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

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Introduction

This document provides a concise explanation of the principles of balanced and unbalanced power networks. Additionally, it employs real-world data to illustrate the disparities between balanced and unbalanced network scenarios.

The query I am addressing pertains to Eskom and other power distributors' awareness of unbalanced network conditions and their corresponding actions to rectify it.

Crucially, I will demonstrate how customers, who are exposed to unbalanced network conditions, bear a significant financial burden through their electricity bills. Meanwhile, those generating electricity – whether through coal-fired power stations, nuclear, or renewable energy – may remain indifferent. This is because the inefficiencies caused by these unbalanced network conditions could potentially boost their profits.

Perfectly Balanced Network Condition

In an ideally balanced system, the magnitudes of currents and voltages should be identical, with phase displacements precisely at 120 degrees. Furthermore, such a balanced system should exclusively contain a Positive-Sequence Component, devoid of any Negative- or Zero-Sequence Components.

As depicted in Figure 1, the positive-sequence voltage component represents a perfectly balanced system. The sole vector present corresponds to the positive-sequence component.

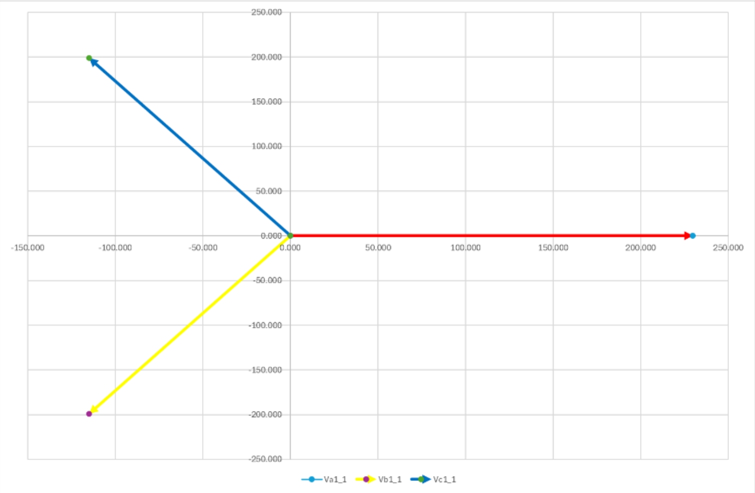

Figure 1: Balanced Voltage Vector

Unbalanced Networks Conditions

While I had the option to replicate the full explanation of Symmetrical Component Analysis from the Agulhascorp website into this text, I chose a different approach. To understand the rationale behind this analysis and gain insights into Negative Phase Sequencing, I encourage you to explore these topics further. This will equip you with the necessary background to comprehend the forthcoming discussion.

I have had ongoing concerns about an imbalance in the power distribution system in our area for quite some time. Since 12 March 2024, I have made repeated attempts to prompt City Power to investigate these issues. However, it seems my alerts are either being dismissed or overlooked, without a thorough examination of my claims or the commencement of any investigative action.

Having encountered similar situations before, I am able to interpret the signs accurately. Therefore, I have taken it upon myself to conduct a more extensive investigation, given the lack of assistance from the authorities tasked with overseeing these inquiries for the power distributors.

Inefficiency Powers

Before delving into the data analysis from both locations, Linden, and Modderbee, I must share an additional insight with you.

Understanding all elements contributing to the energy balance is crucial. Within an unbalanced network, beyond **reactive** and **active power**, additional *inefficient powers* arise from imbalances, amplifying the system's **apparent power**. Compared to a mesh network, a radial network exhibits *greater imbalances*.

Radial versus Ring Main Electrical Power Distribution Systems

A radial system is a type of power distribution network where various feeders extend out from a central substation or generating station, linking to the primary distribution transformer. The defining feature of a radial system is its single route for power transmission from the source (the substation) to the end users (the consumers). However, this straightforward design has a downside: if a feeder malfunctions, the consumers connected to that feeder will experience a power outage. This is because there is no backup route to supply power to the transformer. Likewise, if a transformer breaks down, the power supply will be disrupted.

To address the shortcomings of radial systems, ring main distribution systems were developed. In such a system, feeders form a closed circuit or ring, with consumers drawing power from this loop. This circular configuration allows power to flow in both directions. Consequently, if a feeder becomes non-functional, power can still be delivered via the other section of the ring. Ring main systems, while slightly more intricate to set up, offer superior reliability and resilience compared to radial systems, ensuring redundancy and uninterrupted power supply.

Damages Resulting from Unbalanced Networks

Upon reviewing the “Power Quality Data Linden” spreadsheet that I sent to the City Power officials on the 15th of March 2024, they should have promptly asked: What is the impact of voltage imbalance on electric motors, generators, transformers, and power supply cables?

Motor performance is contingent on voltage. A **1 percent voltage imbalance** at a fully loaded motor’s terminals can lead to a **6 to 10 percent phase current imbalance**. This imbalance elevates the motor’s operating temperature, diminishes its energy efficiency, and curtails its lifespan. Furthermore, unbalanced voltage alters the motor’s speed and torque characteristics. It results in an unbalanced stator current, escalating losses and net torque. The negative sequence current generates a backward-rotating magnetic field and a torque opposite to the positive sequence component. Consequently, the torque from the negative sequence current attempts to decelerate the motor by applying counter torque.

