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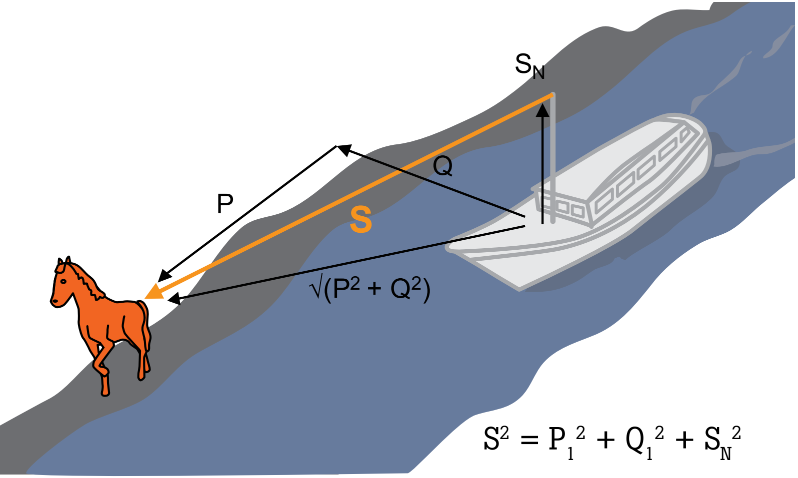
Electrical power explained

Understanding the basics of power measurement theory

Introduction

Electrical power applications are changing rapidly. LED lighting is replacing incandescent lamps, variable speed motor drives replace directly coupled electric motors, and photovoltaic installations and wind turbines generate additional electrical power. This means the load on the electric network is changing. More harmonics and more risk of unbalance. This so called 'bad' power costs money and wastes energy.

To deal with this we need more understanding of the disturbances on the electrical network. This is what Electrical Power Explained is all about: Basic theory to understand what is happening with today's electrical applications.



$$S^2 = P_1^2 + Q_1^2 + S_N^2$$

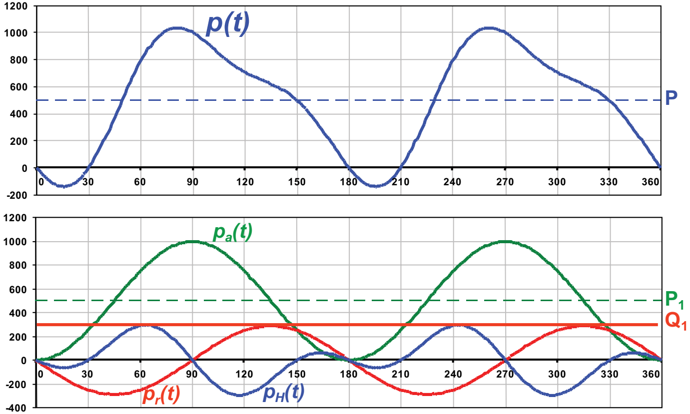
Apparent power

To understand the relation between Active Power P, Reactive Power Q and Apparent Power S, look at this historical Canal Boat metaphor. The boat stands for the electrical load, the horse for the generator and the cable from the horse to the mast for the electrical network.

Because the horse is not pulling exactly in front of the boat but at an angle, it has to deal with two forces: the desired forward pointing force P and the unwanted sideward force Q. The strain on the cable is, according Pythagoras, the square root of the sum of P squared and Q squared.

In a similar way the electrical network has to deal with two powers if the voltage and current of a load are at an angle to each other: the active power P, doing the work, and the reactive power Q, wasting network resources.

To complicate matters, harmonic components SN on the network, symbolized by choppy waves beneath the boat, stress the cable between horse and boat, and hence the electrical network, even further. The horse gets tired faster and we pay money for wasted electrical energy.



