Power Factor Correction - The Easiest, Biggest, Green Initiative

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Abstract

Poor power factor costs our community in increased electricity charges and unnecessary greenhouse gases. Incentives for customers to maintain the required power factor varies across Australia from those that are charged a penalty by way of a kilovoltamperes (kVA) demand charge to those that should comply with the local service rules, legislated or National Electricity Rules requirements.

Some states require operation at only 0.8 power factor which cause series losses of 36% over unity power factor.

This paper sets out to detail what power factor is, the need to improve power factor, state by state power factor requirements and penalties for poor power factor, the costs to the community and the environment, suitable power factor limits, a consistent method of encouraging rectification of poor power factor by penalty tariffs right across Australia, and a method of introduction of the recommended penalty tariff regime.

1. Introduction

The efficient use of electricity assists in the profitability of Australian companies and helps to minimise greenhouse gas emissions. Poor power factor (PF) (or the drawing of voltamperes reactive (VArs) to express it in different terms) unnecessarily adds to inefficiencies and increased greenhouse gas emissions.

Power factor correction can be seen as one of biggest and easiest greenhouse gas initiatives that can be implemented. In this paper we aim to provide a methodology for power factor correction for the future in Australia.

2. What is Power Factor?

2.1. Non-technical Explanation

Various analogies have been used to describe poor power factor including the following:

2.1.1. Horse Pulling Cart

A cart on a railway track is being towed by a horse that is off to the side of the railway track (refer Figure 1). The pull directly between the horse and cart is the apparent power (kVA – apparent power). The effective work by the horse is the cart moving down the track, or the real power (kilowatts (kW) – real power). The pull at right angle to the track does no effective work (kilovoltamperes reactive (kVAr) - the reactive power). The horse would ideally pull the cart directly down the railway track so the apparent power equals the real power, thus minimising wasted energy.

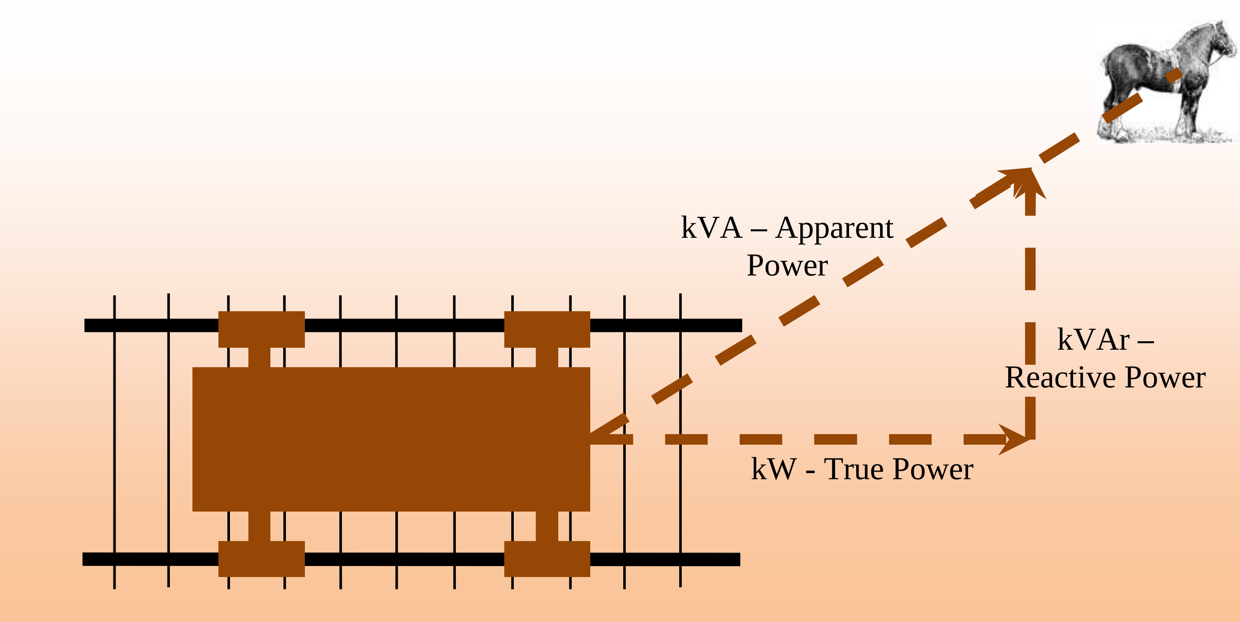

Figure 1 – Power factor analogy with horse pulling cart on tracks off-set [1]

2.1.2. Beer with Froth

A large beer is ordered to quench the thirst of a thirsty individual. The beer has some froth on top that does nothing to quench the individual's thirst – this represents the kVAr or reactive power. The beer does quench the thirst – this represents the kW or real power. The total contents of the mug (the beer and the froth) - represents the kVA or apparent power. The glass must be full of beer with no froth for the person to gain maximum benefit from the glass of beer. It is the same for maximum efficiency with power as the system should not be drawing any kVAr (or froth in the analogy).