In the Excel workbook attached to my email from 17 March 2024, I have omitted the current data to avoid creating a misleading impression and causing confusion. The measurements were taken in a residential setting with all single-phase appliances, where achieving balanced currents is nearly impossible. However, the scenario would be entirely different at substations where the currents are expected to be balanced.

As depicted in Figure 5 and Figure 12, where voltages are symbolized by the vector's solid lines, it results in a significantly high neutral current and elevated circulating currents within the delta windings of transformers. This phenomenon is responsible for the generation of heat. **The component known as the zero-sequence is the primary source of heat production in both transformers and cables.**

Modderbee Municipal Substation

I came to know that an Eskom representative was informed about potential imbalances in the network conditions at the Modderbee municipal substation, but it was possibly dismissed as improbable. However, as I was not in attendance, I cannot guarantee the veracity of the information that I obtained indirectly.

The secondary motive behind this article's publication is my attempt to contact an individual who claims to have comprehensive knowledge of power quality at Eskom. I sent not just one, but two emails. Despite successful delivery, the first email remained unanswered, and the second was "erased without being read," according to the alert I received in my email account.

In my initial email, I expressed, "If you are the appropriate individual to collaborate with in examining the evident issue of unbalanced currents and voltages, as detailed below, please inform me." I also stated in that same email, "I would greatly appreciate your inclusion of me in such an investigation." Whether the emails were read and subsequently deleted, or not read at all, remains uncertain to me. However, it is perplexing that he would not have acknowledged the email sent on the 2nd of April 2024 by this time.

From September 2023, I have actively posted on the Agulhas Utilities Corporation website, blog, LinkedIn, and Facebook. I genuinely hoped that he might notice my LinkedIn posts and respond to my findings, or that other Eskom employees on LinkedIn might see the posts and inform those who handle power quality at Eskom. However, this has not occurred so far, and I am left wondering if anyone from Eskom will ever notice this post. Additionally, my email to the Group Executive (Distribution) seems to have been "deleted without being read". My attempts to reach out to senior individuals in the electricity department of the City of Ekurhuleni Metropolitan Municipality via email have also gone unanswered. The emails in question were sent to the senior officials as listed on their website.

Consequently, I have determined that it is the appropriate moment to publish this fresh article.

Modderbee Municipal Substation Recordings

In August 2023, I was tasked with monitoring the load on a municipal feeder at the Modderbee substation located in Springs, Gauteng. This assignment was given by a consulting engineer who aimed to ascertain the additional load that could be accommodated by a specific 6.6kV feeder.

On August 30, 2023, during the installation of the Power Quality Monitor, we observed an absence of one of the phase-to-neutral voltages. To verify this, I employed a secondary device. Upon confirmation that the voltage was indeed less than 2 volts, we speculated that the cause might be a blown fuse on the secondary side of the busbar-VT. Despite this, we proceeded with the installation as the current measurements were likely of greater significance.

The Modderbee municipal substation receives its supply via two 6.6kV cables from the Eskom substation, located roughly 20 metres away. The municipal substation is equipped with two 6.6kV busbars and an open bus-section breaker. Essentially, the busbar-VTs are responsible for measuring the incoming voltages from the two 6.6kV cables.

To obtain a reliable measure of the minimum, average, and maximum loads, I typically let the instrument operate for about a week. Consequently, the recording was carried out for roughly a week, starting from August 30, 2023, and concluded on September 5, 2023.

Data Analyses

Initially, my focus was primarily on examining the measurements of **real (P)**, **reactive (Q)**, and **apparent power (S)**. However, when the consulting engineer raised concerns about the elevated neutral currents, I began to scrutinize the data more thoroughly. It was during this detailed analysis that I uncovered the unusually high levels of unbalanced currents and voltages.

The images below depict the symmetrical components of the unbalanced three-phase system, as documented at the Modderbee substation from August 30, 2023, to September 5, 2023.

Positive-Sequence Component

Figure 2 illustrates the positive-sequence component of the voltages, documented at 03:40:00 on September 5, 2023.

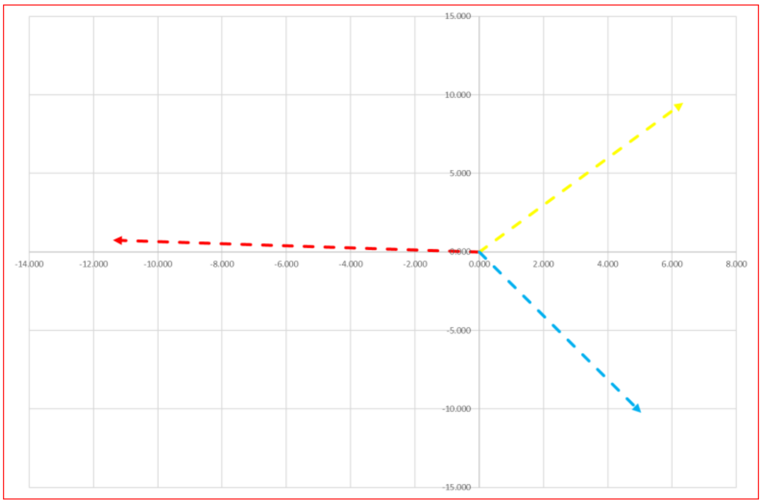

Figure 2: Modderbee Positive-Sequence Component

The initial observation to make is that the complete vector has undergone a rotation close to 180-degrees, given that the red line is expected to align with the X-axis, pointing to the right.

Negative-Sequence Component

Figure 3 illustrates the negative-sequence component of the voltages, captured at the timestamp of 03:40:00 on September 5, 2023.

