Advice on Power Factor and Accuracy of Temperature Dependant Outputs

REPORT

- WP03749-EE-RP-0001
- Rev. 1
- 3 September 2009

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Executive Summary

This report documents the advice provided to the Independent Marker Operator (IMO) regarding the application of power factor to generator ratings and the validity of using a 0.1°C gradient calculation of the temperature dependence of a generation facility. Physical limits on provision of reactive power and reactive power control are also covered in this report.

Power Factor

To remain consistent with the requirements of the Technical Rules, the following power factors should be applied:

- Synchronous generators – most dispatchable generators : 0.8
- Induction generators – some smaller generators: 0.95
- Inverter generators- most wind-farms: 0.95

However, for some synchronous generators this may marginally overstate the capability of the generator to meet the requirements of the Technical Rules and therefore these calculations should be checked against a generator capability curve, to be supplied by the applicant, or against the registered maximum active power output detailed in the applicant's Access Contract. Permitted derogation from the Technical Rules may also impact the power factor to be applied.

Accuracy of De-rate Temperature Data

A 0.1°C change in temperature would reduce output of most gas turbines by approximately 0.065%. The ambient temperature will need to rise by 1°C before a decrease in output of approximately 0.5% can be seen. Furthermore, calculating temperature dependence using a 0.1°C gradient will not capture the true effect of the temperature change as other factors that affect generator output are also present. For example a loss of 1mbar of compressor inlet pressure will reduce output of industrial gas turbines by approximately 0.05%. This reduction of 0.05% will interfere with the accuracy of measurements that are intended for a 0.1°C increase in temperature.

SKM has undertaken no review of the impact changing the accuracy of the site temperature reference may have on the operation of the Wholesale Energy Market and therefore makes no comment with regards to this.

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1. Application of Load Factor

1.1. Use of Load Factor within the IMO Market Processes

The IMO Capacity Certification process requires the IMO to determine the maximum active power (MW) capability of generating plant in order to determine the number of capacity credits applicable to that generator. SKM understand that generators provide the capacity of plant to the IMO in active power (MW) or apparent power (MVA). Typically capacity provided in MW is with reference to the capability of the engine or prime mover to produce real power. A reference to MVA is reference to the current carrying capacity (Amps) of the generator or alternator and includes an active (MW) and a reactive (MVAr) component of power.

If the capacity of the generating plant is provided in MW (at a given temperature), this rating can be applied directly in the IMO capacity certification process. If the capacity for a generating plant is provided in MVA, an appropriate "power factor" must be applied to convert this MVA to the appropriate MW.

This section of the report is to provide IMO advice on the appropriate power factor applicable to various types of generation and to provide an overview of situations in which the application of the power factor may not be appropriate due to other limitations of particular machines.

1.2. Explanation of Power Factor

The **power factor** of an AC electric power system is defined as the ratio of the real power (P- measured in the units MW) flowing to the load, to the apparent power (S - measured in the units MVA). It is always a number between 0 and 1. Reactive power (R – measured in the units MVAr) is always present in alternating current (AC) systems. This reactive power fluctuates around the average real power. Reactive power can be understood as the component of apparent power that is necessary for an AC system to operate, however it does not do any useful work. Apparent power is the product of the root mean squared current and root mean squared voltage of the circuit and measured in volt-ampere (MVA). It is consists of both real and reactive power vectorialy added together. Due to energy being stored in the load and returning to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power can be greater than the real power. The power factor is defined as:

$$pf = \frac{P}{S}$$

Expressed using the common units

$$pf = \frac{MW}{MVA}$$

Or as would typically be used by the IMO .

$$MW = MVA \times pf$$

When power factor is equal to 0, the energy flow is entirely reactive, and stored energy in the load returns to the source on each cycle. When the power factor is 1, all the energy supplied by the source is consumed by the load. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle between voltage and current.

For example, to get 1 MW of real power, if the power factor is unity, 1 MVA of apparent power needs to be transferred (1 MW / 1 = 1 MVA). At low values of power factor, more apparent power needs to be transferred to get the same real power. To get 1 MW of real power at 0.2 power factor, 5 MVA of apparent power needs to be transferred (1 kW / 0.2 = 5 kVA).