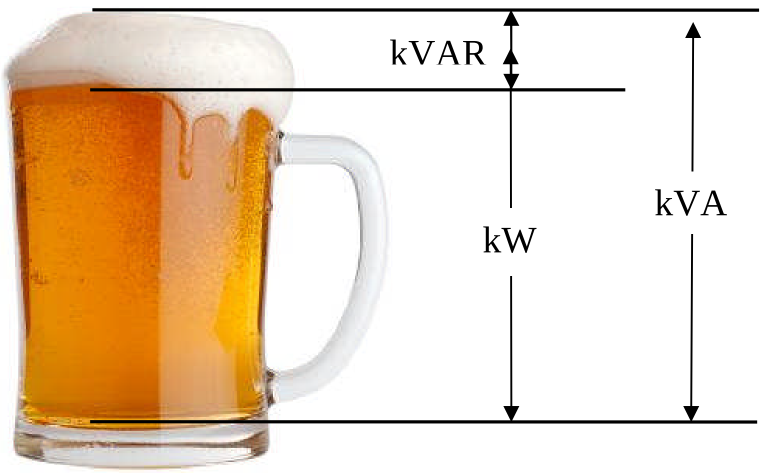

Figure 2 – Power factor analogy using a beer mug

2.1.3. Summary

Just as with the cart being pulled off set or the froth on beer, electrical power can be used inefficiently by what is called poor power factor. It is mainly caused by the use of electric motors but can be easily corrected by the connection of shunt capacitors. These capacitors are installed in a cabinet with a controller that governs how many capacitors are connected to the electricity supply at anyone time (refer Figure 3).

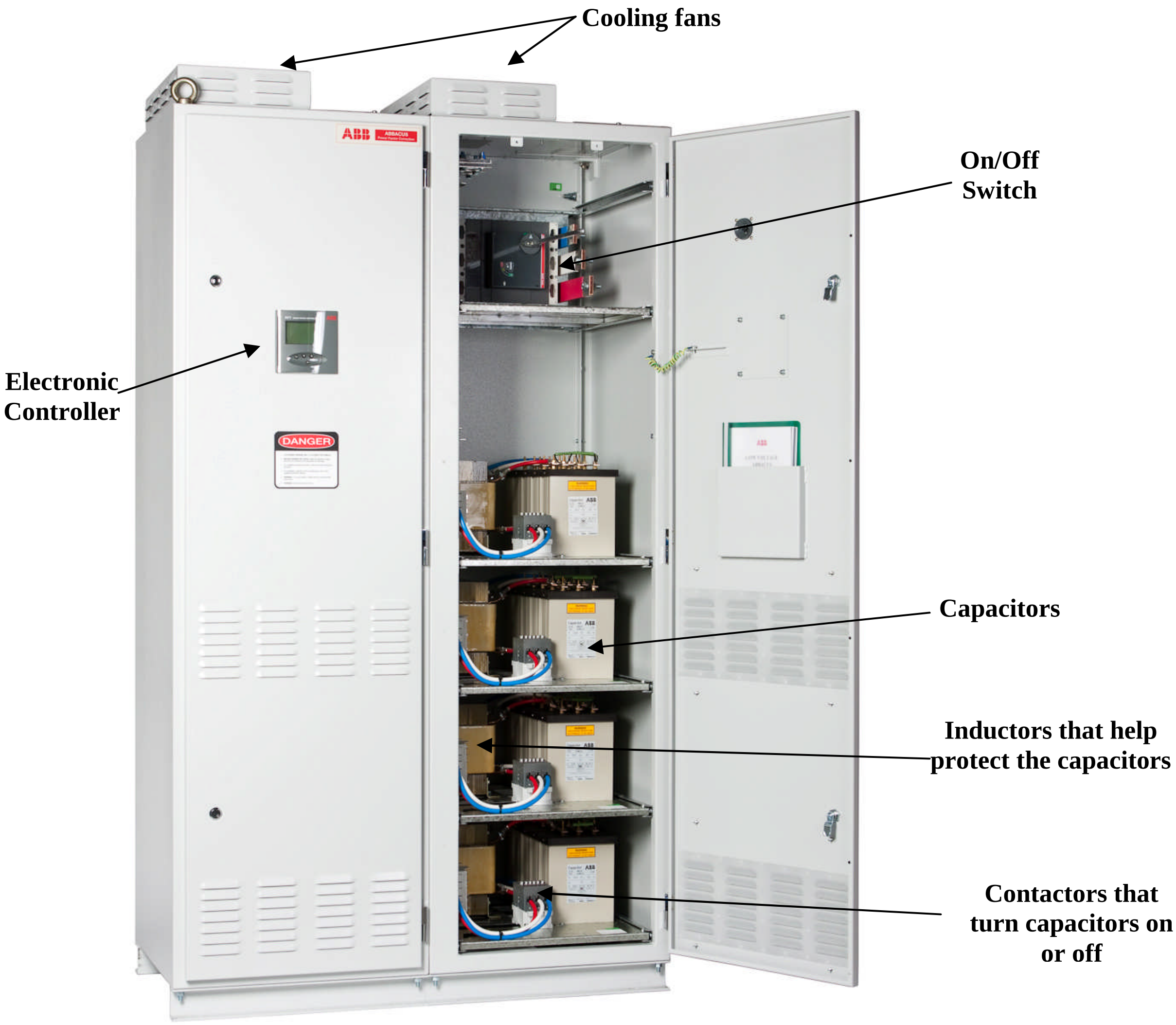

Figure 3 – Low Voltage Power Factor Correction Unit

2.2. Technical Explanation

Power factor, in an alternating current (a.c.) circuit, is the ratio of actual power in watts to the apparent power in volt-amperes.