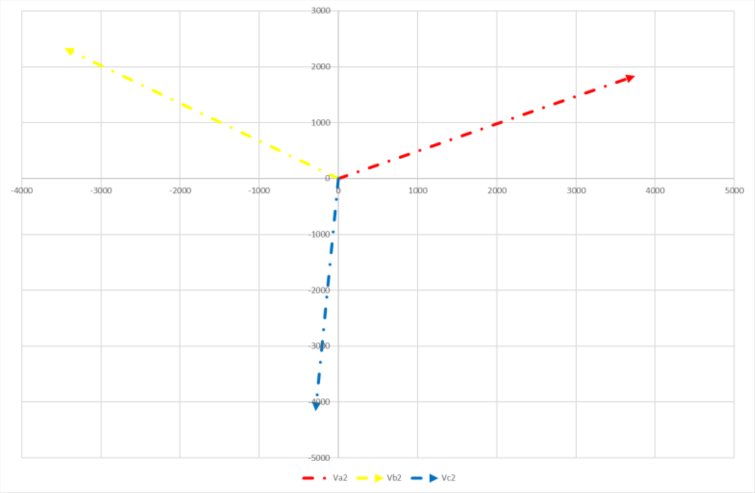

Figure 3: Modderbee Negative-Sequence Component

Observe the elevated magnitudes of the three negative sequence components. **Ideally, these should be non-existent, resulting in no lines at all.**

Additionally, pay attention to the color order of the three phases. It is not the conventional red, yellow, and blue sequence – keep in mind that the vectors rotate in an anticlockwise direction. In this instance, the sequence is red, blue, and then yellow, which is why it is referred to as the Negative Phase Sequence.

Zero-Sequence Component

Figure 4, depicted below, illustrates the zero-sequence component of the voltages, documented at 03:40:00 on September 5, 2023.

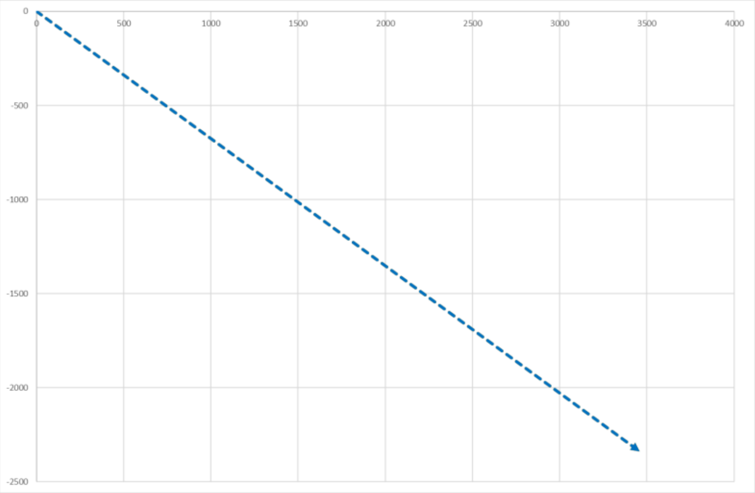

Figure 4: Modderbee Zero-Sequence Component

The blue dashed line is the only visible one because the red and yellow lines are concealed beneath it. All three lines share the same magnitude and direction.

Observe the elevated magnitudes of the three zero-sequence components. **Ideally, these should be non-existent, implying there should be no lines at all.**

Cartesian Coordinates of Recorded Voltages

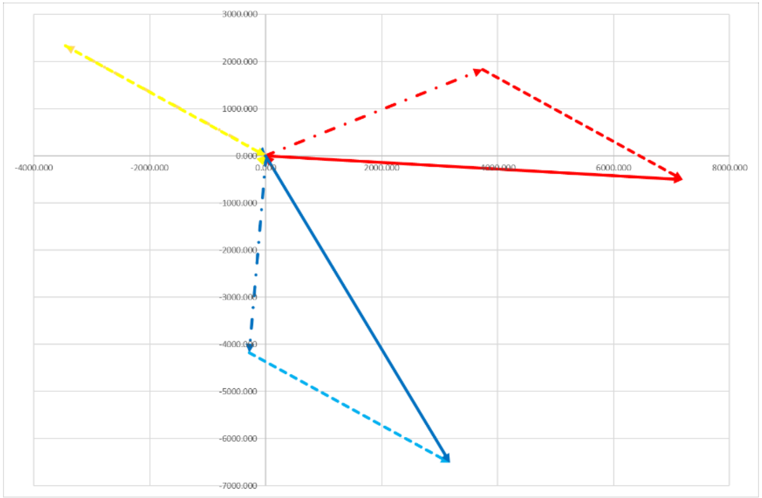

Figure 5: Modderbee Voltages

The above Figure 5 illustrates the three symmetrical components constituting the voltages, as documented at 03:40:00 on September 5, 2023.

The visibility of the solid yellow line, which represents the recorded voltage, is compromised because it is overlaid by the three lines symbolizing the positive, negative, and zero-sequence components. Additionally, the brevity of the solid yellow line contributes to its lack of clarity.

Please observe the proximity between the solid red and blue lines. Additionally, pay attention to the order of the "phases".

Phase-To-Phase Voltages

Figure 6 illustrates the phase-to-phase voltages of an ideally balanced network juxtaposed with the unbalanced phase-to-phase voltages of a network. These were recorded at the Modderbee municipal substation at 03:40:00 on September 5, 2023.

