400V $_{L-L}$, 3ph, but at unity (1.0) pf.

$$\text{Current flowing} = \frac{1000,000}{\sqrt{3} \times 400} = 1443A \text{ per phase.}$$

The following example assumes the alternator is 100% efficient.

A 1000kWm engine driving an alternator could provide 1000kWe @ 1.0pf therefore 1000kVA. From above formula the current would be 1000kVA / [√3 x 400] = 1443A.

Same engine, but slightly different load characteristics, which now mean the supplied power, is to be at 0.8pf. To absorb the full engine power the load would be 1000kWe @ 0.8pf = 1000/0.8 = 1250kVA. From this formula the current would be 1250kVA / [√3 x 400] = 1804A.

The operating power factor of a load determines the current required to support that load. Lower power factor means higher kVA. The current therefore, has increased and so the alternator must now be suitably rated to supply the higher current.

The load sets the power factor, by the inherent characteristics of the component parts within the load. A good rule of thumb: if copper windings and electrical lamination steel are component parts of the connected load, e.g. motors, transformers, lighting unit ballast chokes [and capacitors], welders, etc, then the power factor will be not be at unity but will be lagging and typically 0.8 pf.

The only time the alternator is in control of its operating power factor is when it is in parallel with the mains supply.

Now, for reasons of operation control, the alternator's excitation system must include a unit often referred to as a power factor controller and this is used to determine the power factor of the power being supplied from the Generating Set and pushed into the mains supply.

The operating conditions, and this includes the power factor setting, are dependent upon the customer's requirements and expectations for the Generating Set.

For instance, if a customer is exporting to the grid, the power factor wants to be as close to unity as possible, as the electricity companies pay for the kW's supplied.

If for example, the customer has a lot of motors or transformers at his local site load and therefore is operating with a poor power factor. Now the customer could well be penalised by his local Mains Electricity Supply Company, simply because his load is demanding lots of Amps simply to support his low pf load. Technically his problem is said to be importing too many kVArs.

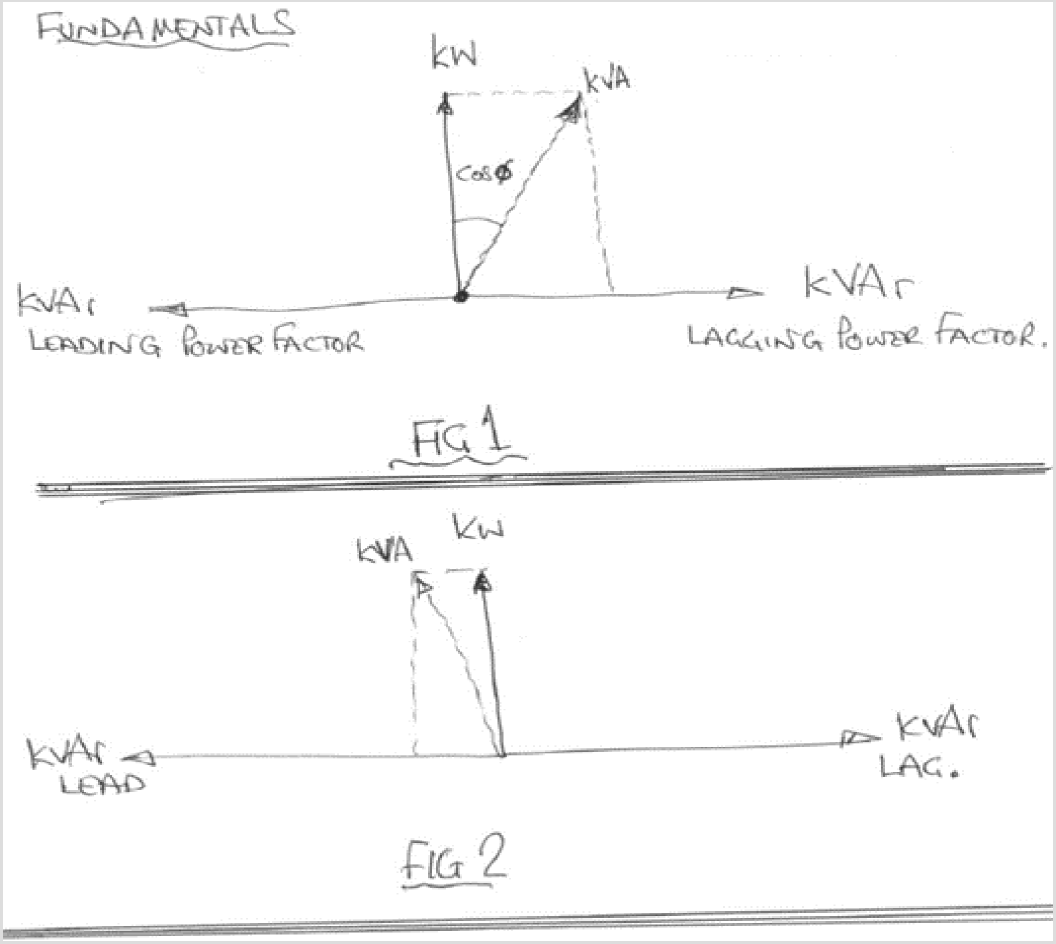
The introduction of his own Generating Set, which he operates in parallel with the local mains supply, will enable him to provide his loads demand for kVAr's from the Generating Set and so increase the power factor of the incoming mains supply.

