BALANCING THE UNBALANCED

How do you determine whether you are paying too much for electricity? You may get the meter tested, but that will cost you extra. Alternatively, you may try to take power measurements to determine whether you are paying too much. Using a clip-on ammeter and a voltmeter you can determine the volt-ampere (VA), the apparent power, which you then multiply by the tariff. That will give you an indication of what you would be paying based on instantaneous readings.

Power Networks in Flux

Table of Contents

Introduction

In this document I am briefly explaining the concept of balanced and unbalanced power networks. Furthermore, actual recorded data will be used to show the differences between balanced and unbalanced network conditions.

A question that I am answering is whether Eskom and the power distributors are aware of unbalanced network conditions and what they are doing about it?

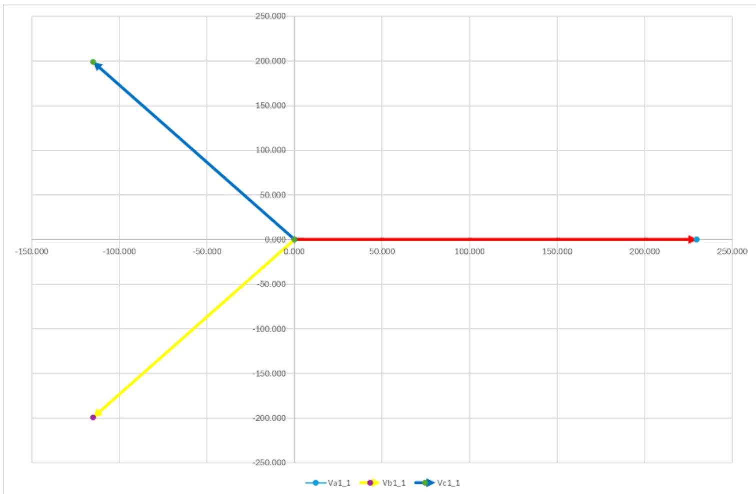
More importantly, I am going to show how customers who are subjected to unbalanced network conditions are paying a hefty price through their electricity bills while those who are generating electricity, whether that is by means of coal-fired power stations, nuclear, or renewable energy, would not really care because their *profits* due to the increases in *inefficient powers* caused by the imbalances will increase.

Perfectly Balanced Network Condition

With a perfectly balanced system, the magnitudes of the currents and voltages should be the same and the phase-displacements should be 120-degrees exactly. Secondly, with a perfectly balanced system, there should ONLY be a Positive-Sequence Component and NO Negative- or Zero-Sequence Components.

The image below is the positive-sequence voltage component of a perfectly balanced system.

There is only one vector and that is the positive-sequence component.



Unbalanced Networks Conditions

I could have copied the entire content of the Symmetrical Component Analysis explanation from the Agulhascorp website and then post it into this document, but I have decided not to do that.

You can also read what is being said about Negative Phase Sequencing so that you, as a reader, can get a good grasp of what I am about to explain below.

I also wish to point out that I have a vast amount of experience in this field dating back to the early 1980s. There are several articles that I have already posted on the blog which I encourage you to read. One of the articles I specifically wish to draw your attention to is the one about Untransposed Transmission Lines. There are quite a few more covering Unbalanced Network Conditions which I urge you to read.

Damages Resulting from Unbalanced Networks

A question that should have been raised by the City Power officials immediately after looking at the data in the spreadsheet which I have sent them on March 15, 2924, called "Power Quality Data Linden" is: how does the voltage unbalance affect electric motors, generators, transformers, and power supply cables?

The performance of the motor depends on the voltage. A voltage unbalance of 1 percent at the terminals of a fully loaded motor can result in phase current unbalance of 6 to 10 percent, which raises the operating temperature of the motor, reduces its energy efficiency, and shortens its life. Secondly, the speed and torque characteristics change if the voltage is unbalanced. The unbalanced voltage causes an unbalanced stator current, increasing the losses and the net torque. The negative sequence current produces the backward-rotating magnetic field and produces the opposite torque to the positive sequence component. Thus, the torque produced by the negative sequence current tries to retard the motor by exerting opposite torque.

In my Excel workbook attached to my email dated 17 March 2024, I remove the data about the currents since it would present a distorted image and make people confused. The recording was done at a house with all the appliances being single-phase with currents that can hardly be balanced. However, at the substations, it would be a completely different situation. The currents should be balanced.

With voltages represented by the solid lines of the vector as displayed in the last image, you will get a very high neutral current and very high circulating currents in the delta windings of transformers. This is what causes heat generation. The zero-sequence component is the one that produces **heat in transformer and cables**.

Modderbee Municipal Substation

Introduction

I recently learnt that, when an Eskom official was briefed about a possible unbalanced network conditions at the Modderbee municipal substation, it was perhaps passed off as highly unlikely. Since I was not present, I cannot vouch for the authenticity of the message that I have received through another party.

The second reason for posting this article is that I have reached out to someone who professes to be on top of power quality at Eskom with not one, but two emails. Both these emails were successfully delivered with no response to the first email while the second was "deleted without being read", as per the notification I received on my email account.

In my first email I said that "if you are the right person to cooperate with to investigate this apparent issue of unbalanced currents and voltages, as explained below, kindly let me know". In the same email I said, "I would really welcome it if you can include me in such an investigation". Whether the emails were read and then destroyed or not read at all, I cannot say, but I cannot understand that he would not have noticed the email dated April 2, 2024, by now.