The red triangle symbolizes the recorded phase-to-phase voltages, while the green dashed-line triangle signifies an ideally balanced network.

It is crucial to observe that the center point of the ideally balanced network aligns with the intersection of the X- and Y-axes. However, the center point for the recorded voltage (depicted by the red solid line) is noticeably off-center.

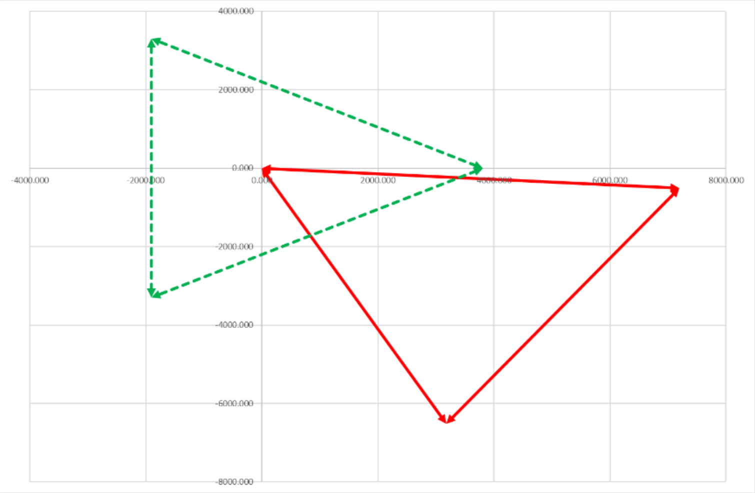

Figure 6: Modderbee Phase-To-Phase Voltages

The individual who previously stated that the network at Modderbee substation being unbalanced was “highly unlikely” might find the above explanation enlightening.

City Power Area – Linden

Despite numerous appeals to City Power to investigate potential imbalances in the network at the Roosevelt Park substation in Johannesburg, and even volunteering my services to help pinpoint if this issue was localized, I took the initiative to set up my own Power Quality Monitor at a nearby three-phase installation. I had suspicions that our area was experiencing unbalanced network conditions, and I was keen to confirm this.

City Power Recordings

On the 12th of April 2024, I set up my Power Quality Monitor at a residence in my neighborhood for a duration of roughly 20 hours.

Upon retrieving the device and briefly examining the data, I observed a significant dip in two out of the three phases at 04:23:55. Initially, I was unsure why only two phases were impacted while the third remained stable. However, a meticulous review of the data revealed that our residential area is indeed prone to unbalanced network conditions.

Despite my efforts to have City Power conduct a parallel assessment for unbalanced network conditions, I have yet to receive the requested results. However, I have already provided them with my data.

Data Analyses

As previously mentioned, in an ideally balanced system, the voltage magnitudes should be identical, and the phase shifts should be precisely 120 degrees. Furthermore, such a balanced system should exclusively exhibit a Positive-Sequence Component, with the absence of any Negative- or Zero-Sequence Components.

Hence, the sole vector for this region should resemble the one depicted in the subsequent image, Figure 7.

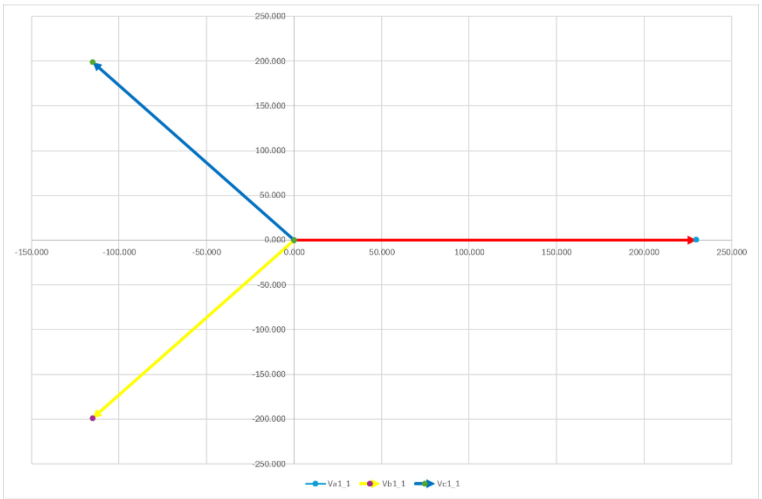

Figure 7: Linden Balanced Network Condition - Voltage Vector

Observe that the three phases have the same length and are separated by an exact displacement of 120 degrees. Pay attention to the position of phase 1, depicted by a red line. It lies on the X-axis and is situated to the right of the Y-axis.

The direction of the phase rotation, whether it is clockwise or anti-clockwise, is irrelevant. The line will consistently be located on the X-axis and to the right side of the Y-axis.

Positive-Sequence Component

The positive-sequence component depicted in the Figure 8 below is derived from the recording taken at 21:20:00 on April 12, 2024.