**Real, Reactive and Complex Power Relationship**

A situation where the current is in phase with voltage is described as Unity power factor (1.0pf), which is generally called real power (P). If the loading situation results in the current being out of phase with the voltage, then the phase angle displacement is described in terms of Cos phi, which in turn is usually quoted as a power factor. A power factor of a typical value of 0.8pf lagging has long been the Rule of Thumb value for a typical industrial type loads consisting of many different items of electrical equipment, where the predominance is running induction motors.

A Generating Set supplying such a load has no control over what that power factor value will be. The Generating Set therefore, has no control over the current consuming characteristics of the total (combined) industrial load, setting the currents phase angle displacement to applied voltage. The electrical supply to such a load can now be broken down into REAL power (P), which represents the kW being provided to do the required work. Knowing the load is operating at a lagging pf means that some level of kVAr (Watt less power) (Q) is present.

P & Q can be considered as vectors, which are displaced by 90 degrees. It therefore, figures the vector sum of P & Q will provide guidance of the load in kVA terms (Apparent power) (S). The following FIG 1 and FIG 2 are aimed at demonstrating the P Q S relationship:




However, if a Generating Set is connected to an electrical network (Mains Grid System), then operational P, Q & S can be adjusted and controlled by functions associated with the Generating Set. Real power P is controlled by the mechanical power (torque) being applied to the Generator's input shaft.

Operating at unity power factor is achieved by running at the ideal level of excitation required to cope with the alternator's need to maintain an output voltage, which is in perfect balance with the voltage of the network to which it's connected, combined with providing the necessary excitation to overcome the demagnetising effect of current flowing through the stator winding, resulting from the engines (prime-mover) desire to push kW into the grid.

Changing the power factor from this 'ideal' situation is often required for reasons of contractual requirements, to assist the local network in satisfying operational requirements. To introduce a level of Q is achieved by changing the excitation level. To provide the network with kVAr requires the alternator's excitation level to be increased, which in turn, will result in the alternator operating at a lagging power factor. Under such a condition the 'extra' excitation will also tend to marginally raise the voltage at the point of connection to the grid [Point of Common Coupling (PCC)].