Since September 2023, I have made several postings on the Agulhas Utilities Corporation website, blog, LinkedIn, and Facebook. I sincerely counted on him perhaps seeing what I have posted on LinkedIn and reacting to my findings, or for other Eskom employee on LinkedIn to perhaps see the postings and make those who deal with power quality at Eskom aware of it. This has not happened up until now and I wonder if anyone from Eskom will see this post. Furthermore, my email to Group Executive (Distribution) has suffered the same fate: “deleted without being read”. My emails to senior people in the electricity department of the City of Ekurhuleni Metropolitan Municipality have also not evoked any reaction. The emails I am referring to were sent to the senior officials as per their website.

I have therefore decided that it is time to post this new article.

Modderbee Municipal Substation Recordings

In August 2023, I was commissioned to record the loading on a municipal feeder at Modderbee substation in the Springs, Gauteng, for a consulting engineer who wanted to determine how much extra load can be added to a specific 6.6kV feeder.

On August 30, 2023, when we installed the Power Quality Monitor, we noticed that one of the phase-to-neutral voltages was “missing”. I then used a second instrument to check our findings. When the voltage was indeed below 2-volts, we thought that it could be a blown fuse on the secondary side of the busbar-VT. We continued to install the instrument since the measurement of the currents were probably more important.

The Modderbee municipal substation is supplied by means of two 6.6kV cables from the Eskom substation which is approximately 20-metres away. The municipal substation has two 6.6kV busbars with a bus-section breaker which remains open. Essentially, the busbar-VTs thus measure the incoming voltages on the two 6.6kV cables.

To get a good indication of the minimum, average, and maximum loads, I usually leave the instrument running for a week or so. The recording was therefore done for the period of approximately a week from August 30, 2023, and removed on September 5, 2023.

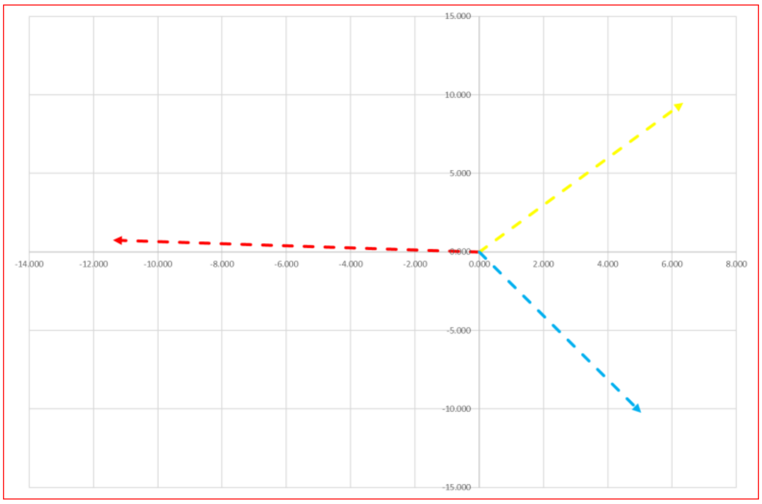
Data Analyses

At first, I did not pay much attention to anything else but to check the real-, reactive-, and apparent-power measurements, but when the consulting engineer asked about the high neutral currents, I started to analyze the data in more detail, and it was then I discovered the exceptionally high unbalanced currents and voltages.

The following are images representing the symmetrical components of the unbalanced three-phase system as recorded at Modderbee substation between August 30, 2023, and September 5, 2023.

Positive-Sequence Component

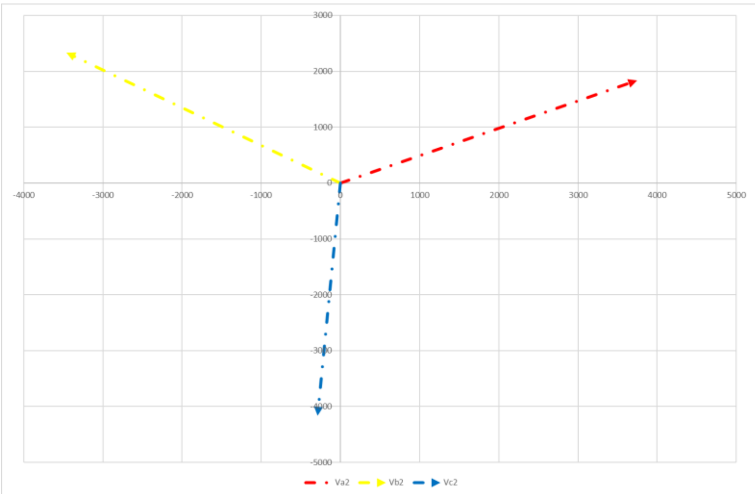
The first image is the positive-sequence component of the voltages as recorded at 03:40:00 on September 5, 2023.



The first thing to notice is that the entire vector is rotated by nearly 180-degrees since the red line should essentially be on the X-axis pointing towards the right.

Negative-Sequence Component

The image below is the negative-sequence component of the voltages as recorded at 03:40:00 on September 5, 2023.