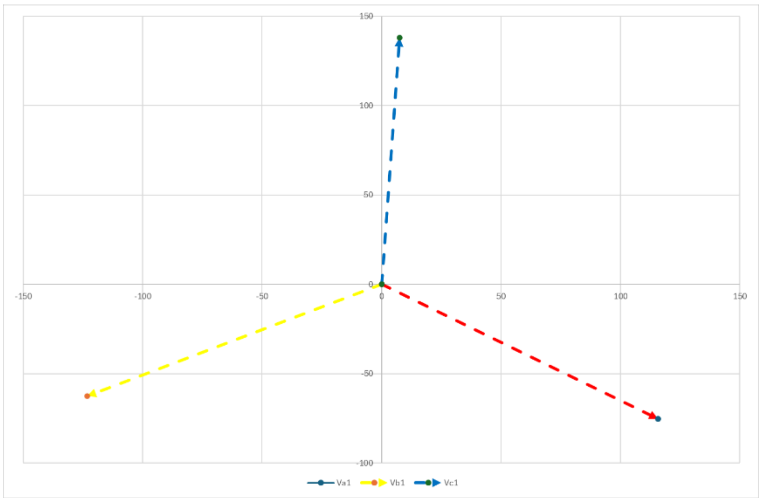

Figure 8: Linden Positive-Sequence Component

Observe the location of phase 1, indicated by the dashed red line. The whole positive-sequence component has moved in a clockwise direction. Additionally, pay attention to the length of the dashed lines. They are expected to match the length as is in Figure 7. This evident discrepancy signals an issue.

As depicted in Figure 9 below, the positive-sequence voltage components documented in Linden, along with the voltages from an ideally balanced network, are displayed.

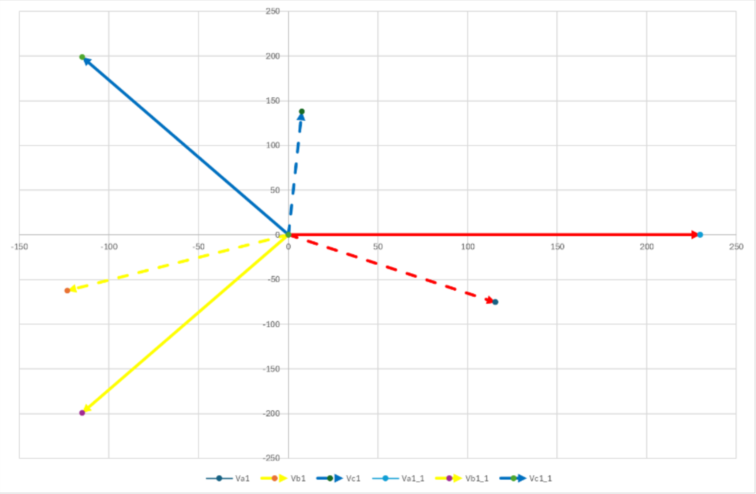

Figure 9: Linden Balanced and Positive-Sequence Component

The solid lines illustrate the positive-sequence voltage components of an ideally balanced network, whereas the dashed lines depict the unbalanced positive-sequence voltage components.

Initially, observe the differences in lengths between the solid and dashed lines. Subsequently, pay attention to the displacement in two vectors.

Negative-Sequence Component

The negative-sequence component of the voltages, as documented at 21:20:00 on April 12, 2024, is depicted in the following Figure 10.

Recall the previous discussion: in an ideally balanced system, a Negative-Sequence Component should not exist. **Therefore, the canvas area of Figure 10 should appear empty.**

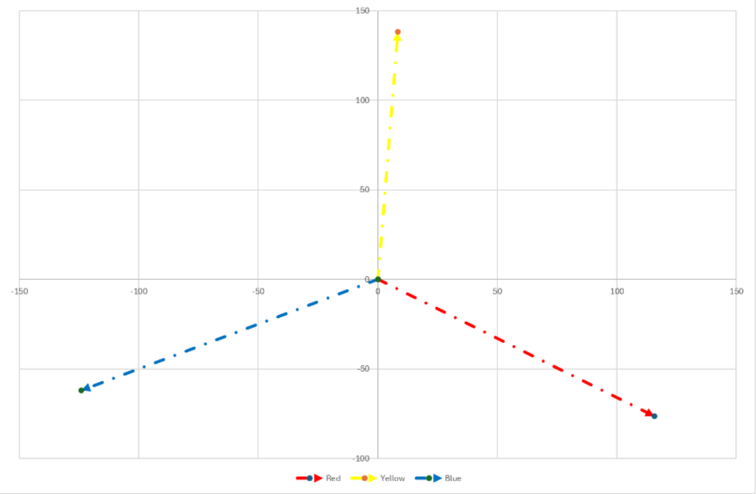

Figure 10: Linden Negative-Sequence Component

I would like to highlight that the phase 1, indicated by the red dashed line, has the same angle and magnitude as the red dashed line in Figure 9 above, which symbolizes the positive-sequence voltage component.

Zero-Sequence Component

The zero-sequence voltage components, as documented at 21:20:00 on April 12, 2024, are depicted in the following Figure 11.

Recall the previous statement: a perfectly balanced system should not contain a Zero-Sequence Component. **Therefore, the canvas area of the subsequent image should have been empty.**

The blue dashed line is the only visible one because the red and yellow lines are concealed beneath it. All three lines share the same magnitude and angle.