Power factor = P/EI

If the current and volts are in phase with each other, then the power factor is at 1.0 or unity, as it is also called. However, when there is reactance in the circuit, the current and voltage are out of phase and there will be parts of each cycle where the current is negative and the voltage positive. This results in value of power that is less than the product of the current and the voltage.

There is zero power flow when the current and voltage are out of phase by 90º, as in purely inductive or capacitive circuits (reactive circuits). However, the value of power factor is normally somewhere between 0 and 1 as circuits generally contain a combination of reactance and resistance. Motors cause the current to lag the voltage and hence the power factor will also be lagging. Capacitors cause the current to lead the voltage and hence the power factor will also be leading.

The relationship between components of power flow/power factor are best shown via the power triangle (refer Figure 4). The cosine of the angle Θ equals the power factor:

Power factor = Cos Θ

Cos Θ = kW/kVA

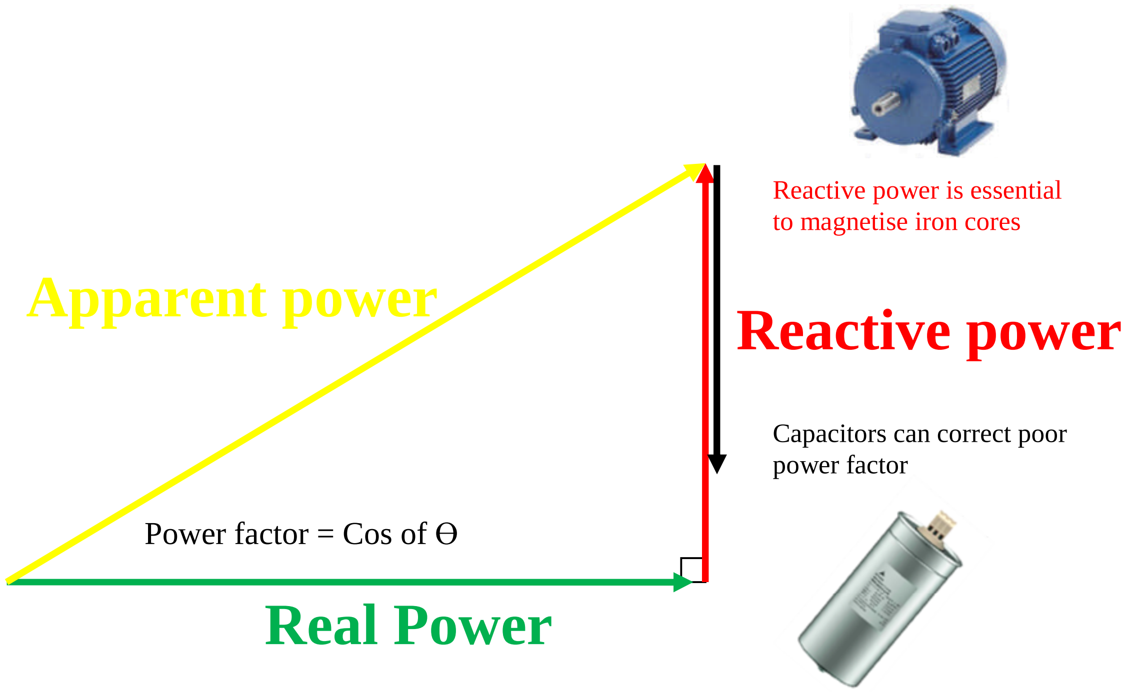

Figure 4 – Power Triangle shows the relationship between all components

It would seem from the previous explanations that reactive power is wasted power but this is not the case. Reactive power is essential for magnetising the iron or steel cores of the countless electric motors, generators, fluorescent light ballasts, transformers etc connected to the electricity network.

Reactive power can be supplied from turbo-generators at power stations either operating in normal generation mode or as synchronous condensers, from capacitor banks or static compensators at transmission nodes or zone substations, or even along feeders. However, it is not essential to supply reactive power over the electricity network at all, because all reactive power needs can be supplied at the local loads themselves by means of low voltage (LV) capacitors or statcoms. What is required in the end is an economic balance between local provision and importation over the network from more remote locations. The greatest savings in network losses comes for locating capacitors as close to loads as possible but this might not always be the most cost effective solution. The provision of local reactive power has traditionally been expressed in terms of Power Factor Correction.

3. Why Improve Power Factor?

Power factor needs to be improved as poor power factor increases line loses and greenhouse gas emissions. The current in a circuit is a factor of the apparent power and hence the larger the current, the greater will be the heating and line loses in the cables supplying the load:

$Power_{(line\ loses)} = I^2/Z$ where Z is the impedance of the cables.

Correcting poor power factor will reduce the current and line losses as the current in the circuit will reduce as the apparent power approaches the real power.

Some power companies impose penalty tariffs for poor power factor in an effort to encourage power factor correction and reduce line loses. The most common method of achieving this is via a peak demand tariff where the electricity user is penalised for the peak kVA for each month. A cost-benefit-analysis of the installation of power factor correction equipment generally shows a pay back within 1-2 years.

The correction of poor power factor also improves network efficiency (and hence improves network utilisation) and releases capacity from the network that can be better utilised at any time in the future. For example:

A business may be looking at expanding but the mains cables to the installation and the supply transformer are fully loaded. This upgrade is generally very expensive and often difficult to carry out if the cables are underground. The correction of poor power factor may release enough capacity to negate the upgrade work.

