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Challenges in Power Quality Affecting Client Billing

Contemporary Approaches to Power Measurements

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Introduction

In the evolving landscape of power systems, the role of power electronics equipment has become increasingly significant. However, this advancement brings with it a set of challenges, particularly in terms of power quality. Power electronics equipment, while offering improved efficiency and control, can introduce distortions in the power system, leading to power quality concerns.

One of the key aspects of power quality is the level of harmonic content in the overall power supply. Harmonics, or the distortion of the normal sinusoidal waveform of power, can lead to a variety of issues, including equipment overheating, malfunctions, and inefficiencies. Solid-state power meters are frequently viewed as a dependable technique for power measurement, encompassing the monitoring of harmonic power. However, is this assumption valid? It is anticipated that these devices will provide accurate and immediate data, thereby enhancing the management of power quality.

In the context of billing, the presence of unbalanced and non-sinusoidal voltage supply poses unique challenges. Traditional billing methods may not accurately reflect the actual power usage in such scenarios. Therefore, the concept of balanced billing must be introduced. Balanced billing aims to ensure fair and accurate billing by considering the complexities of unbalanced and non-sinusoidal voltage supply.

This paper provides an understanding of how the advent of contemporary equipment like inverters can lead to harmonic disruptions, possibly making conventional power measurements outdated.

Additionally, I will explore the importance of measuring harmonic power, and I will also tackle my own inquiry about whether Eskom and other electricity distributors are worried about balanced billing amidst unbalanced and non-sinusoidal voltage supply.

The interplay between power electronics equipment, harmonic power, and balanced billing in the face of unbalanced and non-sinusoidal voltage supply forms a complex yet fascinating area of study in modern power systems. This investigation is expected to uncover knowledge that could greatly improve the efficiency, dependability, and equity of our power systems.

In an earlier blog entry, I demonstrated how consumers, when subjected to imbalanced network situations, could experience a substantial financial impact via their electric bills. Conversely, electricity producers — whether they use coal-fired power plants, nuclear energy, or renewable sources — might be unaffected. This apathy originates from the possible increase in profits they could reap from the inefficiencies induced by these imbalanced network conditions.

Association between Power Electronics and Quality

It is widely recognized that there is an increasing trend towards the use of renewable energy sources and the trading of electrical power, which often requires the implementation of HVDC transmission systems.

Both solar power generation and HVDC transmission systems heavily rely on power electronics devices.

As we look to the future, we can expect a rise in the introduction of grid-forming converters (GFMCs) as the size of microgrids continues to expand. These structural shifts will undoubtedly alter the operational paradigms of the system, necessitating a deeper comprehension of how these new devices operate and their impact on network stability and, notably, power quality.

Numerous studies have identified that the widespread use of power electronics devices significantly contributes to power quality issues, particularly voltage sags and swells.

The ongoing trend of decommissioning rotating generation plants could potentially lead to grid instability if not carefully monitored and addressed proactively before major problems arise. At present, gas and steam turbine power generation play a crucial role in maintaining grid inertia and stability.

As the transition towards renewable energy sources continues and the trend of decommissioning rotating generation plants persists, it becomes imperative for national grid companies to explore alternative solutions to mitigate power quality issues caused by power electronics devices. These alternatives include capacitors, static VAR compensators, and static compensators.

The deployment of capacitor banks at substations is a well-established practice. They are relatively inexpensive, reliable, and straightforward to install. However, they occupy a significant amount of space and necessitate specialized control devices. Standard circuit breakers are incompatible with capacitor banks. Another limitation is their ability to only supply reactive power and not absorb it. Consequently, when the load increases rapidly and voltage drops, the effectiveness of capacitors decreases.

Static VAR Compensators (SVCs), composed of shunt capacitors and reactors, may provide enhanced voltage control, but they are less effective for rapid voltage fluctuations.

While static synchronous compensators (StatComs), with their advanced power electronics, present a superior option, they come with a significant drawback — they are considerably more expensive than basic equipment.