Observe the elevated magnitudes of the three zero-sequence components. **These should be non-existent, implying there should be no lines whatsoever, or as previously mentioned, it should be presented as an empty canvas.**

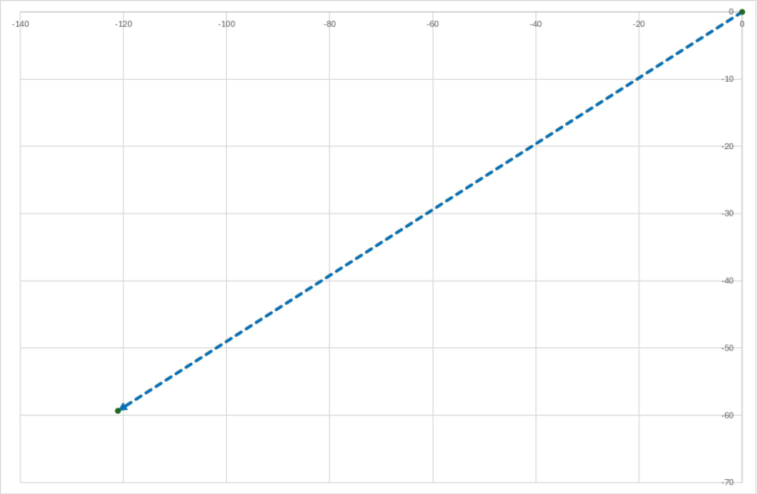

Figure 11: Linden Zero-Sequence Component

Cartesian Coordinates of Recorded Voltages

The illustration below, Figure 12, depicts the three symmetrical components constituting the voltages, as documented in Linden at 21:20:00 on April 12, 2024.

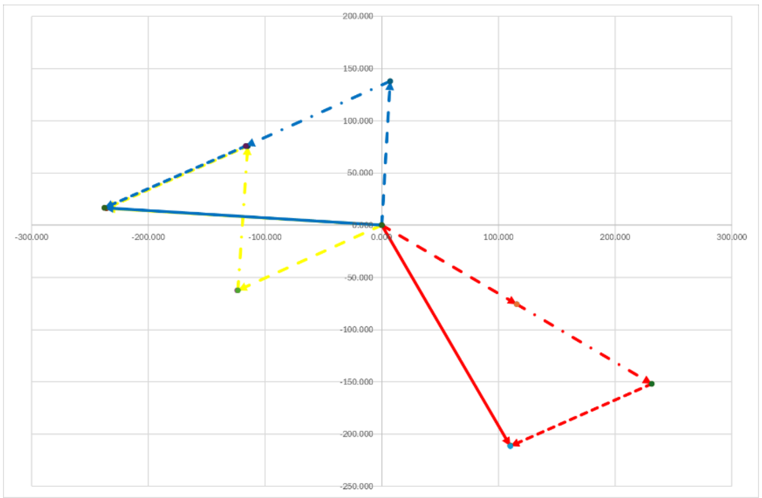

Figure 12: Linden Final Voltage Vector

A crucial observation is the apparent absence of a solid yellow line.

Before you assume a phase is absent, I can confirm that this is not the case. The phase-displacement between two of the phase-to-neutral voltages is nearly identical. What has occurred is that phases 2 and 3 are almost equal in magnitude and share a similar phase-displacement angle.

Phase-To-Phase Voltages

The diagram depicted in Figure 13 illustrates the phase-to-phase voltages of an ideally balanced network, contrasted with the unbalanced phase-to-phase voltages of a network. These measurements were recorded in Linden at 21:20:00 on April 12, 2024.

The red "triangle" in the diagram symbolizes the measured phase-to-phase voltages, whereas the green dashed-line triangle signifies an ideally balanced network. However, in this instance, the red "triangle" is absent. Instead, the phase-to-phase voltages seem to be depicted as a "straight line", deviating from the expected triangular representation. This anomaly is due to the phase-to-phase voltage between phase 2 and 3 being only 0.33 volts.

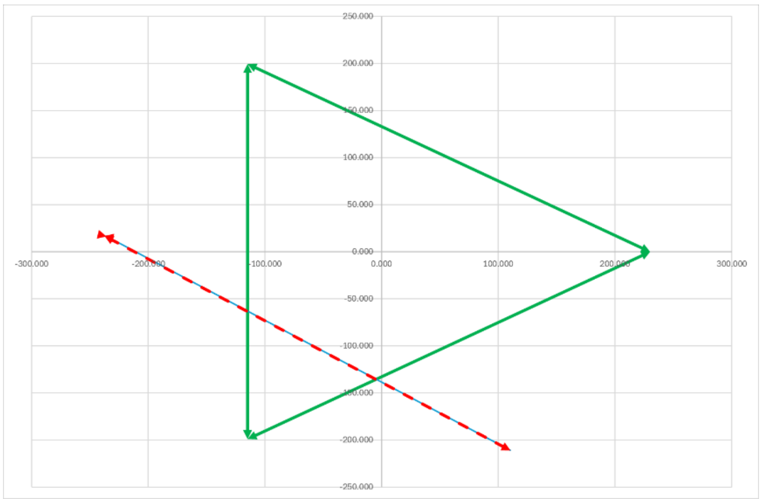

Figure 13: Linden Phase-To-Phase Voltages

Effect on Electricity Bill

A question of equal significance might be: does the imbalance in voltages and currents impact the consumer's electricity charges? The concise response is indeed, it does!

Within the power triangle of an AC circuit, three components exist.

The **real power**, denoted as (**P**), also referred to as true or active power, is responsible for executing the actual work within an electrical circuit. The unit of measurement for real power is watts (W).

The power triangle's second component is the **reactive power** (**Q**), also referred to as wattless power. It does not contribute to any productive work but significantly influences the phase shift between voltage and current waveforms. Reactive power is absent in DC circuits. In contrast to **real power** (**P**) that performs all the work, **reactive power** (**Q**) detracts power from a circuit. This happens due to the generation and diminution of both inductive magnetic fields and capacitive electrostatic fields, making it more challenging for the true power to directly supply power to a circuit or load. The units of measurement for reactive power are volt ampere reactive (VAR).