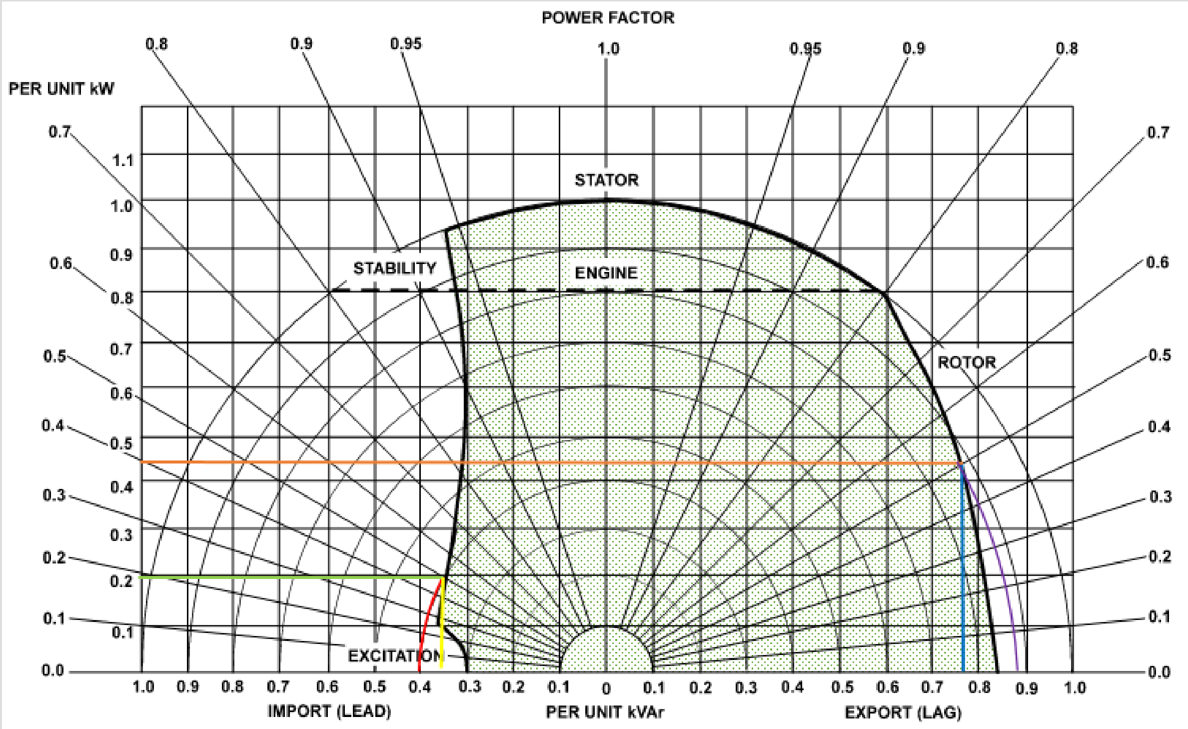
Under this change of excitation, the introduction of an amount of Q, the contributed P will remain the same, assuming the prime mover is under a closed loop control system with tight tolerance.

The Generating Set is however; now delivering an amount of current associated with the P vector, plus an amount of current associated with the Q vector. The vector sum identifies the Generating Set is operating at an S level of kVA at an identified power factor. It should now be obvious that the alternator's operating losses have increased and will therefore, be absorbing more mechanical shaft power from the prime mover. For this reason the set level of prime mover power required to be delivered is sensed and processed based on electrical output from the alternator.

If, for some reason the level of required lagging pf is below 0.8pf, then the corresponding level of over excitation will result in the alternator's excitation system being 'overloaded'. Therefore, at power factors below 0.8pf lag, a de-rate factor must be applied. The alternator's Operating Chart, also sometimes called Capability Diagram, is referred to and the degree of de-rate can be determined.

There are instances where the DNO needs to introduce an operational control over their network and therefore, request the Generating Set to deliver the contractual kW (P), but with the alternator operating under a leading power factor condition. Now the Q is still at 90° to P, but with Q leading P. The vector sum of P & Q still identifies S and associated pf angle. This mode of operation requires the alternator's excitation level to be reduced from the ideal unity pf condition.

This leading pf mode of operation can be tolerated by alternators, but their 'capability' is seriously limited, with any specified contractual requirement below 0.95pf lead, needing careful consideration, by due reference to the alternator's Operation Chart. AGN004 provides a detailed explanation of a typical Operating Chart. The Op Chart has been reproduced on the next page.