1.3. Technical Rule Requirements

The reactive power requirements stated in Western Power's Technical Rule Requirements for generators are presented below:

Synchronous generating units operating at any level of active power output between its registered maximum and minimum active power output level must be capable of:

- Supplying at its generator machine's terminals an amount of reactive power of at least the amount equal to the product of the rated active power output of the generating unit at nominal voltage and 0.750 (equivalent to 0.8 power factor).
- Absorbing at its generator machine's terminals an amount of reactive power of at least the amount equal to the product of the rated active power output of the generating unit at nominal voltage and 0.484 (equivalent to 0.9 power factor).

A synchronous generating unit must therefore operate with a power factor between 0.8 lagging and 0.9 leading, while producing at its maximum active power output.

Induction generating units operating at any level of active power output between its registered maximum and minimum output level, must be capable of supplying or absorbing an amount of reactive power at the connection point of at least the amount equal to the product of the rated active power output of the generating unit at nominal voltage and 0.329 (equivalent to 0.95 pf leading or lagging).

Inverter coupled or converter coupled generating units operating at any level of active power output between its registered maximum and minimum output level, must be capable of supplying reactive power such that at the inverter or converter connection point the lagging power factor is less than or equal to 0.95 and must be capable of absorbing reactive power at a leading power factor less than or equal to 0.95**.**

1.4. Calculating Active Power (MW) from Apparent power (MVA)

In most cases, to calculate the active power (MW) capability of a generator the apparent power (MVA) capability of the generator should be multiplied by:

- 0.8 for synchronous generators.
- 0.95 for induction generators and inverter connected generators.

This rule will hold for the majority of the generators connected to the SWIS. Exceptions to this rule are discussed below.

1.5. Exceptions to the Rule 1

1.5.1. Scenarios Where a Case May Be Put That the Technical Rules Should Not Define Power Factor

When a Generator is permitted to be in power factor control or Western Power have provided an alternative derogation, a generator will be excused from following the Technical Rules. Depending on the nature and duration of this derogation, it may be appropriate for the IMO to consider the use of alternative load factors for the calculation of real power in these scenarios. Such derogation may be applicable in cogeneration plant or plant that is providing "top up" power to the grid, depending on the nature of the customer load.

1.6. Exceptions to the Rule 2

1.6.1. Capability Curves of the Generator

All synchronous generators / alternators (item of plant that creates the electricity) have the capability to supply both reactive power and real power. However, the amount of reactive power capability varies with the generation of real power. This depends on the generator parameters and associated network parameters.

Figure 1 presents a typical generator reactive capability curve. These rated reactive power curves provided by manufacturers are strictly a function of generator's design parameters at the rated terminal voltage and the hydrogen pressure. They show that different generator loads in (MW) produce greater heating in different parts of the generator. The segment (AB) of Figure 1 is limited by rotor heating; (BC) is limited by stator heating and (CD) by armature core end heating [1].