The power triangle's third element is the **apparent power** (**S**), which is the product of Volts and Amps (VI). The unit of measurement for apparent power is volt-ampere (VA).

The billing for single-phase customers is determined by the product of the apparent power and the tariff. On the other hand, many, but not all, three-phase customers have an extra charge on their bills that is calculated based on the reactive power (kVAR) component.

Envision that your rate is R2.41 per kWh, but it is R2.41 per kVAh. It is important to note that standard meters do not log kWh.

Kempton Park

Initially, we must examine the load characteristics of a “nearly perfectly balanced network”. To do this, I will utilize data gathered from a residential complex in Kempton Park.

The loads are significantly increased, yet the crucial factor is the ratio between apparent and real power. In this instance, the highest recorded total apparent power (SΣ) was 59.554 kVA, while the highest total real power reached 57.160 kW. Consequently, the ratio of total apparent power to total real power is 1.04:1 – $\left({}^{59.554}/_{57.160}\right)$.

In Figure 14, the horizontal green line symbolizes the real power, the angled red line denotes the apparent power, and the vertical grey line stands for the reactive power. The angle it forms with the X-axis is 16.30 degrees – $\cos^{-1}\left({}^{57.160}/_{59.554}\right)$

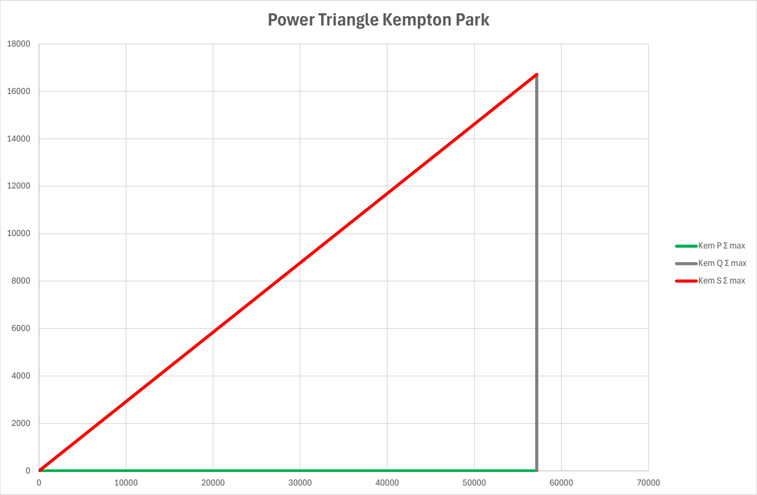

Figure 14: Kempton Park Power Triangle

Linden

Just like the scenario in Kempton Park, the values in this instance are derived from real data collected in Linden.

The highest recorded total apparent power (SΣ) was 3.666 kVA, and the peak total real power reached 1.549 kW. These measurements were taken at 21:20, a time when it is probable that all the “high power-consuming appliances” were turned off.

In Figure 15, the upward slope of the apparent power is noticeable. The angle it forms with the X-axis measures 65.01 degrees – $\cos^{-1}\left({}^{1.549}/_{3.666}\right)$.

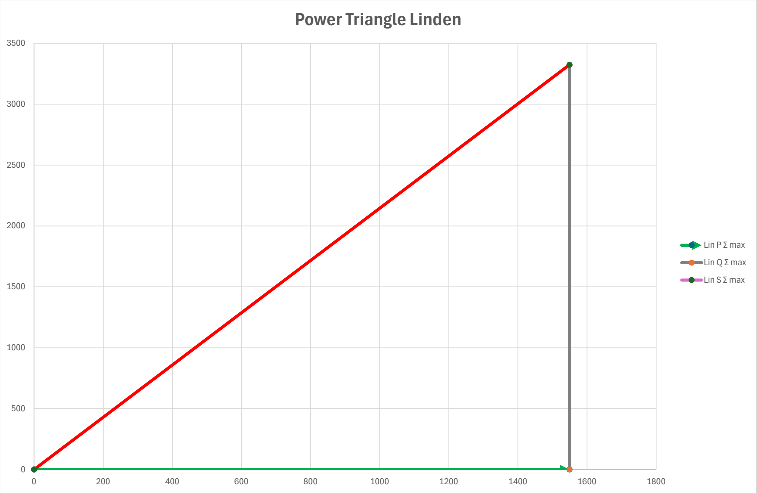

Figure 15: Linden Power Tiangle

An important yet often overlooked fact is that unbalanced network conditions cause the apparent power to rise significantly due to other inefficient powers. The customer, unfortunately, has no control over this. Despite this, they are required to pay a premium for something they cannot influence.

Given that most customers use prepaid services, it becomes challenging to confirm their consumption habits. Consequently, the ratio of total apparent power to total real power stands at 2.37:1 – $({}^{3.666}/_{1.549})$.

The customer reports that their average monthly bill amounts to R1,000.00, which corresponds to an estimated monthly consumption of around 414.94kVAh – $(\frac{R1000}{R2.41})$.

Analogical Reasoning

Initially, to make an accurate comparison, both the maximum total apparent power (SΣ) and the maximum total real power (PΣ) need to be normalized to a common base.