The above Op Chart is in fact based on a (half) circle diagram. The P vector is the central vertical radial line (12 o'clock), with the lagging Q out to the right (3 o'clock) and the leading Q out to left (9 o'clock). Around the clock face there are radial lines, against is assigned a power factor.

Dominating the semicircle is an irregular shape scribed by a heavy black line. The requirement is to keep the alternator's mode of operation within the confines of the black lines irregular envelope shape.

The array of semicircle lines start and finish on the X axis, against each is a value, with the outer being 1.0, this 1.0 indicating that if the heavy black line is on the 1.0 semicircle, then the alternator can be operated at 1.0pu designed load - therefore no de-rate of the alternator's output is required.

If however, there is a need to operate at 0.7pf lag, then by following the 0.7pf lag radial line inwards from the number 0.7 towards, the centre until the 0.7 line crosses the heavy black line. This occurs at a point, which is halfway between the 1.0 and 0.9 semicircles. This then indicates that at 0.7pf lag, the alternator must be de-rated. The de-rate factor taken from the graph is 0.95. The alternator's kVA rating must be de-rated by a rating factor of 0.95.

When considering leading power factor conditions, it soon becomes apparent that an alternator's capability under leading power factor is much reduced. Consider 0.8pf lead and the de-rate factor identified is 0.52. This hefty de-rate is brought about by the operation being under much reduced excitation and therefore, much reduced strength of magnetic field 'holding' the alternator in synchronism with the network. Which, in electro-magnetic terms, means a very high rotor load angle and so, a rotor very close to the edge of slipping out of synchronism if the network suffers some form of momentary disturbance.

## Loads with Leading Power Factor Characteristics

The most commonly encountered example of a component with a leading power factor characteristic is the capacitor; it is the classic reactive load in which the ac sinusoidal current waveform at its terminals has a 'leading' phase angle displacement, when compared to the voltage at the component terminals.

Capacitors form an essential component part within many equipment packages. Therefore, all such equipment packages must be carefully considered to identify the risk of that equipment package operating in such a mode that the supplied current is at a potentially troublesome level of leading power factor.

Generating Set suppliers have long been aware of the risks when encountering power factor correction capacitors, installed within an electrical distribution system. This has more recently been extended to include careful consideration of the harmonic filter packages associated with Non Linear Loads. Today, certain power electronic packages, under certain modes of operation, will operate with a leading power factor. One example being a recent technological development for switched mode power supplies using a PWM technique.