A synchronous compensator is a substantial piece of equipment that combines a spinning generator and a flywheel. When connected to the high-voltage transmission network via a step-up transformer, it remains synchronized with the grid frequency, thereby contributing to network stability by dampening frequency fluctuations. This concept is not novel; for instance, Eskom installed several Synchronous Condensers in the late 1970s.

The intermittent nature of wind energy and the widespread use of power electronics devices, such as those found in HVDC transmission systems and solar power generation equipment, underscore the increasing importance of grid stabilization and AC filters in mitigating the harmonic impact on AC network performance for a successful energy transition.

Coal-fired power stations can be repurposed by removing the steam turbine and replacing it with a large-mass flywheel and a Synchro-Self-Shifting (SSS) clutch. The existing generators and other electrical rotating equipment are then reconfigured to function as synchronous condensers. Since these are already connected to the high-voltage transmission network via a step-up transformer, they serve as stabilizing devices.

As we swiftly transition towards renewable energy sources, it becomes imperative to contemplate strategies for network stabilization. This can be achieved by increasing the installation of synchronous condensers and AC filters to mitigate the harmonic impact on AC network performance. An article in the Engineering News dated 20 November 2023 reported that Eskom plans to deploy 11 synchronous condensers — seven new and four repurposed — throughout its transmission system to bolster grid stability as the integration of variable renewable-energy generators escalates. Furthermore, the Australian Renewable Energy Agency (ARENA) endorsed a report published on 22 June 2023, which also discusses the installation of synchronous condensers.

An immediate pledge to install synchronous condensers is crucial, given the already forming “long queue for new SCs” [based on my understanding from various readings on this subject]. With the noticeable increase in reports concerning subpar power quality issues, it raises the question: Did the industry not anticipate this? The extensive application of power electronics in solar power generation and HVDC power transmission has been prevalent for several years.

Measuring Harmonic Power Using Solid-State Meters

In the recent past, the energy metering sector has gradually transitioned to electronic methods, moving away from the traditional electromechanical technology that has been in use for over a century. The benefits of these electronic methods are manifold. They not only usher the sector into the digital era but also facilitate the execution of value-added services like automatic meter reading (AMR), multi-tariff billing, peak demand tracking, and power quality supervision.

Electronic meters enhance the precision of active power measurements by incorporating harmonics filtering. As household electrical appliances become increasingly complex, they generate higher harmonic levels that need to be factored into the active power measurement. While electromechanical methods can only measure harmonic power up to the 5th harmonic, electronic methods can accurately estimate up to and beyond the 63rd harmonic.

Inherently, electronic methods are precise. However, variations in the architecture of the electronic system can influence the accuracy of the harmonic active power measurement. This article provides a summary of the advantages and disadvantages of the three primary implementations of electronic energy meters.

Understanding the Importance of Measuring Harmonic Power

Harmonic active power refers to the active power produced by the harmonic frequencies of the base frequency, which is 60 Hz in North America and 50 Hz in Africa and Europe. Harmonic active power is created when these harmonics exist in both the voltage input and the load current.

Non-linear loads, such as home entertainment systems, energy-efficient lighting, desktop computers, and adjustable speed drives (ASD) used in heat pumps or air conditioners, are known to generate harmonic load currents in low voltage setups. The test conditions for static energy meters, as outlined in IEC 62053-21 (formerly IEC 61036), accurately depict the current drawn by these non-linear loads. However, these tests do not account for the presence of harmonics on the voltage input, suggesting that no harmonic power is present in the active power calculation.

Nonetheless, a common consequence of non-linear loads is the distortion of the line voltage, which results in harmonics appearing on the voltage input. For instance, the resulting harmonic power has been observed in the field to constitute up to 9.3% of the total active power flow, with signals reaching up to the 50^{th} harmonic. These figures underscore the importance of being able to measure the harmonic active power, a capability as crucial as the traditional accuracy metrics used to categorize energy meters.