The maximum total real power (PΣ) for Kempton Park is being scaled by a factor of 0.0.3 – $({}^{1.549}/_{57.160})$ – The maximum total real power (PΣ) is given as 1.549 kW. This value is then scaled by a factor of 1.04 to calculate the maximum total apparent power (SΣ), which results in 1614.14 kVA. This calculated value is subsequently divided by the maximum total apparent power (SΣ) that was recorded in Linden (Kempton Park) scaled by a factor of 1,000, resulting in a "new bill" amounting to R440.21. Hence, it is likely that a customer in Linden is overpaying by approximately R559.79 each month.

While it may be challenging to discern the angles in the following image, the line that signifies the apparent power for a house in Kempton Park with a comparable load pattern has a slope of 16.30 degrees. Conversely, the line indicating the apparent power for a house in Linden has a slope of 65.01 degrees, making it **3.99 times steeper**.

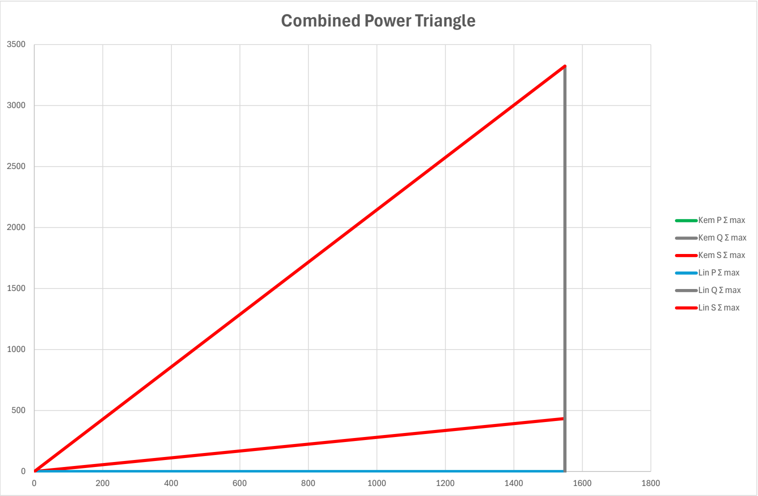

Figure 16: Combined Linden / Kempton Power Tiangle

Effects of Unbalanced Networks in Linden

As previously mentioned, the component known as the zero-sequence is responsible for generating heat in transformers and cables.

In a previous statement, I mentioned that there would be an exceptionally high neutral current and intense circulating currents in the delta windings of transformers. This can lead to the overheating of transformers and cables, potentially causing unexpected shutdowns or even more serious failures like cables igniting or the insulation within the transformer catching fire.

Reflect on the frequency of cable and transformer malfunctions in the northern suburbs, particularly in Linden, over the previous years, and form your own conclusions.

All are free to peruse the Analogical Reasoning and perform the calculations independently. However, it is likely that residents in specific areas of Johannesburg's northern suburbs are bearing a substantial cost due to imbalanced network conditions, reflected in their electricity bills. Considering the percentage difference between the "new bill" amounting to R440.21 and the current electricity payment, there is a surge of 127.16%.

Customers might be able to contribute to balancing the currents if they all utilize three-phase power. However, they have no influence over the unbalanced voltages that are being delivered.

Conclusion

Primarily, it is crucial to understand that the zero-sequence component is responsible for generating heat in transformers and cables, hence the need for its elimination. Secondly, imbalanced network conditions lead to an extremely high neutral current and elevated circulating currents in the delta windings of transformers. These conditions can cause transformers and cables to overheat, potentially leading to unexpected shutdowns or even more serious failures like cables being burnt off or transformer insulation ignition.

Reflect on the recent surge in reported cable and transformer malfunctions, and then form your own opinion: Are Eskom and other power distributors cognizant of the imbalanced network conditions? Furthermore, do they take adequate measures to inspect the networks for this issue? Based on my observations, it seems unlikely. They appear to disregard any notifications concerning imbalanced network conditions.

A recurring query is: who reaps the benefits from the additional charges customers pay due to unbalanced network conditions? Let us delve into this. Customers require a certain amount of electrical power, or **real power**, to carry out specific tasks. However, these unbalanced network conditions lead to a substantial rise in inefficient powers, causing an increase in **apparent power**. Since customers' bills are primarily based on this apparent power, they end up paying more for these inefficient powers. On the generation side, power must be produced to offset the losses. Each unit generated includes a profit margin. Therefore, the more units produced, the greater the profits. It is important to note that none of the power plants, whether coal-fired, nuclear, or renewable, operate as non-profit entities.

It might be beneficial for individuals like the Eskom executive to peruse this article, along with other articles I have shared on my blog. Additionally, web pages such as Symmetrical Component Analysis and Negative Phase Sequencing could provide further understanding of this concept.

Those who have comprehended the aforementioned information can independently determine the validity of the claim that Modderbee and Linden are not experiencing unbalanced network conditions.

What is crucial is that consumers need to determine if they are willing to pay a significantly higher price for electricity, considering that the issues should be resolved by the power supply distributors, including Eskom.

Equally significant is the fact that imbalances in networks are not readily apparent in power supplies. For instance, in Linden, individuals might assume the power supply is functioning normally by checking the phase-to-neutral voltages. Similarly, in Modderbee, Eskom and electricity department officials might perceive the network as problem-free when they observe that the phase-to-phase voltages are consistent.

If you are under the impression that residing in a different part of the globe shields you from unbalanced network conditions, it might be worth verifying that assumption. As outlined in this document, you might be totally unaware of such occurrences.