If this concept is applied right across Australia, then the benefits can be seen with the reduction of line loses and greenhouse gases and the release of network capacity that can defer or negate expensive network upgrades.

Following on from the formula above, system losses can be expressed in terms of real and reactive power (P & Q) instead of current (I). This makes it easier to see the effects of the injection of reactive power in the form of capacitors or static compensators (STATCOMS). The following formula details the relationship between P and Q loss components:

$$\text{Losses} = 3I^2R \qquad \text{Equation 1}$$

$$\text{But } \sqrt{3}VI\cos\Phi = P$$

$$\text{and } \sqrt{3}VI\sin\Phi = Q$$

$$P^2 + Q^2 = 3\,V^2\,I^2\cos^2\Phi + 3\,V^2\,I^2\sin^2\Phi$$

$$(P^2 + Q^2)/V^2 = 3I^2(\cos^2\Phi + \sin^2\Phi)$$

$$(P^2 + Q^2)/V^2 = 3I^2 \qquad \text{Equation 2}$$

Therefore (substituting Equation 2 into Equation 1):

$$\text{Losses} = R.\,(P^2 + Q^2)/V^2$$

Where R is the resistance of the particular circuit element power and V is the Voltage.

The following example shows the relationship between P and Q at 0.8 power factor:

Say	P	= 4 MW @ 0.8 PF
Then	Q	= 3 MVAr
If	R	= 1 ohm
And	V	= 11 kV

Substitute these values into: Losses = R. $(P^2 + Q^2) / V^2$

Losses	= $(4^2 + 3^2) / 11^2$ MW
	= (16 + 9) / 121 MW
	= 206kW

This answer is divided between P and Q in the ratio of 16:9.

P	= 132kW
Q	= 74 kW

Q therefore causes 36% of total losses.

It follows then that if all of the systems above were operating at 0.8 PF then approximately one third of present losses could be saved by operating at UPF and approximately one third of carbon dioxide emissions due to those losses

4. Present State Requirements

Each state has different power factor requirements that electricity users must meet and these requirements are imposed on electricity users by a variety of differing documents. Table 1 provides a summary of these requirements across Australia on a state-by-state basis and includes penalty tariff arrangements for each state. The inconsistencies between states for limits and the application of penalty tariffs are easily seen in Table 1.

Table 1 – State-by State Power Factor and Penalty Tariff Requirements

State	Limits	Measuring Method	Requirement Imposed By	Penalty Tariff Structure
Tasmania	0.75 lagging to 0.8 leading but depends on voltage and demand	Not specified	Aurora Energy Service and Installation Rules	Moving from kW demand to kVA demand
Victoria	0.75 lagging to 0.8 leading but depends on voltage and demand	Not specified	Electricity Distribution Code	Fixed or Peak kW demand
NSW	> 0.9 lag – unity (not leading) Leading and lagging ballast requirements for fluorescent lighting	Not specified	NSW Service and Installation Rules	Peak kVA demand
ACT	>0.9 but not leading. >0.9 for discharge/fluorescent lighting	Not specified	ActewAGL Electricity Service and Installation Rules	Peak kVA demand
Queensland	>0.8 to unity – not leading unless entity agrees HV as per 5.3.5 of NER	Over any 30 minutes	Electricity Regulation 2006	kW capacity and actual demand charge
Northern Territory	<66kV: 0.9 lag – 0.9 leading 132/66kV: 0.95 lag - unity	30 minute averages unless specified	PowerWater: Power Networks – Network Connection Technical Code	Peak kVA demand
Western Australia	0.8 lagging to 0.8 leading or per connection agreement	At period of daily peak demand	WA Electrical Requirements and distributor codes and rules.	Western Power - Peak kVA demand
South Australia	0.8 lagging to 0.8 leading but depends on voltage and demand	At monthly maximum demand	ETSA Utilities Service & Installation Rules	Peak kVA demand. Some old customers on kW demand
Nationally	0.9 lagging to 0.9 leading but depends on voltage	Not specified	National Electricity Rules	N/A

5. Cost to the Community and Environment

There are 16 Distribution Network Service Providers (DNSPs) in Australia that report their Distribution Loss Factors (DLFs) to the Australian Energy Regulator (AER). Only a handful of these DNSPs have reported their total network losses in megawatthours (MWh) and these reports have been compiled in different formats. It is therefore difficult to determine the total amount of electrical losses for the whole of Australia, their cost in dollar terms to electricity customers and their cost in terms of carbon dioxide to the environment. Table 2 summarises what is known. Transmission losses have not been included in this analysis as power factor is most often improved at the transmission company substations.

Table 2 – Australian DNSP Reported Losses

DNSP	*Losses*	*Unit Cost*	*Total Cost*	*Tonnes CO2*	*Year*
Energy Australia	1,541,697 MWh	$ 40	$61,667,872	1,490,821	2006/07
Integral Energy	922,626 MWh	$ 40	$36,905,040	892,179	2006/07
United Energy	409,867 MWh	$ 40	$16,394,680	396,341	2008/09
SP Ausnet	572,148 MWh	$ 40	$22,885,920	553,267	2008/09
PowerCor	766,069 MWh	$ 40	$30,642,760	740,789	2008/09
Subtotal	**4,212,407 MWh**		**$168,496,272**	**4,073,397**	

Table 3 attempts to estimate the total losses and the cost to the community for all Australian DNSP's based on the contents of Table 2. The estimates have been apportioned using customer numbers and a similar type DNSPs from Table 2 as a basis as it was difficult to determine a more suitable methodology. The Q component of line losses has been estimated at one third of total line losses using the logic described further over in this section. It is realised that different pool coefficients (an indicator of the average emissions intensity of electricity) apply from year to year and across the differing states but this has been ignored for the purposes of this paper. However, the results and methodology used in Table 3 provides a guide to the likely line losses and cost to the community that occur each year across Australia.