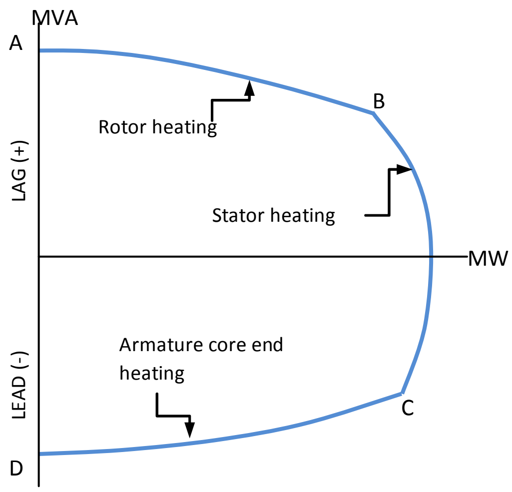
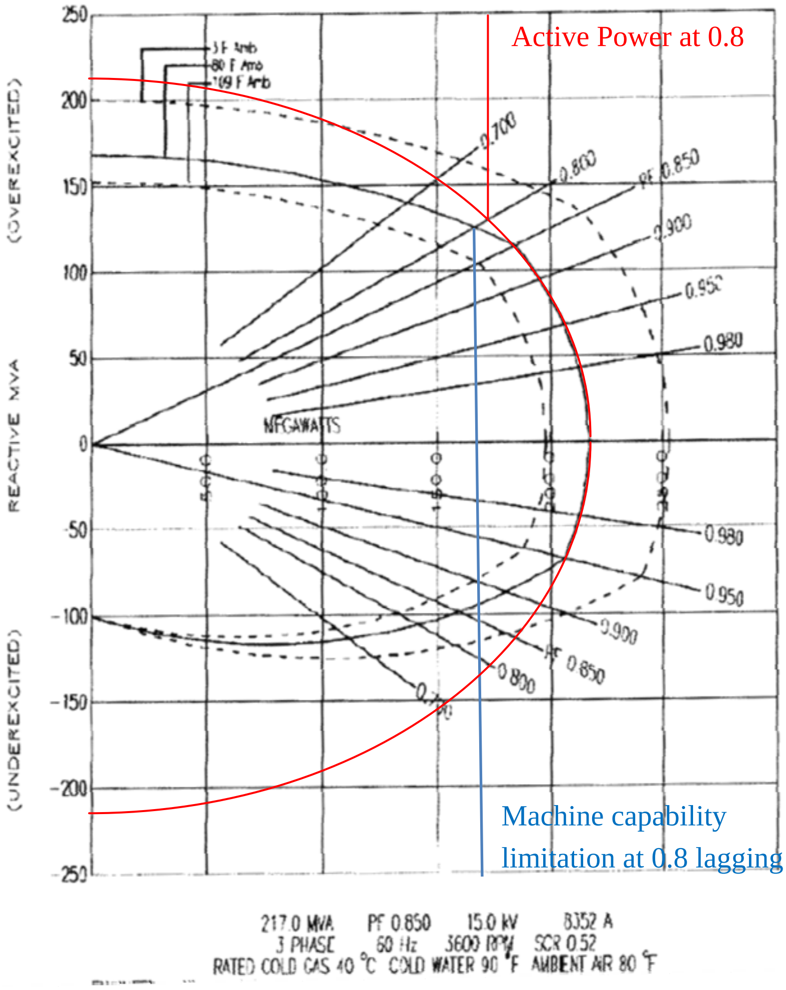


Figure 1 Generator Reactive Capability Curve

The approach to calculating the MW capability of particular generators described in section 1.4 holds in general when curve BC encompasses the 0.8 lagging to 0.9 leading power factors. If this curve does not encompass this range the segments AB (rotor heating limitation) or segment CD (armature core end heating limitation) may limit the generators capability to deliver active power as calculated in section 1.4. This is discussed further below.

1.6.2. Impact of Capability of Synchronous Generators in the Active Power Calculation

A typical synchronous generator capability curve where the 0.8 lagging to 0.9 leading power factor is not encompassed by the section BC is provided is shown in Figure 2. The curve represented by a “continuous line” indicates the normal operation of the generator. The other two curves represented by “dashed-lines” are with higher and lower hydrogen pressure. Normally these curves are dependent on the cooling performance of the machine, which is represented by hydrogen pressure.



- **Figure 2 Typical Capability Curve of Synchronous Generator**

From this figure it can be seen that the machine active power (MW) capability at 0.8 lagging is less than the active power calculation at 0.8 lagging. In this figure the apparent power (MVA) basis is defined by the active power (MW) at unity power factor (horizontal axis).

Most generators connected to the SWIS will have the section BC applying over the 0.8 lagging to 0.9 leading power factor range and as such the calculation in section 1.4 should hold. However, to confirm this is the case the IMO could either request from the applicant the generator capability curve or refer to the registered maximum active power output detailed in the applicants Access Contract to confirm this position.

2. Environmental Correction Factors for Generation Facility

2.1. Quantification of Parameters Affecting Prime Mover[1] Performance

There are many parameters that affect generation unit performance (depending on the type of prime mover) and some can be relatively complex in their application.

Typically, a prime mover (eg. gas turbine) unit supplier will "guarantee" the operation of a unit at particular environmental conditions. The test against this guarantee is typically undertaken shortly after the installation of the machine whilst the machine is in optimal condition. From this point the output of the machine will degrade over time (performance degradation) and will change as environmental conditions change, described by the correction factors of the machine.