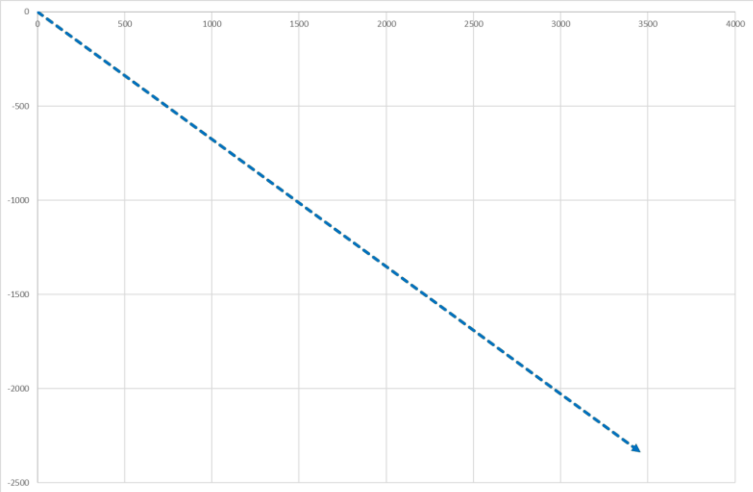


Now look at the high magnitudes of the three negative sequence components. **This should be NIL and therefore absolutely NO lines at ALL.**

Also look at the colors of the three phases. It is not Red, Yellow, and then Blue – remember the vectors are turning anticlockwise. In this case, it is Red, Blue, and then Yellow and that is why it is called Negative Phase Sequence.

Zero-Sequence Component

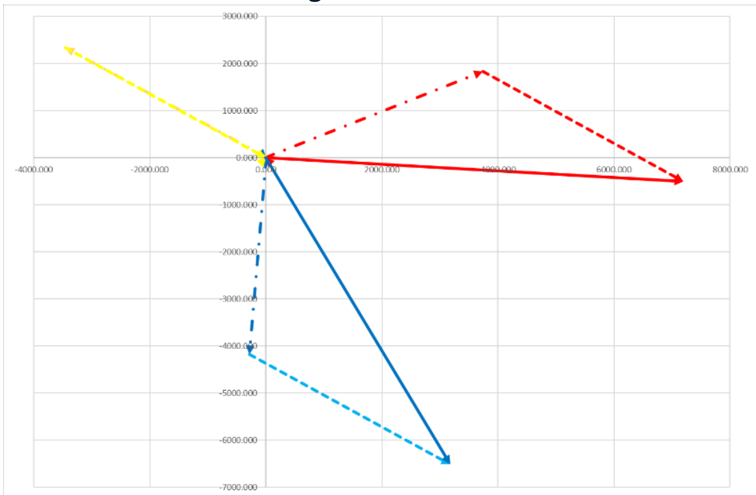
The image below is the zero-sequence component of the voltages as recorded at 03:40:00 on September 5, 2023.



The reason why you only see the blue dashed line is that the red and yellow are hidden underneath the blue. All three are of the same magnitude and angle.

Now look at the high magnitudes of the three zero-sequence components. **This should be NIL and therefore absolutely NO lines at ALL.**

Cartesian Coordinates of Recorded Voltages



The image above shows the how the three symmetrical components that make up the voltages as recorded at 03:40:00 on September 5, 2023.

The reason why the yellow solid line (recorded voltage) is not clearly showing is that all three lines representing the positive-, negative-, and zero-sequence components are on top of each other. The fact is that the solid yellow line is very short.

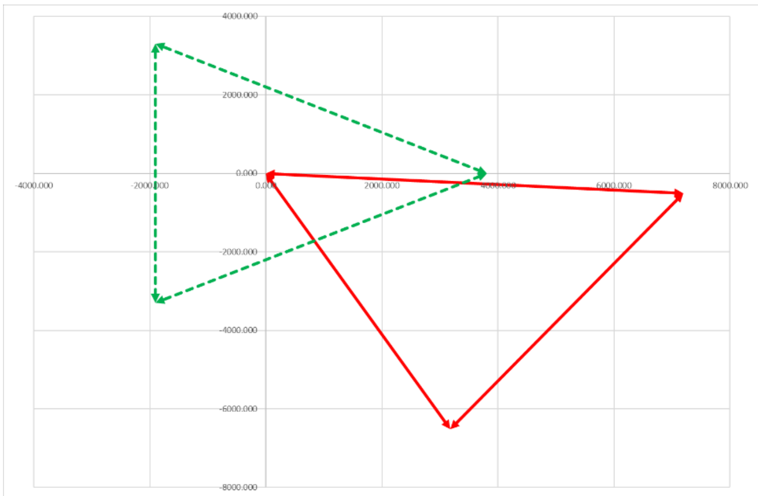
Also take note of how close the solid red and blue lines are to each other. Secondly, look at the sequence of the "phases".

Phase-To-Phase Voltages

The image below shows the phase-to-phase voltages of a perfectly network with the unbalanced phase-to-phase voltages of network as recorded at Modderbee municipal substation at 03:40:00 on September 5, 2023.

The red triangle represents the recorded phase-to-phase voltages while the green dashed-line triangle represents a perfectly balanced network.

It is important to note that the center point for the perfectly balanced network is at the crossing point of the X- and Y-axes. The center point for the recorded voltage (red solid line) is completely off-center.