Table 3 – Estimated Cost to the Community for Poor Power Factor Per Year

DNSP	*Estimated Total Losses (MWh)*	*Estimated Q Losses (MVARh)*	*Estimated Cost due to Q Losses*	*Estimated Tonnes CO2 due to Q*	*Km's of Line*	*Customer Numbers*	*Sub No's*	*Estimate Basis*
Energy Australia	1,541,697	510,000	$20,400,000	495,000	49,000	1,500,000	28,000	2006/07
Integral Energy	922,626	300,000	$12,000,000	295,000		770,000	27,800	2006/07
United Energy	409,867	135,000	$5,400,000	130,000	11,000	300,000		2008/09
SP Ausnet	572,148	190,000	$7,600,000	185,000	46,000	600,000		2008/09
PowerCor	766,069	250,000	$10,000,000	245,000	80,000	683,000		2008/09
ACTEWAGL	160,000	55,000	$2,200,000	50,000		135,000		Integral
Aurora Energy	290,000	95,000	$3,800,000	90,000		259,000		Powercor
Citipower	350,000	115,000	$4,600,000	115,000		295,000		Integral
Country Energy	980,000	325,000	$13,000,000	310,000	200,000	870,000	113,000	Powercor
Energex	1,300,000	430,000	$17,200,000	430,000	50,000	1,300,000	43,420	Energy Australia
Ergon Energy	730,000	245,000	$9,800,000	235,000	150,000	650,000	70,000	Powercor
ETSA Utilites	900,000	300,000	$12,000,000	290,000		803,000		Powercor
Horizon Power	40,000	13,000	$520,000	13,000		36,000		Powercor
PowerWater	80,000	25,000	$1,000,000	25,000		70,000		Powercor
Western Power	940,000	300,000	$12,000,000	300,000	89,700	840,000	58,000	Powercor
Estimated Total	**5,770,000**	**1,903,000**	**$76,120,000.00**	**1,858,000**				

Table 3 provides an annual saving of $76M/year and improving the power factor from 0.8 to unity equates to taking approximately 430,000 cars off the road based on an average of 4.3 tons usage per car per year [2].

The following analysis attempts to verify the accuracy of the estimated percentage of Q losses provided in Table 3.

Figure 5 details a typical daily load plot for a distribution substation, selected at random for this analysis, in an industrial section of Country Energy's Queanbeyan district. It shows the apparent power in kVA over several days.