2.1.1. Correction factors.

The impact of environmental conditions on the output of a generation machine are described through correction factors.

Historically, correction curves representing these factors were used. However these curves are now typically only used to demonstrate effects and for estimating purposes only.

For accurate assessment and evaluation, correction algorithms built into supplier proprietary performance software are used. Correction factors apply to both environmental and system operating characteristics. Some correction factors have greater influence on unit performance than others. The relative influence of these factors may also change depending on the generator operating load at any given time. Every generator supplier has their own series of prime mover correction factors depending on type of mover, supplier and model. There is no general set of correction factors that can be applied across a range of different supplier prime mover models or types.

Similarly, suppliers may potentially develop and present correction algorithms or curves for specific project applications rather than publish overall generic corrections. In such instances the corrections are presented to best suit the expected performance around the actual guaranteed conditions, with performance at the extreme end of the range typically degraded. Basic correction factors affect the prime mover's gross power output and corresponding input energy consumption (usually expressed either in terms efficiency, heat rate or specific fuel consumption).

[1] Refernce to "Prime Mover" used to avoid confusion with the use of "generator" to describe the electrical component of electricity generating plant in the previous section.

These correction factors influence mainly the machine airflow, which will influence the gross power output capability of the prime mover (turbine or reciprocating engine) and the generator or main generator transformer equipment.

Typically the external influencing correction factors include

1) Gas Turbine Generator Equipment
   - Compressor inlet temperature (usually equal to ambient temperature unless inlet conditioning is used).
   - Compressor inlet air pressure (equal to ambient pressure less inlet system pressure losses).
   - Compressor inlet air relative or specific humidity.
   - Compressor inlet pressure losses (separate correction if atmospheric pressure is used as the principal correction).
   - Exhaust pressure losses.
   - Generator cooling system inlet temperature.
   - Bottoming cycle cooling system supply temperatures (combined cycle only).
   - Fuel type.
   - Fuel calorific value.
   - Generator unit operating speed.
   - Connected system frequency (may be the same as the generator unit operating speed, but can be different depending on generator type and load conditions) .
   - System power factor.
   - System voltage.

2) Reciprocating Engine (Diesel or Gas Engine) Generator Equipment
   - Ambient air temperature (effects typically only significant at higher ambient air temperatures of 25°C or greater).
   - Atmospheric air inlet pressure (typically only significant at atmospheric inlet pressures equivalent to 1500m elevation or higher).
   - Exhaust pressure losses.
   - Generator cooling system inlet temperature.
   - Fuel type.
   - Fuel calorific value.

- Generator unit operating speed almost universally directly related to connected system frequency.
- System power factor.
- System voltage.

3) Thermal Generation Plant (Boilers + Steam Turbine Generators)
   - Primary cooling system supply temperatures.
   - Generator cooling system inlet temperature.
   - Fuel type.
   - Fuel calorific value.
   - Fuel moisture and ash content.
   - Carbon Ash content.
   - Generator unit operating speed almost universally directly related to connected system frequency.
   - System power factor.
   - System voltage.

   Such plant performance is normally presented in the form of varying Heat Balance Diagrams.

2.1.2. Performance Degradation Information Available

Performance degradation refers to the degradation of machine output over time due to wear in machine tolerances. This degradation is usually partially recovered at machine overhaul times. Performance degradation is again dependent on unit type, but also importantly on the operating regime.

Suppliers typically only make available generic overall average fleet performance degradation information. This information is not used to assess the specific performance of any individual generating units at any particular point in its life cycle. If this is required then suppliers will provide this information in conjunction with some form of Long Term Service Agreement (LTSA), with the actual quoted degradation values being more commercially than technically driven.

2.2. Environmental Factors Affecting Generators and Applicable De-Rating Values for Various Generation Technologies

All gas turbines, irrespective of the fuel type that powers them, require air for the combustion process to occur efficiently. An increase in the ambient temperature will reduce the density of air flowing into the compressor; this reduces the output of the prime mover.