Perhaps the person who said that it "highly unlikely" that the network at Modderbee substation in unbalanced will perhaps benefit from the explanation above.

City Power Area – Linden

Introduction

After repeated request to City Power to check for possible unbalanced network conditions at the substation in Roosevelt Park, Johannesburg, even offering my service and participation to determine whether this may be restricted to one area, I decided to install my own Power Quality Monitor at a three-phase installation near me. I already suspected that our area is being subjected to unbalanced network conditions and I wanted to find out whether that is so.

City Power Recordings

On April 12, 2024, I installed my Power Quality Monitor at a neighbor's house for approximately 20-hours.

When I removed the instrument and took a quick look at the results, I noticed a severe sag on two of the three-phases that occurred at 04:23:55. At that time, I did not know why it only happened in two phases while the third one remained unaffected. After careful analysis of the results, I discovered that the area we live in is indeed subjected to unbalanced network conditions.

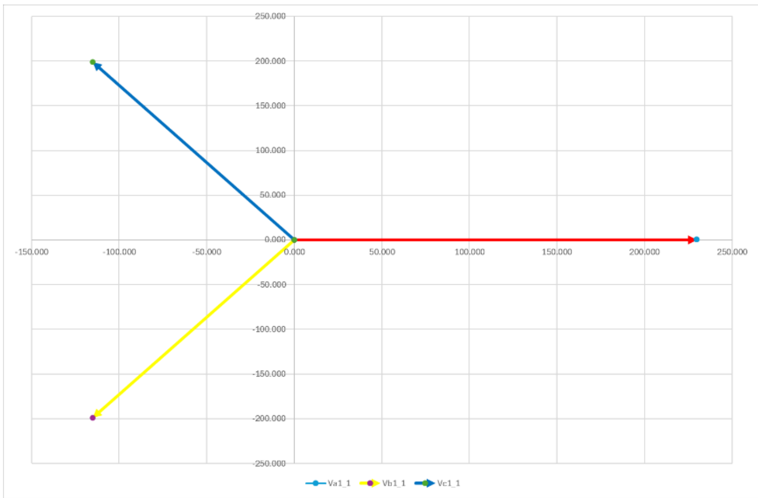
My attempts to get City Power to do a similar check for unbalanced network conditions did not materialize since I have not yet received their results, which I have requested. I nevertheless shared my data with them.

Data Analyses

As I have said above, with **a perfectly balanced system, the magnitudes of the voltages should be the same and the phase-displacements should be 120-degrees exactly.**

Secondly, with a perfectly balanced system, there should ONLY be a Positive-Sequence Component and NO Negative- or Zero-Sequence Components.

Therefore, the only vector for this area should look like in the image below.

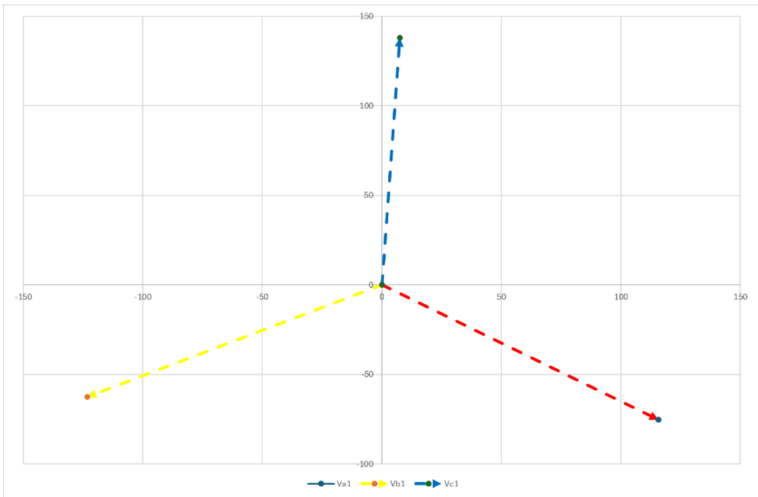


Notice that the three phases are equal in length and displaced by exactly 120-degrees. Also notice the placement of phase 1 which is represented by a red line. It is on the X-axis and towards the right-hand side of the Y-axis.

It really does not matter whether the phase rotation is clockwise or anti-clockwise. That line will always be on the X-axis and towards the right-hand side of the Y-axis.

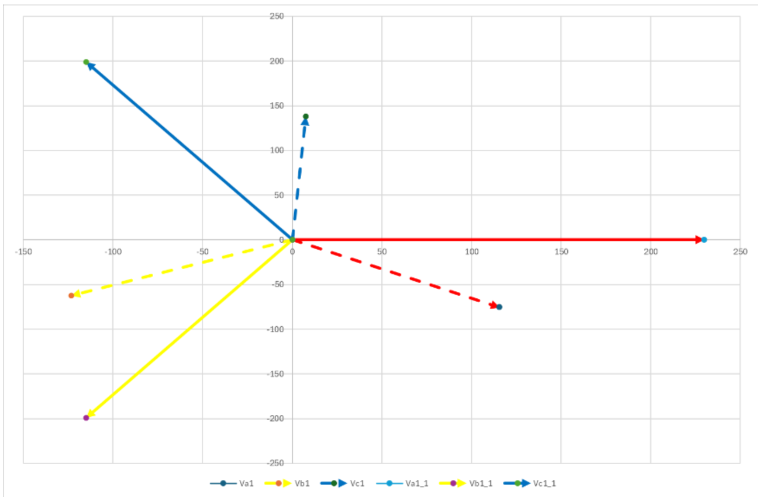
Positive-Sequence Component

The image below represents the positive-sequence component based on the recording done at 21:20:00 on April 12, 2024.