Harmonics

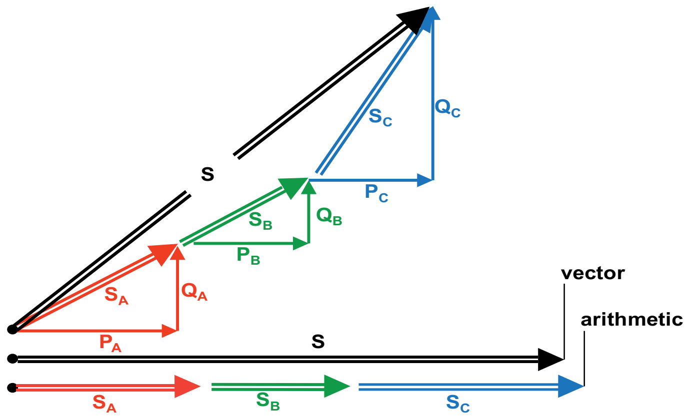
To be able to do something about this waste of money and energy we first must be able to distinguish between phase shift and harmonics.

These disturbing phenomena each require different counter measures. With Fourier analysis we can separate fundamental and harmonic power. The fundamental power can be split into an active part $p_a(t)$ and a reactive part $p_r(t)$. What is left after the fundamental power is split off, is the harmonic power $p_H(t)$.

The active part does the real work: it transfers useful energy from the generator to the load. The reactive part just bounces energy between the load and the generator, loading the network but not contributing to useful energy transfer.

The harmonic part can occasionally transfer some power for some loads but the network cannot deal efficiently with harmonic power transfer and for rotating machines and transformers it is damaging.

Reactive power can be compensated with capacitors and harmonic power with passive or active filters.



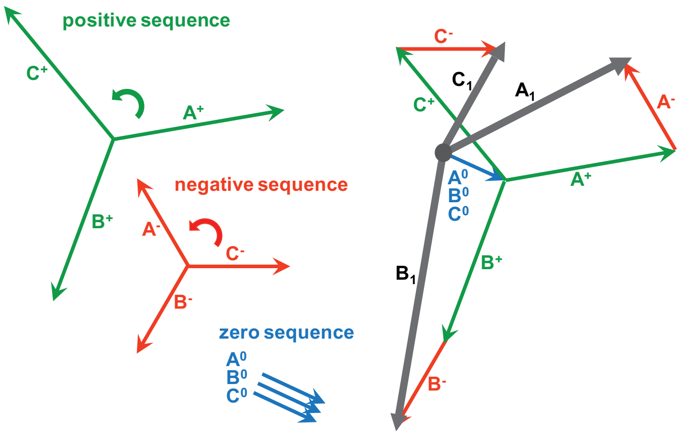
Unbalance

Getting the 3-phase system powers is often more complicated than just adding the results for the individual phases.

The graph shows the powers P, Q and S of a 3-phase system which is unbalanced. It demonstrates how we obtain the wrong answer if we calculate the apparent power S for a 3-phase unbalanced system by simply adding the individual phase results for S. We call this the arithmetic sum.

Though we may always add the active powers P and the reactive powers Q, adding the apparent powers S is only valid if the system is perfectly balanced and contains no harmonics. If this is not the case, calculating an accurate value for the 3-phase system apparent power S is not so trivial.

Although from this simplified graph it looks that the vector sum is the correct answer for S, it will turn out that even this is a too simplistic view. The unbalance causes Unbalance Power, which increases the value of S.



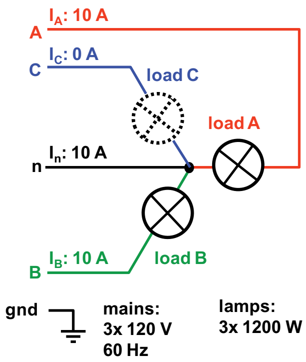
Symmetrical sequences

If we want to study the effect of unbalance in a 3-phase system we need a mathematical tool. The symmetrical sequences theory from C.L. Fortescue in 1918 is such a tool.