The main potential impact of higher altitude is the effect on compressor inlet pressure. Lower compressor inlet pressure means lower compressor discharge pressure, which directly reduces the overall performance of the unit.

Inlet and exhaust pressure losses also cause the air density to decrease. This will also cause a reduction in the generator output.

Table 1 below presents the main de-rating factors for some common gas turbine models.

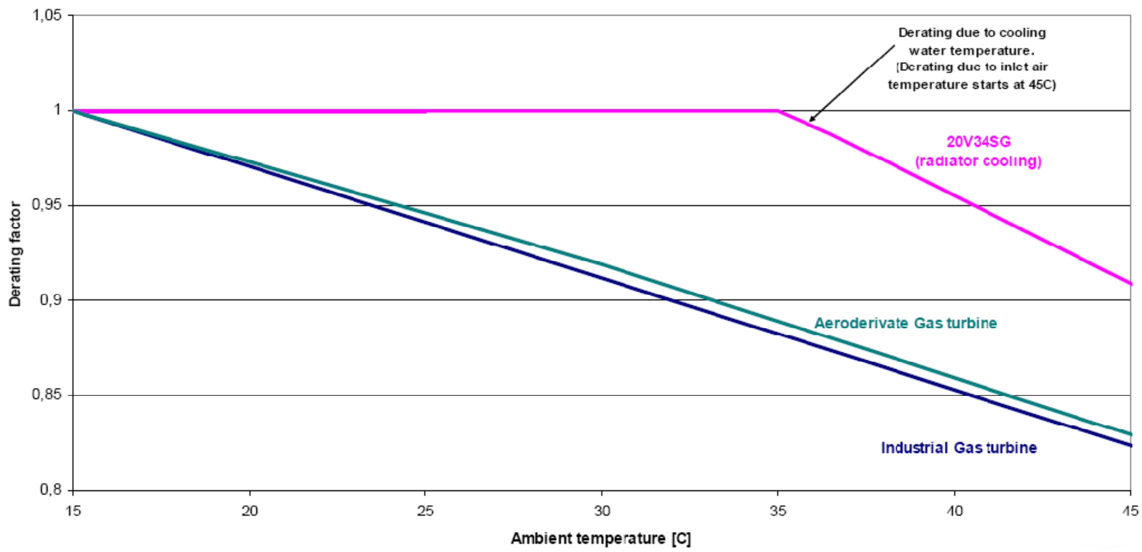
- **Table 1 De-rating Factors for Different Generators**

	Compressor Inlet Temperature effect	Inlet pressure loss effect	Exhaust pressure loss effect
GE Frame 6B	-0.65% per °C	-1.5% per 10 mbar	-0.5% per 10 mbar
GE Frame 9E	-0.65% per °C	-1.5% per 10 mbar	-0.5% per 10 mbar
GE LM 6000PC	-1.25% per °C	-1.35% per 10 mbar	-0.35% per 10 mbar

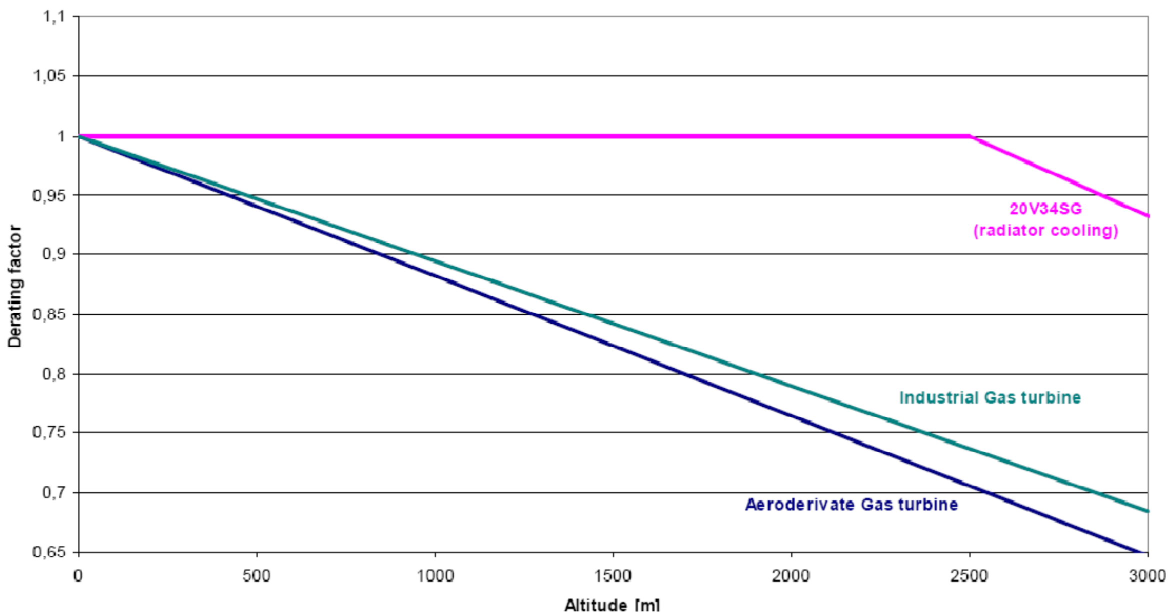
- **Table 2 Effect on Generator Output of Gas Engines**