Now look at the position of phase 1 represented by the dashed red line. The entire positive-sequence component has shifted in a clockwise direction. Secondly, look at the length of the dashed lines. They should be of the same length as in the previous image. This clearly shows that there is a problem.

In the image below the positive-sequence voltage components, as recorded in Linden, plus voltages of a perfectly balanced network are shown.



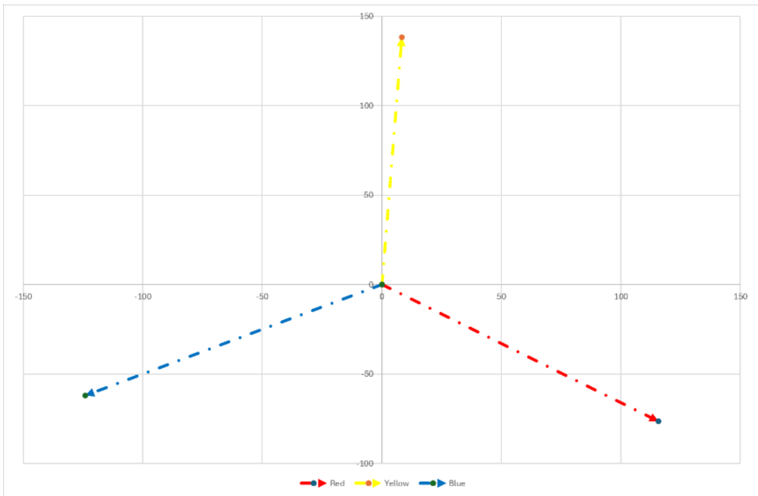
The solid-lines represent the positive-sequence voltage components of a perfectly balanced network while the dashed-lines represent unbalanced positive-sequence voltage components.

First notice the lengths of the solid- versus the dashed-lines. Secondly, notice the shift in two vectors.

Negative-Sequence Component

The image below represents the negative-sequence component of the voltages as recorded at 21:20:00 on April 12, 2024.

Remember what I said above, with a perfectly balanced system, there should **NOT be a Negative-Sequence Component present**. So, the canvas area of the image below should be blank.



I want to point out that phase 1 represented by the red dashed line is at the same angle and magnitude as the red dashed line in the image above, the positive-sequence voltage component.

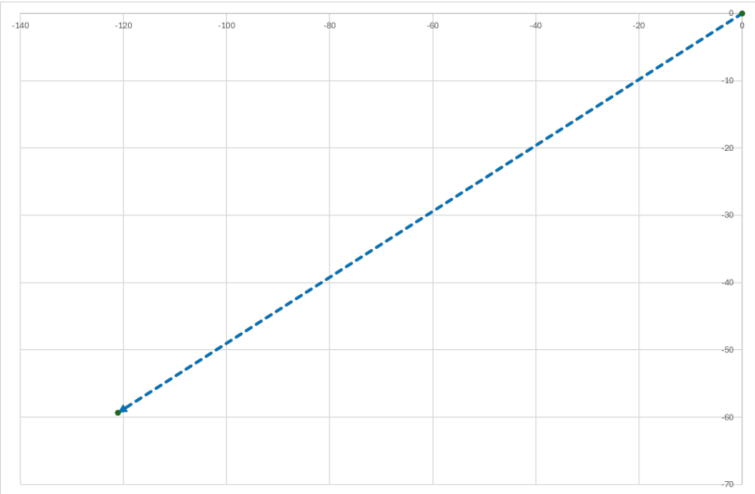
Zero-Sequence Component

The image below represents the zero-sequence voltage components as recorded at 21:20:00 on April 12, 2024.

Remember what I said above, with a perfectly balanced system, there should **NOT be a Zero-Sequence Component present**. So, once again, the canvas area of the image below should have been blank.

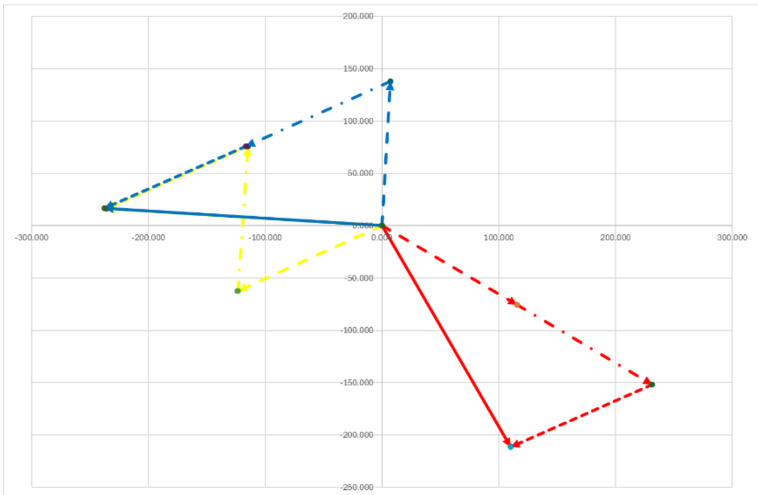
The reason why you only see the blue dashed line is that the red and yellow are hidden underneath the blue. All three are of the same magnitude and angle.