Designing and implementing test equipment capable of replicating these conditions is a complex task. However, the fundamental features of an electronic energy meter are often adequate to ascertain whether a solution can measure the harmonic active power and to what degree. These criteria should be considered alongside the meter's accuracy class as a quality benchmark when selecting an electronic energy meter.

Evaluating Harmonic Power

The primary difficulty in assessing harmonic energy lies in ensuring that the system can detect harmonics in both voltage and current inputs. The crucial attributes of the electronic system include:

Bandwidth of the Analog Input

The bandwidth of the analog input sets the frequency threshold beyond which the signal's strength is reduced by more than 3 dB (29.2%). A narrow analog input bandwidth implies that the analysis of higher harmonic orders will be inaccurate. For instance, an analog input bandwidth of 500Hz restricts the harmonic analysis to the 10^{th} order for a 50Hz setup. It is advisable to have an analog input bandwidth exceeding 4kHz, ensuring that all harmonics below the 63^{rd} order are accurately processed by the system in Africa, Europe, and North America.

Sample Rate and Computations

The frequency of sampling, denoted as (Fs), represents the rate at which the analogue-to-digital converter (ADC) samples the incoming signal. It is worth mentioning that ADCs are now commonly used in almost all electronic energy meters. According to the Nyquist theorem, if the input signal has frequencies exceeding Fs/2, accurate interpretation of the signal is not possible due to the alteration of its digital equivalent frequency during the sampling process, a phenomenon referred to as aliasing. Bearing in mind the requirements for analogue input bandwidth, the sampling frequency should be at least double the desired input bandwidth of 4kHz, which equates to 8 kilo-samples per second (ksps).

Characteristics and Operations of Solid-State Energy Meters

When viewed broadly, meters from various manufacturers exhibit similar structures. They typically include an analogue front end that interfaces with voltage and current sensors; analogue-to-digital converters that transform real-world signals into digital data; digital signal processing to calculate energy data; a microcontroller unit (MCU) to oversee the system and its peripherals; and an unspecified number of peripherals such as a display, an infrared port, or other communication channels. However, upon closer inspection, it becomes evident that the key decisions made during the implementation of this architecture result in distinct system behaviors when exposed to harmonic power.

Multi-chip

In this scenario, the focus is on selecting the optimal performance at an appropriate cost, with each function being executed by distinct electronic components. This structure is the priciest and is frequently employed in 3-phase applications. Regarding performance, the ADCs are the pivotal components, and the DSP is selected to manage the signal processing necessary for energy computation. For 3-phase energy meters, a 6-channel ADC with simultaneous sampling is the top choice. It surpasses the precision measurement requirements with a sampling frequency of up to 64ksps and an analogue input bandwidth exceeding 4kHz. This approach allows the meter manufacturer to control the signal-processing algorithm.

Integration of a Microcontroller Unit with an Analog-to-Digital Converter

This structure is appealing due to the integration of ADCs, digital signal processing, and management operations into a single unit. Minimal additional analogue components are required for conditioning the inputs of the ADCs. This results in a streamlined design where the processing of energy data remains under the purview of the meter producer.

Nonetheless, it is important to highlight a few constraints:

- The MCU in this structure has restricted digital signal processing (DSP) capabilities. Consequently, it can only process the ADC inputs at a low sampling rate, for instance, 1 to 2 ksps. This limits the harmonic content incorporated in the active energy measurement.
- The limited DSP capabilities lead to insufficient filtering for energy measurement. Inadequate filtering impacts the stability and reproducibility of results under testing conditions where harmonics exist. This stability is crucial in production as it reduces calibration and testing time.
- This streamlined design will not readily adapt to changing specifications such as AMR add-on, RMS, or reactive energy measurements. It will necessitate a comprehensive re-engineering of the energy meter to optimize the new MCU code for each additional function.