In short it states that you can build any unsymmetrical 3-phase system from 3 symmetrical systems: one positive sequence system with the order A, B, C, one negative sequence system with the order A, C, B, and one zero sequence system in which A, B, and C all point in the same direction.

The picture gives a graphical demonstration of this. Note that the positive and negative sequence systems are symmetrical.

The zero sequence is a sort of common single phase system. The positive sequence is the only one transporting useful power. It makes a motor run. The negative sequence acts as a break for a motor and the zero sequence just produces heat. The negative and the zero sequence added together result in unbalance power. It is this unbalance power that increases the apparent system power in case of unbalance. So unbalance in a 3-phase system means wasting energy!



2 - lamps (phase)			
	A	B	C
P	1200	1200	0
Q	0	0	0
S	1200	1200	0

2 - lamps (system)			
	Classical	IEEE	UPM
P	2400	2400	2400
Q	0	0	0
S	2400	3600	2939
S_{1U}	-	2683	1697

Classical-IEEE-UPM

How unbalance power S_{1U} influences the apparent power S is illustrated in this example.

Three 1200 W spotlights are connected to a 3-phase system. In the balanced situation this means 3600 W active power and 3600 VA apparent power. There is no phase shift, so no reactive power Q. Now one of the spotlights burns out completely. The remaining active power P is 2400 W, but the resulting apparent power S depends on the applied calculation method.

The Classical method ignores unbalance all together. This is obviously wrong as there must be unbalance power involved! The IEEE method comes to the surprising conclusion that the apparent power S does not change due to a large unbalance power S_{1U}. The Unified Power Measurement (UPM) method leads to more moderate values for apparent and unbalance power.

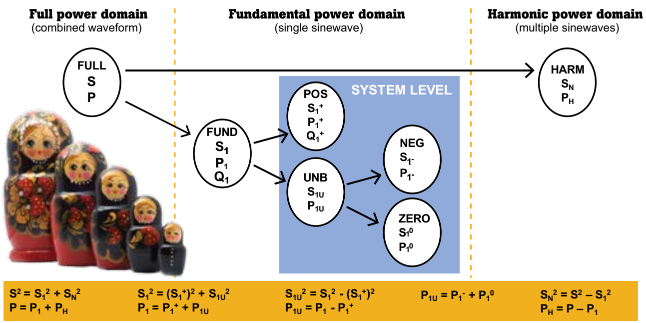
Which of the two is better? Hard to say! The academic debate about the definition of apparent power under extreme conditions is still going on. Fortunately the numbers of the competing theories are closer together as the conditions are less extreme.

Power

This picture shows how the full powers can be broken down into smaller components each with particular characteristics. This process makes analysing power problems possible.

The power components fit inside each other like a set of Russian Matryoshka dolls. Starting with the full powers, we first split off the fundamental components. The remainder forms the non-fundamental components, including harmonics.

The fundamental components can be further broken down into a positive sequence and unbalance parts. The unbalance part contains the negative and zero sequence components. By performing this power decomposition we can analyse the individual effects of unbalance and harmonics on a power system. The other way around it enables us to take efficient counter measures in case of 'bad' power.