Now look at the high magnitudes of the three zero-sequence components. **This should be NIL and therefore absolutely NO lines at ALL**, or, as I have said above, it should have been a blank canvas.



Cartesian Coordinates of Recorded Voltages

The image below shows the how the three symmetrical components that make up the voltages as recorded in Linden at 21:20:00 on April 12, 2024.



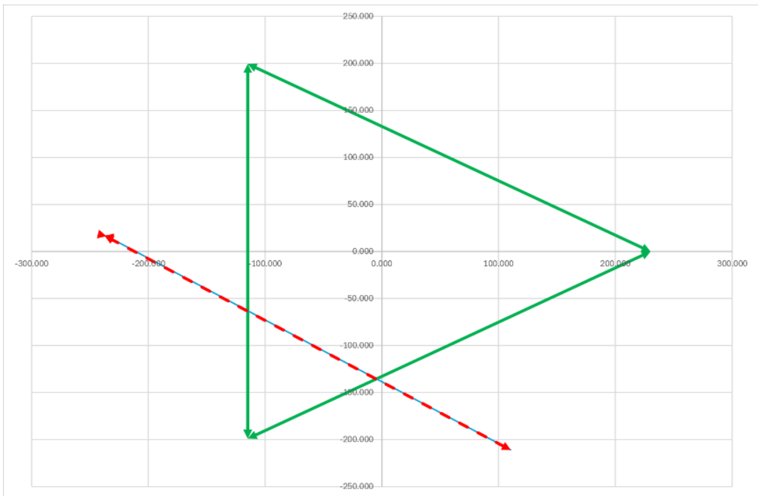
The important thing to notice is that that there appears to be no yellow solid line.

Before thinking that there is a phase missing, let me assure you that it is not so. The phase-displacement of two of the phase-to-neutral voltages are very close to each other. However, what has happened is that 2 and 3 is almost of the same magnitude and at the same phase-displacement angle.

Phase-To-Phase Voltages

The image below shows the phase-to-phase voltages of a perfectly network with the unbalanced phase-to-phase voltages of network as recorded in Linden at 21:20:00 on April 12, 2024.

The red "triangle" represents the recorded phase-to-phase voltages while the green dashed-line triangle represents a perfectly balanced network. Well, in this case there is no red "triangle". It appears that the phase-to-phase voltages are represented by a "straight line" rather than a triangle, which it should be. The reason is that the phase-to-phase voltage between phase 2 and 3 is 0.33-volts.



Effect on Electricity Bill

Perhaps an equally important question is: do the unbalanced voltages and currents affect the customer's electricity bill? The short and simple answer is yes, it does!

In the power triangle of an AC circuit there are three parts.

The **real power (P)** is also known as **true** or **active power**, and it performs the "**real work**" within an electrical circuit. **Real power** is measured in **watts (W)**, **kilowatts (kW)**, or **megawatts (MW)**.

The second part of the power triangle is the **reactive power (Q)** which is sometimes called wattless power and it does not perform any useful work but has a big effect on the phase shift between the voltage and current waveforms. Reactive power does not exist in DC circuits. Unlike real power (P) which does all the work, reactive power (Q) takes power away from a circuit due to the creation and reduction of both inductive magnetic fields and capacitive electrostatic fields, thereby making it harder for the true power to supply power directly to a circuit or load. **Reactive power** is measured in **volt ampere reactive (VAR)**, **kilovolt-ampere-reactive (kVAR)**, or **megavolt-ampere-reactive (MVAR)**.

The third part of the power triangle is the **apparent power (S)**. This is Volts multiplied by Amps (VI). **Apparent power** is measured in **volt-ampere (VA)**, **kilo-volt-ampere (kVA)**, or **mega-volt-ampere (MVA)**.

Single-phase customers' bills are based on the **apparent power** multiplied by the **tariff**.

Not all but a great number of three-phase customers' bills have an additional item which is based on the **reactive power (kVAR)** component.

Imagine you are being charged at R2.41 / kWh – it is R2.41 / kVAh. Ordinary meters do not record kWh.

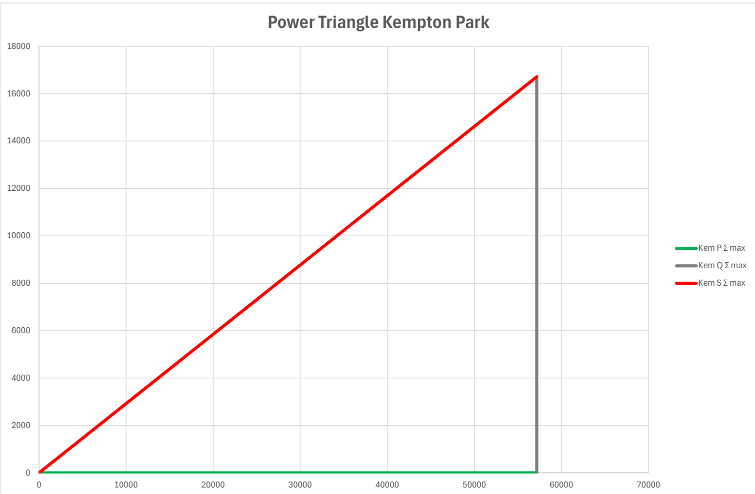
Kempton Park

First, we need to look at what the load characteristics of “near perfectly balanced network” looks like.