Low-Cost Microcontroller Units in Energy Metering

The ADE product line from Analog Devices [numerous articles on this topic can be found online] suggests a unique partitioning of the energy meter architecture. This involves merging the ADC and digital signal processing into a single unit. This approach not only offloads real-time signal processing from the MCU but also enables the use of a basic, cost-effective 8-bit MCU for administrative and communication tasks. From an energy measurement standpoint, this configuration offers several benefits:

- ADE components boast a high sampling rate of 800 ksps and an analogue input of 14kHz, facilitating the signal processing of harmonic power up to the 230th.
- ADE family products can directly interface with current and voltage sensors, eliminating the need for an additional analogue front end.
- ADE components perform comprehensive filtering, ensuring consistent and repeatable energy measurements.

Conclusion

Factoring in harmonics when calculating active energy enhances the precision of billing and the management of the grid, especially as the prevalence of non-linear loads in domestic appliances rises. Without a standardized method for measuring harmonic power, a qualitative assessment of electronic energy meters can aid in determining whether a solution is capable of such measurement. Thanks to recent progress in integrated circuit technology, as suggested by Analog Devices' ADE product line, designers of energy meters can now offer low-cost harmonic energy measurements, meeting the evolving demands of energy suppliers.

Balanced Billing

Utility companies often impose extra charges on medium and large customers with low power factors. However, these charges can be unjust in situations where the installations are exposed to voltage imbalance and harmonic distortion. It is essential to determine the fairest definitions of Power Factor (PF) and their corresponding measurement methods when powering a constant impedance load or an induction motor with unbalanced and non-sinusoidal voltages.

The concept of fairness is defined by the expectation that a meter, constructed based on a specific definition and measurement method, should yield values under non-ideal supply conditions that are very close to those it would produce under an ideal balanced sinusoidal supply.

To achieve this goal, both meter manufacturers and power distribution companies need to incorporate a range of computational simulation methods in their design and production processes. These methods should simulate various scenarios where a balanced customer, represented as a constant impedance load or an induction motor, incurs costs due to a voltage supply that is no longer balanced and sinusoidal. The same methodology should be applied to an induction motor under a broad array of unbalanced, non-sinusoidal supply situations.

Drawing from the results of the simulations and experimental tests, it is recommended to establish specific power factor definitions and measurement techniques that are largely resistant to voltage imbalance and harmonic distortions. These proposed power factor definitions should guarantee the fairest billing under circumstances with unbalanced, non-sinusoidal voltages.

When voltages are skewed and imbalanced, various meters may generate differing power factor (PF) measurements, resulting in a range of readings for the same circumstance.

A case was reported at BC Hydro by Andrew Berrisford where the PF dropped from 0.95 to 0.88 after a meter replacement. If not for the technician's vigilance, this new meter could have led to a 4% hike in the customer's bill. It is worth noting that these meters were approved for commercial use.

In a previous blog post, I illustrated the significant financial implications on consumers' electricity bills due to imbalanced network conditions. Everyone is welcome to review the Analogical Reasoning in the document included in the blog post and independently carry out the computations. Nonetheless, it appears that inhabitants of certain northern suburbs in Johannesburg are shouldering a considerable expense because of these imbalanced network situations, as evidenced in their electricity bills. Considering the percentage increase between the "new bill" and the existing electricity charge, there's a notable escalation of 127.16%.

It is essential for utilities to be able to install any meter in any electrical environment (sinusoidal or non-sinusoidal) with full confidence that they will all yield identical readings for the same load. Anything less is unacceptable.

Understanding the potential causes for these measurement discrepancies is key to achieving this level of assurance.

The principles of power components for both sinusoidal single-phase and balanced three-phase voltages and currents are well established. Yet, the deregulation of the energy market has highlighted an issue with accurately measuring electric energy in non-sinusoidal situations. This issue is still a topic of active debate, and there is no universally accepted power theory that can serve as a standard for billing, power quality assessment, detection of harmonic sources, and compensation in power systems. Similarly, there are no specific accuracy requirements or test conditions outlined in the standards for situations with harmonic distortion.