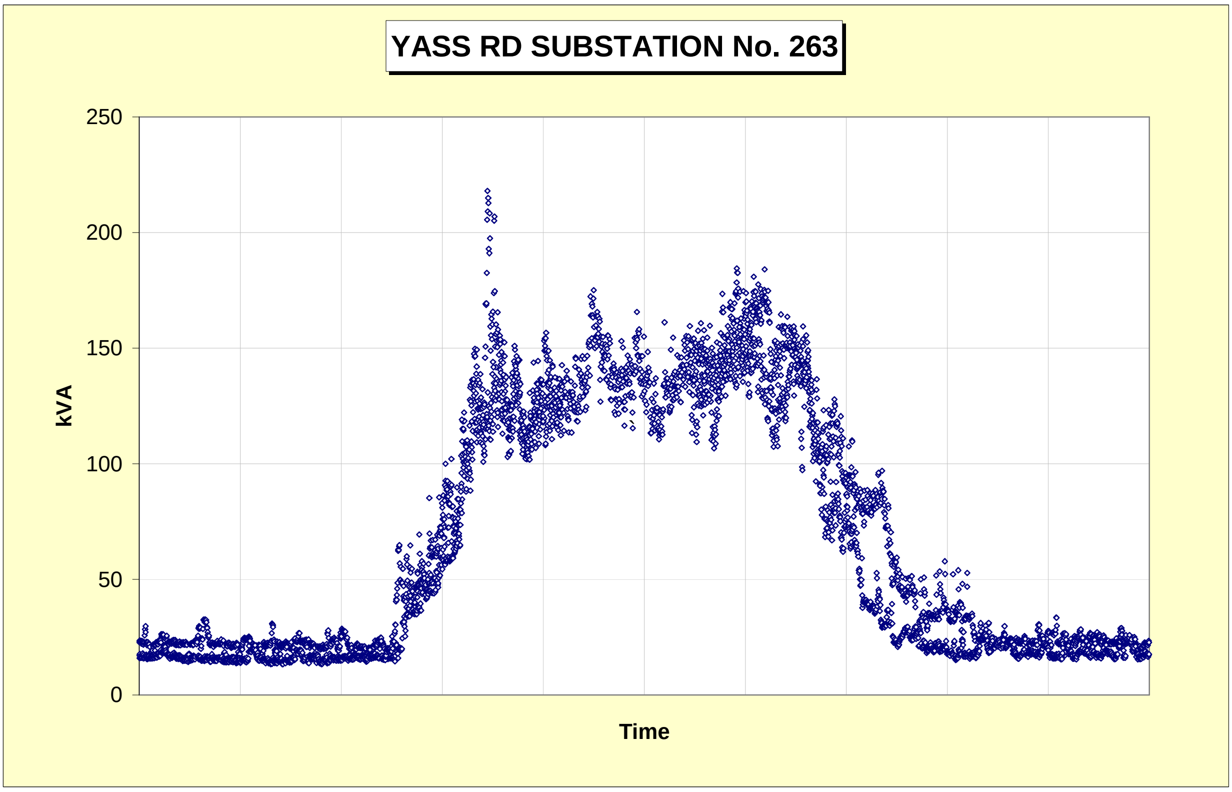

Figure 5 – Apparent power in kVA

Figures 6 and 7 chart, for the same period as Figure 5, P^2 losses in the distribution system due to the real power component and Q^2 losses due to the reactive component of the load. At full load, the losses due to P^2 average around 5kW and those due to Q^2 average around 3kW when the transformer is loaded in the middle section of the charts (power factor correction could totally eliminate this second component).

Table 3 shows Q losses at approximately 33% of total losses which is roughly confirmed by the above figures – 3/8=37%. Whilst this analysis is but one simple example, further detailed analysis has shown that up to 50% of losses are typically caused by Q in NSW but this percentage can increase, particularly in industrial areas where kVA peak demand tariffs are not in place e.g. in other Australian states. Therefore the estimate for the cost to the community in dollar and greenhouse gas terms is likely to be grossly underestimated.