For this purpose, I will use data recorded at a housing complex in Kempton Park.

Understandably the loads are substantially higher but the ratio of apparent to real power is what is important. In this case the recorded **maximum summated apparent power (SΣ)** was 59.554 kVA with the **maximum summated real power** being 57.160 kW. **Therefore, the ratio of summated apparent to summated real power 1.04: 1** ($^{59.554}/_{57.160}$).

In the image below, the green horizontal line represents **real power** while the red angled line represents **apparent power** with the grey vertical line representing the **reactive power**. The angle from the X-axis is 16.30 degrees. It is $\cos^{-1}\left(^{57.160}/_{59.554}\right)$

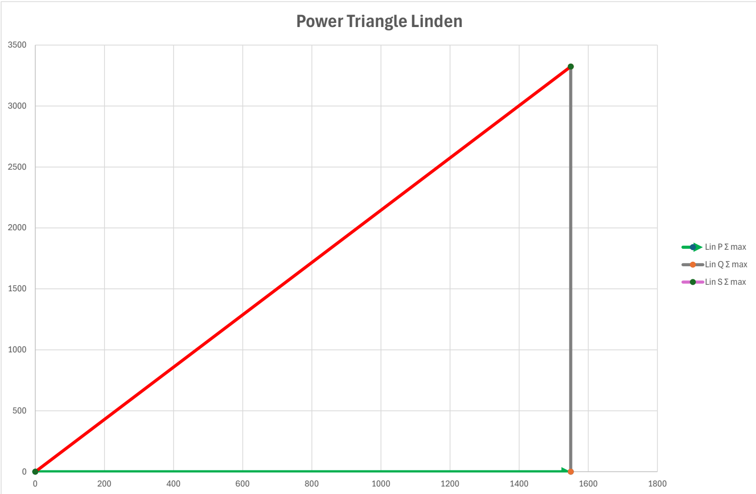


Linden

As is in the case of Kempton Park the values in this example are based on actual data recorded in Linden.

The recorded **maximum summated apparent power (SΣ)** was 3.666 kVA with the **maximum summated real power** being 1.549 kW. These readings were recorded at 21:20 when the “heavier power consuming appliances” were likely all switched off.

In the image below it can be seen that the **apparent power** slopes upwards. The angle from the X-axis is 65.01 degrees. It is $\cos^{-1}\left(^{1.549}/_{3.666}\right)$



What is important and unnoticeable is that the apparent power is increased significantly due to other *inefficient powers* caused by the imbalances and there is absolutely nothing the customer can do about that, **but he is made to pay a premium for something over which he or she has no control**.

Since most customers are on prepaid, it becomes very difficult to verify such consumption patterns. **The summated apparent to summated real power ratio is thus 2.37:1** ($^{3.666}/_{1.549}$).

According to the customer, his monthly average bill is R1 000.00 which relates to an average consumption of approximately 414.94kVAh ($\frac{R1000}{R2.41}$) per month.

Analogical Reasoning

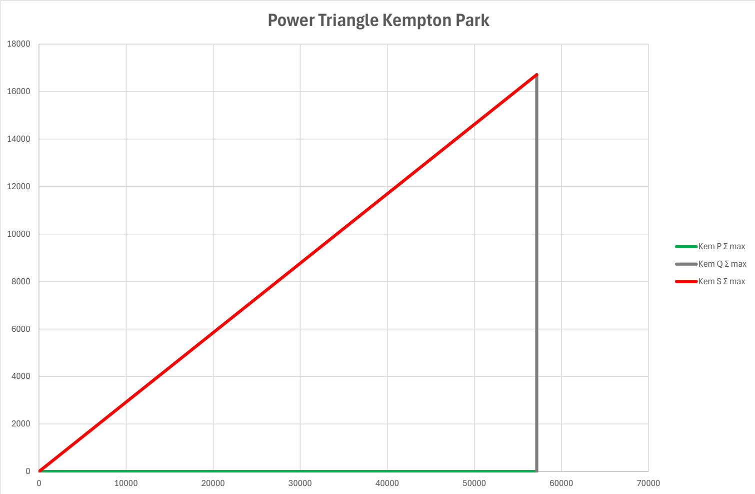
First, for a proper comparison, the **maximum summated apparent power (SΣ)** and **maximum summated real power (PΣ)** must be brought to the same base.

The **maximum summated real power (PΣ)** of Kempton Park is multiplied by 0.03 ($^{1.549}/_{57.160}$) giving a **maximum summated real power (PΣ)** of 1.549 kW. Then the **maximum summated real power (PΣ)** is multiplied by a factor of 1.04 to obtain the **maximum summated apparent power (SΣ)** of 1614.14 kVA. The latter is then divided by the **maximum summated apparent power (SΣ)** recoded in Linden (Kempton Park
First, we need to look at what the load characteristics of "near perfectly balanced network" looks like.

For this purpose, I will use data recorded at a housing complex in Kempton Park.