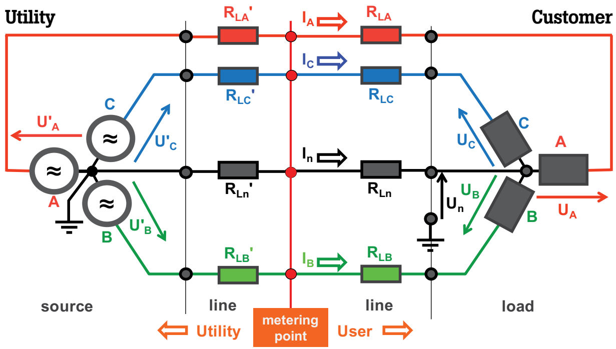


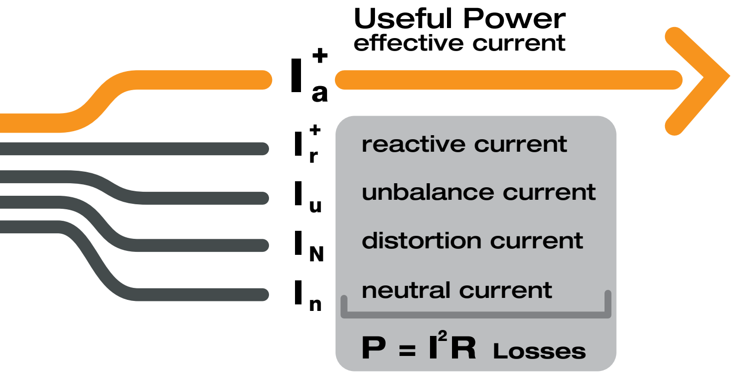
Utility to customer

The Utility part of the network is separated from the Customer part of the network by the metering point. This is where the amount of energy delivered is measured and billed to the Customer.

Not all energy paid for is efficiently used. Currents flowing through the in-house wires with finite resistance cause I^2R losses in the form of heat. These losses register at the metering point as delivered active power, but do not contribute to the power delivered to the load. So you pay for your wires heating up!

The Utility puts the money wasted in his part of the network in the energy tariff. To minimize all this waste, we need insight in how the currents in the wires are composed to take effective countermeasures.





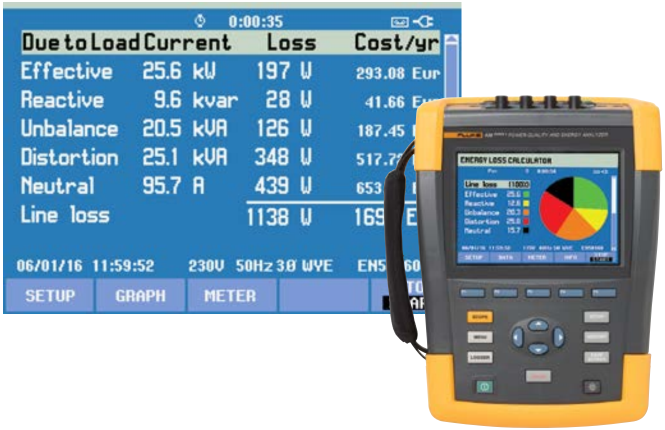
Current

By splitting up the currents into components that can be attributed to individual phenomena, we can deal with each current component in the most efficient way.

We can identify 5 major current components, each leading to some sort of loss. The effective current is the only one giving useful energy transport. Reactive, unbalance and distortion currents do not contribute to efficiently transferring energy to the load. Unbalance and distortion leads to neutral currents causing losses in the neutral conductor.

Now we have decomposed the current we can deal with the unwanted components individually. Reactive currents can be decreased with capacitors at the load, unbalance currents with balancing the load or using active or reactive balan-cing circuits, and distortion currents with active or reactive filtering.

If we decrease unbalance and distortion the neutral current will also decrease. Ideally we only have the effective current I_a+ causing I^2R losses. There is little we can do about that except using lower resistance lines.



Cost of power

The Energy Loss Calculator of the Fluke 430 series II allows us to see all the previous discussed phenomena in a glance on a single screen.

The 5 major current components: effective, reactive, un-balance, distortion and neutral are shown with the total power they represent and the losses associated with each component. This enables the user to make a quick 'health check' of the in-house network or the application under test.

Ideally there should only be effective losses. The ratio of the various losses points to the type of countermeasures needed most urgently.

Additionally the money wasted over a given period is extra-polated for each phenomenon. The total amount of money lost over a year gives an indication if counter-measures are economically feasible.

All this in a single, safe, hand-held tool conforming to inter-national standards!

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Found this interesting? Ask your Fluke representative for the complete program and become an expert on electrical power.

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