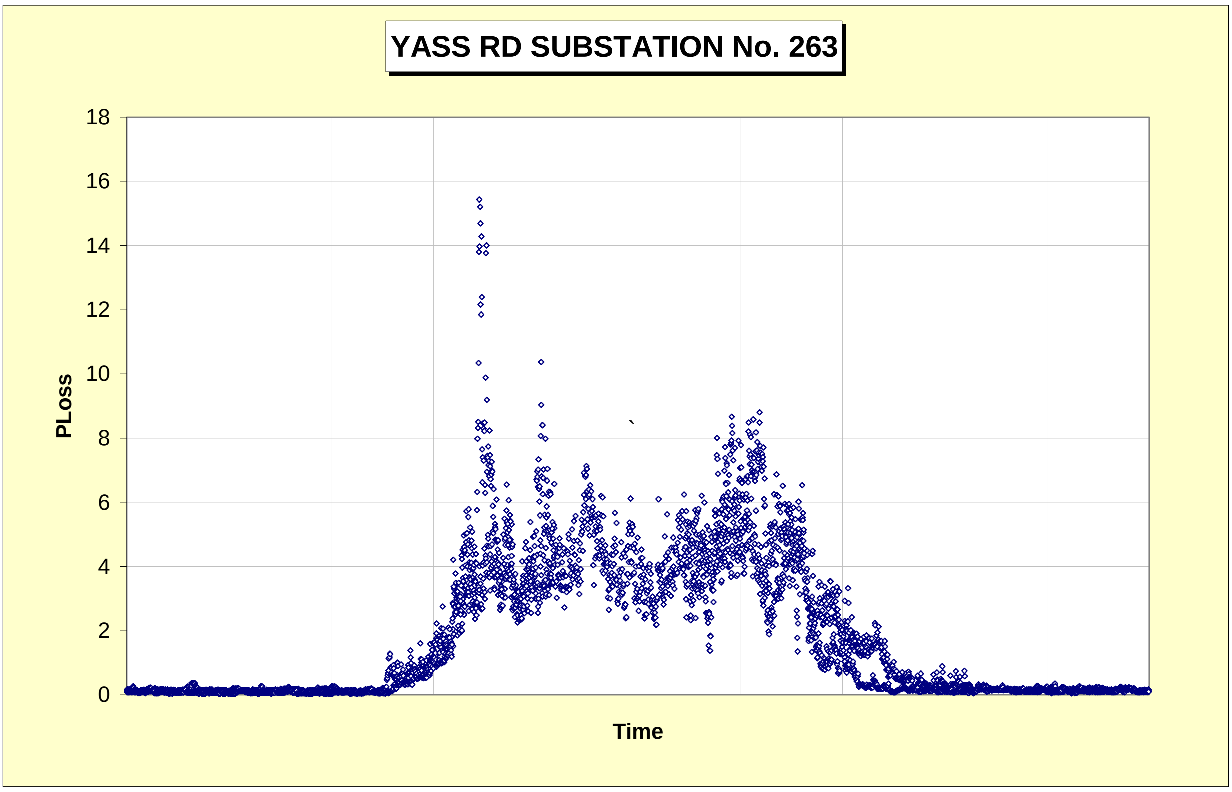

Figure 6 – kW losses due to real power flow P^2

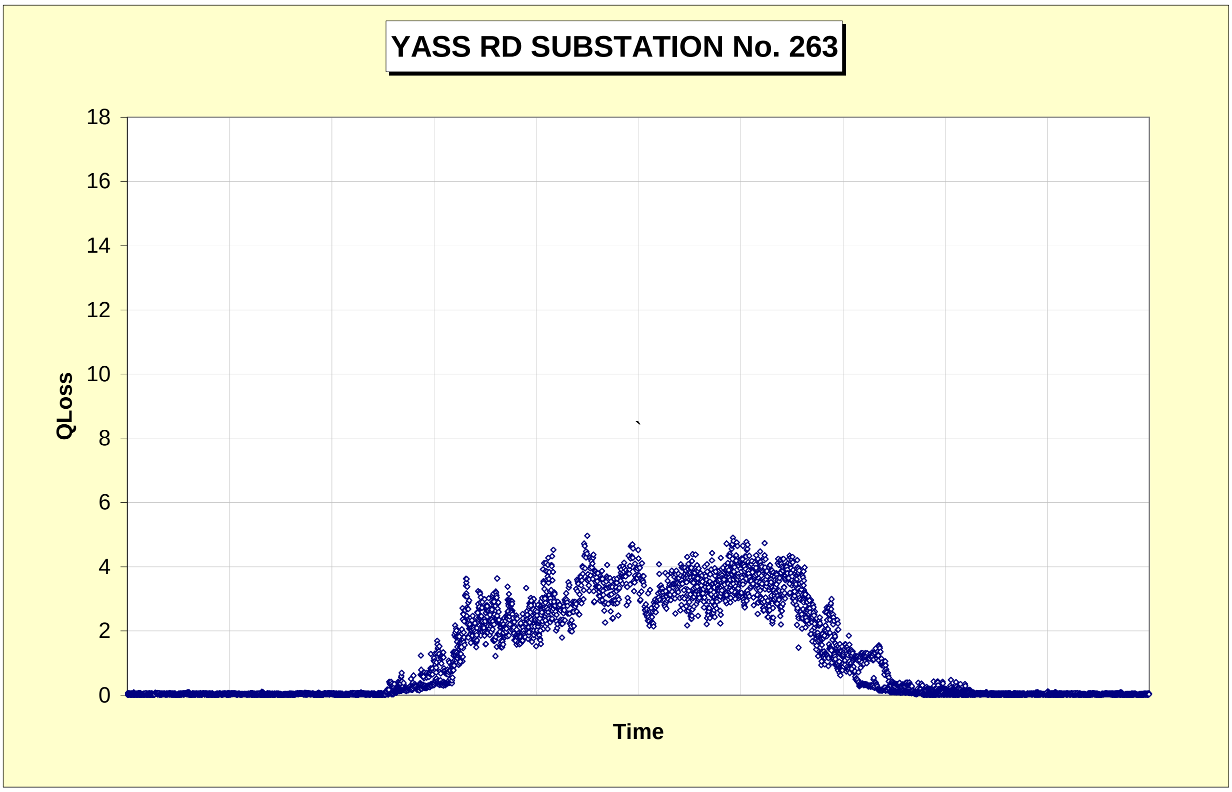

Figure 7 – kW losses due to reactive power flow Q^2

6. Recommended Limits and Tariff Structure

6.1. Limits

Power factor limits are extremely variable across Australian states as seen in Table 1 and some consistency is required if power factor limits are to remain.

It is arguable that power factor limits become obsolete if the right tariff structure is in place as the right tariff structure would dictate economic solutions to poor power factor and excessive VAr usage. Those that do not want to or can't afford to install correction equipment will then simply pay for the absorption of VArs. The issue is then simply a matter of having the right tariff structure and removing present power factor requirements from state based legislation, codes and service rules.

However, if power factor limits are to remain and a limit of 0.9 is selected as the limit, there are still 19% of total lines losses attributable to the VAr component of the load current (see Figure 8). Therefore, a higher target value may be more appropriate.