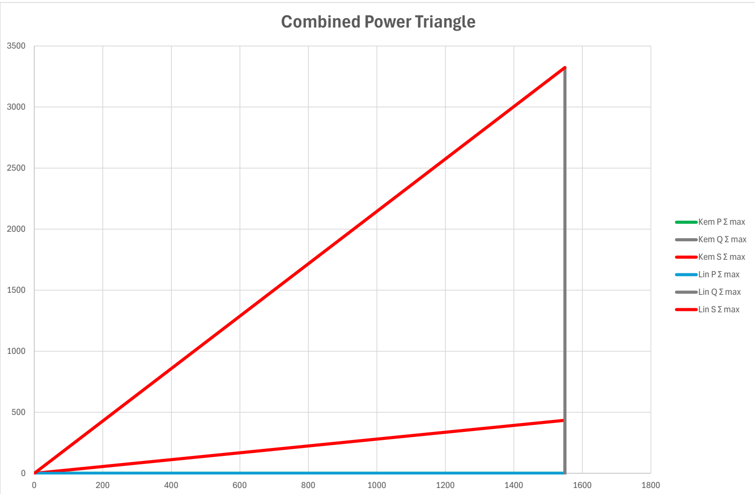
Understandably the loads are substantially higher but the ratio of apparent to real power is what is important. In this case the recorded **maximum summated apparent power (SΣ)** was 59.554 kVA with the **maximum summated real power** being 57.160 kW. **Therefore, the ratio of summated apparent to summated real power 1.04: 1** ($^{59.554}/_{57.160}$).

In the image below, the green horizontal line represents **real power** while the red angled line represents **apparent power** with the grey vertical line representing the **reactive power**. The angle from the X-axis is 16.30 degrees. It is $\cos^{-1}\left(^{57.160}/_{59.554}\right)$



Linden) multiplied by 1 000 (the customer's monthly bill) giving a "new bill" of R440.21. Therefore, a customer in Linden is probably paying R559.79 too much per month.

Although it is not easy to see angles in the image below, the slope of the line representing the **apparent power** for a house in Kempton Park with a similar load pattern is 16.30 degrees. However, for a house in Linden the slope of the line that represents the **apparent power** is 65.01 degrees. The slope is therefore **3.99 times steeper**.



Effects of Unbalanced Networks in Linden

As stated before, the zero-sequence component is the one that produces **heat in transformers and cables**."

Up above I also said "you will get a very high neutral current and very high circulating currents in the delta windings of transformers. Overheating of transformers and cables can eventually result in spurious trips or even more severe failures such as cables burning off or the insulation inside the transformer catching fire.

Now consider the number of cable and transformer faults in the northern suburbs and especially Linden in the past few years, and then you can make up your own mind.

Everyone can read the Analogical Reasoning to do the sums for themselves, but the conclusion is that customers in certain parts of the northern suburbs of Johannesburg are probably paying a very hefty price for the unbalanced network conditions through their electricity bills. If one considers the percentage change between the "new bill" of R440.21 and the amount the customer is currently paying for electricity, it is an increase of 127.16%.

Customers can perhaps help balance the currents if they are all on three-phase, but they have absolutely no control over the unbalanced voltages being supplied.

Conclusion

First and very important to note is that the zero-sequence component produces **heat in transformers and cables**. So, it is important to eliminate the zero-sequence component. Secondly, unbalanced network conditions result in very high neutral current and very high circulating currents in the delta windings of transformers. This also causes overheating in transformers and cables and can eventually result in spurious trips or even more severe failures such as cables burning off or the insulation inside the transformer catching fire.

Now consider the number of cable and transformer faults reported lately and then you can make up your own mind whether Eskom and the power distributors are aware of unbalanced network conditions? Secondly, do they do enough to check the networks for this phenomenon? Probably not. Judging by my experience, they simply ignore any reports about unbalanced network conditions.

A question that is regularly being asked is: who benefits from the extras being paid by the customers for the unbalanced network conditions? Let us examine that. Customers need a specific amount of electrical power to perform certain tasks – **real power** – for which they need electricity. Because of the imbalances there is a significant increase in the *inefficient powers* which causes the **apparent power** to increase. Since the customers' bills are predominantly made up based on the **apparent power** they pay extra for those *inefficient powers*. On the generating side, power needs to be generated to compensate for the **real power plus the losses**. For every unit being generated, there is a margin (*profit*) being added on. **So, the more units being generated, the higher the *profits*.** None of the generating plants, whether it is coal-fire, nuclear, or renewable, are non-profit businesses.

Perhaps people such as the Eskom executive should read this article plus the other articles which I have posted on the blog as well as the web pages such as Symmetrical Component Analysis and Negative Phase Sequencing to understand this concept.

Everyone who has *read and understood* what I have said above can now judge for themselves whether it is true that Modderbee and Linden are not subjected to unbalanced network conditions.

Far more important is that customers must decide whether they are *amenable to pay so much more for electricity* for something that must be fixed by the power supply distributors. That includes Eskom.

What is equally important is how unbalanced networks are not easily manifested in power supplies. In the case of Linden, people may think that the power supply is normal by measuring the phase-to-neutral voltages. In the case of Modderbee, Eskom and officials from the electricity department may think that there is nothing wrong with network when they select the phase-to-phase voltages and notice that it is more-or-less the same.