Metering instruments, which are based on traditional power theories and designed for sinusoidal waveforms, can lead to measurement inaccuracies under non-sinusoidal conditions. As a result, emphasis is placed on traditional billing quantities, which are defined as the fundamental active, reactive, and apparent powers, along with the associated power factor.

The IEEE Standard 1459-2010 provides definitions for the measurement of power and energy, as well as their breakdown, which are essential for the design and utilization of metering instruments under conditions that are sinusoidal, non-sinusoidal, balanced, or unbalanced. This standard adopts a concept that involves dividing power into its basic and residual components. This method of partitioning into basic and harmonic elements is applied to the most critical quantities, which are then standardized as measures of power quality.

Various methods for implementing this standard have been suggested in scholarly works. Two primary strategies have been employed to put this standard into practice: the first is a two-step algorithm that estimates the harmonic spectrum in the initial phase, and the second is an implementation that uses time-domain filtering.

Understanding the harmonic content of a signal data frame enables the computation of power definitions as proposed by the IEEE Standard, even though the standard does not provide any specific measurement techniques.

Estimating the spectrum of discrete-time signals, such as voltage and current, typically involves the use of the Fast Fourier Transformation (FFT). While FFT is highly efficient under conditions of fixed frequency, it is widely recognized that its accuracy diminishes under non-stationary conditions where the fundamental or harmonic frequency may fluctuate over time.

This is a common occurrence in real-world measurement systems. To maintain the accuracy of FFT, the analysis' sampling interval should be an exact integer multiple of the fundamental period of the waveform.

Consequently, synchronization becomes a critical aspect in achieving accurate measurements, which can be challenging in the presence of harmonic and inter-harmonic distortion.

To achieve power measurements aligned with IEEE 1459 definitions, it is crucial to introduce an instrument that utilizes an adaptive resonator-based algorithm for harmonic analysis, along with an externally decoupled module for frequency estimation. The resonator bank structure, a crucial component for implementing transformations, simplifies the harmonic estimation algorithm, resulting in reduced complexity and computational effort. This significantly lowers the computational cost of both harmonic and overall estimation compared to FFT processing in sliding mode. As a result, it becomes feasible to implement this algorithm on digital signal processors or programmable logic arrays using low-level embedded software. Additionally, the algorithm dynamically adapts to input signal frequency drift, effectively resolving synchronization-related challenges.

The spectrum estimation algorithm numerically treats the system frequency as an unknown parameter in the model that requires estimation. This approach mitigates sensitivity to significant frequency variations. By including the power frequency as part of the model's parameter vector, the model becomes nonlinear, necessitating the use of nonlinear estimation techniques.

An alternative measurement method is proposed that utilizes filters and a simple algorithm for the simultaneous estimation of frequency, voltage, and current magnitudes, both the fundamental and total active power, and fundamental reactive power.

The calculation of symmetrical components is accomplished using the transformation matrix of adaptive phase shifters, eliminating the requirement for Clarke-Park transformation. This enables the procurement of instantaneous symmetrical components, regardless of frequency changes, with manageable computational requirements. The algorithm maintains its stability despite changes in the power-system frequency and harmonic distortion of the input signals.

Summary

Is it possible to have confidence in the fairness of billing for electricity consumers, ensuring that the bills accurately reflect all supply situations, whether they stem from a balanced, unbalanced, or non-sinusoidal voltage supply?

Electronic meters, which incorporate harmonics filtering, enhance the precision of active power measurements. However, prepaid meters, which were introduced at a time when the concept of harmonics or the distortion of the standard sinusoidal waveform of power was perhaps entirely unknown, have not been updated. This raises questions about whether the "new smart meters" are designed based on the principles discussed in this paper.

As household electrical appliances evolve and become more complex, they generate higher levels of harmonics that need to be accounted for in the measurement of active power.