	Temperature effect (15-41°C)	Inlet pressure loss effect (0-30mbar)	Exhaust pressure loss effect (0-30mbar)
GE Frame 6B	-17%	-4.5%	-1.5%
GE Frame 9E	-17%	-4.5%	-1.5%
GE LM 6000PC	-33%	-4.0%	-1.0%

Table 2 above presents the effects on prime mover output for a certain changes in the operating conditions of the gas turbines. For a GE Frame 6B and 9E a compressor inlet temperature increase from 15 to 41°C, or increase by 26°C will result in a 17% reduction in output. For a GE LM 6000PC the reduction in output is 33% for the same change in compressor inlet temperature conditions. Similarly the inlet pressure needs to drop by 30mbar for approximately a 4% reduction in output across all three machines. Altitude needs to increase by 1000m in order for a 10% reduction in output to happen.



■ **Figure 3 General ambient de-rating factor for typical gas turbines**



■ **Figure 4 General altitude de-rating factors for typical gas turbines**

Figure 3 illustrates how the de-rating factors change with increasing ambient temperature for a generic reciprocating engine, aeroderivative and industrial gas turbine. Generally a reciprocating engine does not incur any degradation in output until the temperature rises approximately past 35°C. In the case of the aeroderivative and industrial gas turbines, performance degradation occurs when the ambient temperature increases to past 15°C. This is assuming that the performance reference condition is at 15°C. If the performance reference condition is set at another figure then performance degradation will begin when the temperature passes that figure.

Figure 4 illustrates how the de-rating factors change with increasing altitude for a generic reciprocating engine, aeroderivative and industrial gas turbine. The impact here is again air pressure. As altitude increases air pressure drops. For any specific reference installation the altitude does not change. However the air pressure changes constantly. This figure shows that reciprocating engines are less affected by changes in air pressure than aeroderivative and gas turbines.