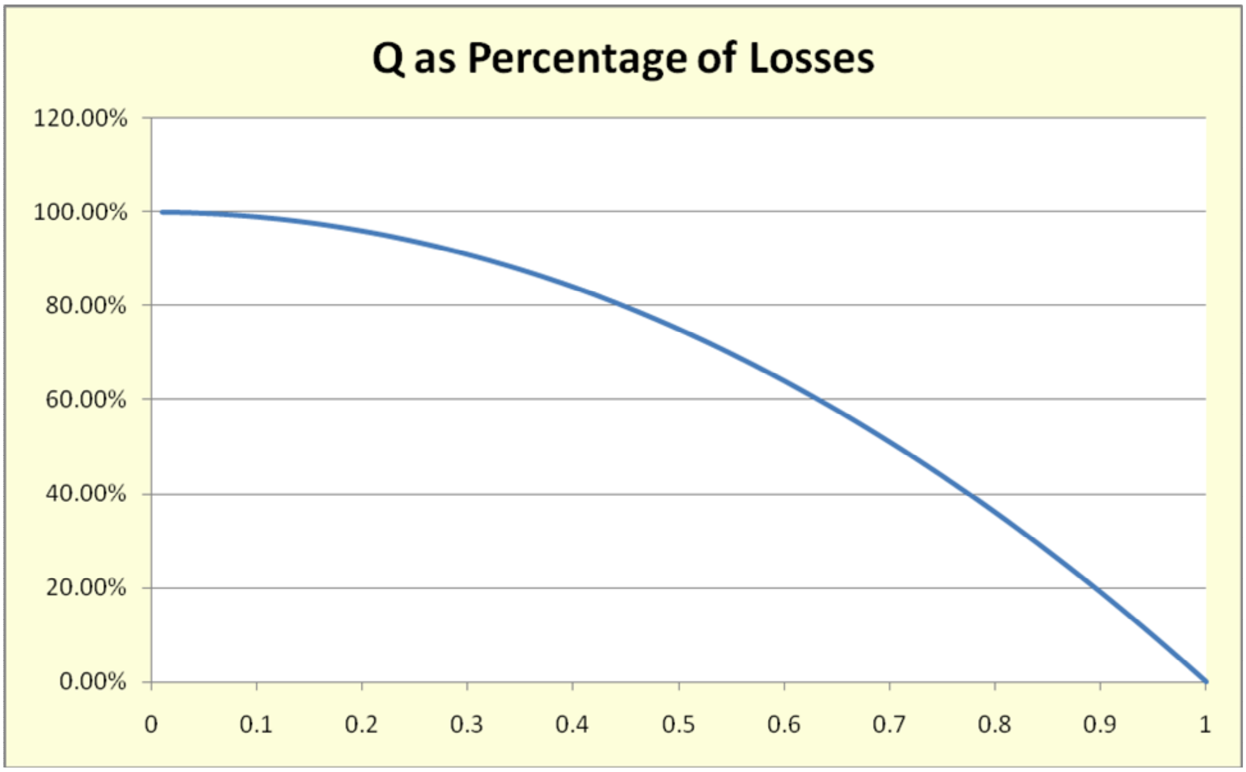

Figure 8 – Q as a Percentage of all Losses

6.2. Tariff Structure

To determine a tariff structure for the future, it is useful to consider both a peak demand and a unit rate to control power factor and the generation of VArs.

Firstly, for peak demand: Presently there are two methods of charging for peak demand i.e. kVA and kW. The kW peak demand does nothing to minimise losses and greenhouse gas emissions. Therefore it is recommended a phasing in of charging by kVA peak demand for those states that presently charge via a kW peak demand tariff. This tariff structure helps distributors provide and maintain assets and customers to cost justify the installation of power factor correction equipment.

Secondly, a peak demand tariff only assists in minimising line losses for VArs, it does not prevent these losses e.g. a large customer hits their peak demand early in the month – the business could then turn off their power factor correction equipment to minimise wear and tear. A charge for apparent power (kVAh's) instead of true power (kWh's) or additional charge on the present status quo for reactive power (kVAr) would provide an additional incentive to reduce VAr absorption from the network. Economics will then dictate to the business on whether they correct to unity power factor, to some lower value or if at all.

All measurements for kVA peak demand, kWh, kVAh or kVArh should be based on the standard 30 minute metering averages presently in place across Australia.

7. Method of Tariff Introduction

It is recommended that the tariff structure proposed by Section 6.2 be introduced after 3 years. This gives business more than enough time to budget for correction equipment and then to have it installed. A staged approach to the introduction of the tariff structure is not recommended as it would make it difficult to cost justify the installation of the equipment in the first few years and achieve little.

8. Tariff Pricing

The recommended kVAh and kVA peak demand pricing should reflect a recovery period for the customer of approximately 18 months. This makes the investment in the correction equipment very attractive for any business, they will also gain the green credits for the initiative.

9. Other Recommendations

Domestic installations have not traditionally corrected for poor power factor as they are generally not large producers of VArs and the installation of power factor correction equipment would unnecessarily complicate matters for domestic electricity customers. However, Minimum Energy Performance Standards (MEPS) could specify requirements for power factor requirements for all basic equipment, e.g. compact fluorescent lamps, when clearly this is an important aspect of their efficiency. Power factor must be taken into MEPS calculations for the resultant star ratings to be truly about efficiency of electrical equipment.

10. Summary and Conclusions

Poor power factor adds to inefficiencies and greenhouse gases and needs to be effectively managed.

Line losses are not only caused by the real power but also by the reactive power with 36% of losses caused by reactive power at 0.8 power factor.

Present requirements to control power factor across Australia are inconsistent and poorly aligned.

The cost to the community of poor power factor is estimated at approximately $76M/yr and 2M tonnes of carbon dioxide each year which equates to taking 430,000 cars off the road. These figures appear to be grossly underestimated due to the higher than expected percentage for Q of total losses (which has been noted by the analysis of energy data from various sites across Australia).

Power factor limits become obsolete with right tariff structure and those that fail to correct for poor power factor would pay additional costs.

Tariffs must dictate economic solutions to poor power factor and excessive VAr usage. A payback period for correction equipment of 18 months is recommended. The recommended tariff includes a kVA demand component and kVAh unit rate. Alternatively, the present system of charging for kWh could continue but with an additional charge for kVArh. This type of tariff structure should be phased in over 3 years to allow companies to budget and install correction equipment.

PF/VAr correction may not be the biggest green initiative but there are opportunities for a significant reduction in electricity delivery costs and greenhouse gas emission.

11. References

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12. Abbreviations

AER	Australian Energy Regulator
CO2	Carbon Dioxide
cos	Cosine
DLF	Distribution Loss Factor
DNSP	Distribution Network Service Provider
E	Electric Potential
F	Phase Angle
I	Current
km	kilometres
kV	kilovolts
kVA	kilovoltamperes
kVAh	kilovoltamperehours
kVAr	kilovoltamperes reactive
kW	kilowatts
LV	Low Voltage
MEPS	Minimum Energy Performance Standards
MVAr	Megavoltamperes reactive
MVArh	Megavoltamperehours reactive
MW	Megawatts
MWh	Megawatthours
P	Real Power
PF	Power factor
Q	Reactive Power
R	Resistance
STATCOM	Static Synchronous Compensator
V	Voltage
VAr	Voltamperes reactive
Z	Impedance