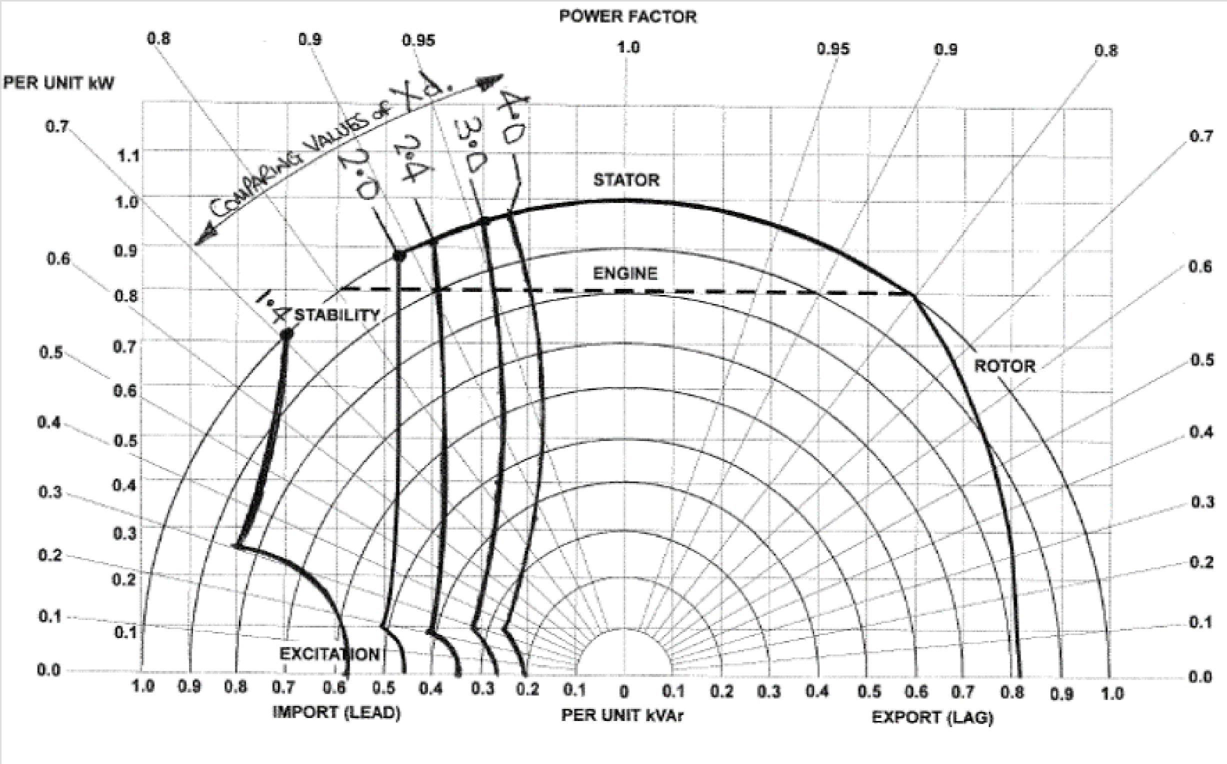
**Technical considerations**

There are few electrical networks that consist of total electrical loads with a sufficiently high percentage of the total absorbed kVA, where the operating power factor is both very leading and low. Recently, concern has been raised with regard to some designs of high technology power electronic packages with regard to associated warnings being issued of operation at 0.2pf lead. But the associated kVA/kW/kVAr as a percentage of the rated input has been provided.

Experience suggests that with further consideration, this same application requires the installed Generating Set to also power the local support equipment. The local support equipment being identified as base loads; including ACU's, vent fans, heating and essential building service type loads. The operating power factor of these base loads will have an inductive element and so an element of lagging power factor will be introduced. It now becomes essential that the Generating Set supplier undertakes a technical exercise to identify the mode of operation of the Generating Set(s) and the associated total load under various scenarios. This will enable the real combined power factor of the total load to be identified.

If the application includes multiple Generating Sets operating in parallel under an n+1 control function, then the identified site load must be technically considered, and the power supply characteristics in terms source impedance can then be related to the load (kVA/kW/kVAr/pf). A route is now open to consider the power generation scheme against the Capability Diagram (Operating Chart) constructed for that power generation scheme.

The modified Op Chart on the next page stands as an example, to indicate the alternators capability. The reference parameter for an alternator's capability is the synchronous reactance (Xd). The lower the level of Xd the stiffer the alternator; therefore, the better its capability to operate under a leading power factor condition. The below chart compares the capability to cope with leading power factor conditions when the value of Xd is varied.




For example; the above Capability Diagram has been created for an alternator rated at 100kVA. From that alternator’s technical data sheet, we can read the synchronous reactance (Xd) value is 2.0pu at 100kVA. The load to be considered has been identified as being 70kVA at 0.8 pf lead.

Consider the semi-circle aligned with the (70/100) = 0.7per unit in the LEAD side of the X axis.

Consider the radial line associated with 0.8pf LEAD (top LH corner).

The intersection of the 0.7 semi-circle and the 0.8pf lead line occurs at a point to right-hand side of the hand drawn line for Xd at 2.0.

By being to the right-hand side, the intersection is ‘inside’ the operating envelope for the alternator and so will result in the alternator remaining under positive AVR control, and so a stable excitation system will exist.

Consider the same above example alternator under a condition of 70% load at 0.2pf lead. The intersection is way outside the operating envelope. If the above 70% load at 0.2pf power supply consists of multi-Generating Sets running in parallel, then a condition can develop whereby the leading power factor load has self-excited the alternators, thereby no longer positive AVR control.  Pole slipping and consequential loss of synchronisation will occur.