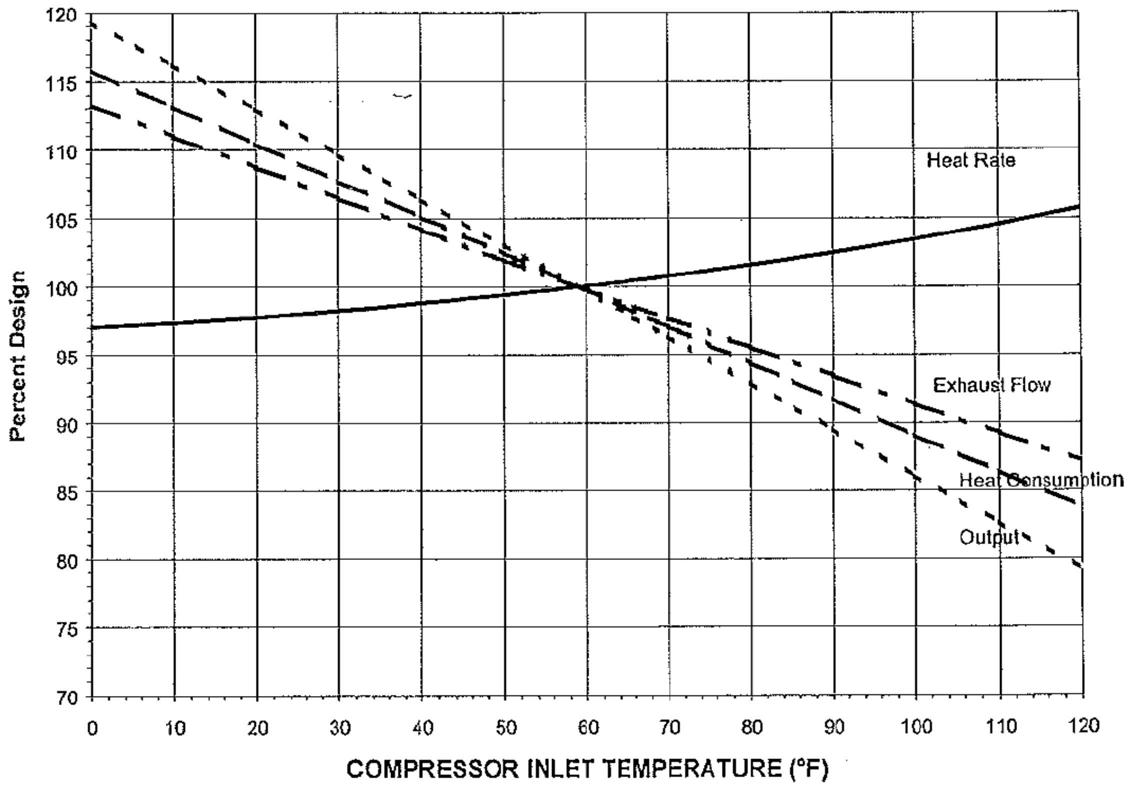
Please note that Figure 3 and Figure 4 have been taken directly from a “Sales Presentation” provided by Wartsila to sell reciprocating engines in comparison to gas turbine generator equipment. Hence they should only be considered to show that reciprocating engines are influenced less than a gas turbine by inlet temperature and inlet pressure.

2.2.1. Main Factors Affecting Generators and Applicable De-Rating Values for Steam Turbines

For steam turbine powered generators, there is negligible effect across changes in the factors mentioned above.

2.3. Conclusions on the Applicability of 0.1 degree Temperature Accuracy

A 0.1°C change in temperature would reduce output of most gas turbines by approximately 0.065%. The ambient temperature will need to rise by 1°C before a decrease in output of approximately 0.5% can be seen. Furthermore, calculating temperature dependence using a 0.1°C gradient will not capture the true effect of the temperature change as other factors that affect generator output are also present. For example a loss of 1mbar of compressor inlet pressure will reduce output of industrial gas turbines by approximately 0.05%. This reduction of 0.05% will interfere with the accuracy of measurements that are intended for a 0.1°C increase in temperature. Figure 5 below is typical performance curve of a generator provided by manufacturers for estimating purposes. SKM has undertaken no review of the impact changing the accuracy of the site temperature reference may have on the operation of the Wholesale Energy Market and therefore makes no comment with regards to this.



- **Figure 5 Typical Generator Performance Graph Provided by Manufacturers**

3. Conclusions

To remain consistent with the requirements of the Technical Rules, the following power factors should be applied:

- Synchronous generators – most dispatchable generators : 0.8
- Induction generators – some smaller generators: 0.95
- Inverter generators- most wind-farms: 0.95

However, for some synchronous generators this may marginally overstate the capability of the generator to meet the requirements of the Technical Rules and therefore these calculations should be checked against a generator capability curve, to be supplied by the applicant, or against the registered maximum active power output detailed in the applicant's Access Contract. Derogation from the Technical Rules may also impact the power factor to be applied.

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4. References

[1] Adibi, M.M., Milaniez D.P. and Volkmann, T.L, “Optimizing Generator Reactive Power Resources”, IEEE Trans on Power Systems, Vol.14, No.1 February 1999, pp 319-323

[2] Adibi, M.M. and Milanicz, D.P., “Reactive Capability Limitation of Synchronous Machines”, IEEE Trans on Power Systems, Vol.9, No.1 February 1994, pp 29-40