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Cloud Based Distributed Data Acquisition

Exemplified on Power Quality Monitoring

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Danksagung

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Abstract

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CHAPTER 1

Introduction

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CHAPTER 2

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CHAPTER 3

Theoretical Foundation

3.1 Power Quality Monitoring

Electric power is often seen as self-evident. It can be consumed at any time and any point all over the country. But, this standard of comfort implies a lot of effort for the power suppliers. The wide variety of power producers makes it hard for the suppliers to deliver a power grid with stable frequency and voltage. On the one hand, nuclear power plants produce a stable high amount of baseline power, on the other hand highly dynamic techniques like solar or wind energy can make the grid unstable. As a result, the grid has to be balanced. Surplus power has to be compensated, for example by pumping water into big artificial lakes in the mountains. Especially the increasing use of electric equipment in private and industrial environments punctuates the need for a stable power grid.

To fulfill the task of keeping the grid stable, precise measurement is needed at defined points in the power grid. Therefore, the term power quality monitoring describes the the monitoring of important parameters of the power grid, such as frequency or different aspects of the voltage. Furthermore, analysis are made to react to imbalances and to predict further events like the outage of a component of the power grid.

The European Standard EN 50160 defines the parameters of the power supply network that have to be monitored to ensure the given limits by the standard. The standard describes the characteristics under normal operation conditions at a supply terminal from a customer to the public network. The following sections describes some example characteristics of the corresponding Austrian standard ÖVE/ÖNORM EN 50160[ÖV11]. Furthermore, the International Standard IEC 61000-4-30 defines testing and measurement techniques for power quality monitoring. [ÖV09]

The goal of the proposed thesis is to develop a measurement system that measures relevant characteristics of a power system for power network supplier. According to the underlying standard (EN 50160), it is sufficient to capture the voltage on a power line to calculate the relevant properties for a power quality analysis. The scenario used in the thesis consist of synchronized measurement devices, distributed over a wider geographical area, that are connected to a cloud system. The cloud system provides functionality for managing the devices and visualization of the measured data. Furthermore, interfaces can be consumed to use the data with external systems. With this design, the power quality of a power supplier network can be captured.

3.1.1 Parameters

Effective Value

The effective value of the power supply voltage has to be 230 V ± 10% in 95% of every 10 ten minute interval and 230 V + 10%/- 15% in every ten minute interval. The following formula is used to calculate the effective value of the captured signal:

$$U_{eff} \approx \sqrt{\frac{1}{n}\sum_{n=0}^{n} x_i^2} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + x_3^2 + \cdots + x_n^2)}$$

In order to calculate the following characteristics, a Fourier transformation (see 3.1.3 for further information) has to be applied to the captured data.

Frequency

The frequency of the power supply voltage has to be 50 Hz ± 1% at 99.5% of the year and 50 Hz + 1%/- 6% at 100% of the year. After the Fourier transformation, the frequency with the highest amplitude is assumed to be the fundamental frequency f_0.

Voltage harmonics

According to the standard, all voltage harmonics up to the 25^{th} order has to be monitored. Each value has to be calculated over an interval of ten minutes and has to be tested against the values listed in the standard as described in appendix **??**. After the fundamental frequency f_0 is extracted out of the results of the Fourier transformation, the voltage harmonics can be calculated. The frequencies of the corresponding harmonics can be calculated by $f_n = n \cdot f_0$. The voltage harmonics of the desired order can then be calculated by the following formula:

$$V_n = \frac{A(f_n)}{A(f_0)} \cdot 100\%$$

where $A(f_n)$ is the amplitude of the signal at the frequency f_n.

Total harmonic distortion

In addition to the voltage harmonics, the total harmonic distortion (THD) has to be $\leq$ 8%. For this, the voltage harmonics up to the 40^{th} order are aggregated by using the following formula:

$$THD = \frac{\sqrt{\sum_{h=2}^{40} V_h^2}}{V_1} \cdot 100\% = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_{40}^2}}{V_1} \cdot 100\%$$

3.1.2 Measuring Electric Characteristics

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To calculate the selected power quality characteristics, the voltage of the power line has to be monitored. In order to accomplish this task, the analog signal has to be digitized for further computational processing. The signal has to be sampled and each sample has to be quantized to a finite number of bits representing the sample in a digital way. The accuracy of the quantization process strongly depends on the number of bits that such an analog/digital converter (ADC) offers. Assume an ADC represents a sample by B bits, the sample is transformed to a value in the range of 2^B bits, furthermore, the full-scale range R has to be taken into account. As a result of this, the full-scale range R is divided in 2^B steps and the resulting quantization with or quantization resolution can be represented using the following formula[Orf95]:

$$Q = \frac{R}{2^B}$$

In the proposed scenario, a ADC with a $R = \pm$ 1200 V = 2400 V and B = 24 bits is used. This results in the following quantization resolution:

$$Q = \frac{2400\ V}{2^{24}\ bits} = 0.000143\ V \approx 143\ \mu V$$

Beside having a efficient quantization resolution, choosing the right sample rate is crucial. In order to reconstruct the measured signal, the time between two sample has to be chosen in a manner that on the one hand, unnecessary often taken samples of the same signal level are generated (oversampling) and on the other hand, not too less samples are taken such that the original signal cannot be reconstructed (undersampling)[Orf95]. To avoid undersampling, the Nyquist sampling theorem has to be applied: Taken a real signal, that is bandlimited to B Hz (only signals with a frequency below B Hz are sampled), can be reconstructed without errors with the frequency R, described by the following formula[WDPP13]:

$$R > 2 \cdot B$$

In the proposed scenario, we examine total harmonic distortion up to the 40^{th} order or harmonics. According to the standard, the maximal allowed frequency is 50 Hz + 1% = 50.5 Hz. Therefore, the 40^{th} harmonic has a frequency of at most 2020 Hz. The signal is bandlimited by a lowpass filter to $B = 5000$ Hz. According to the Nyquist sampling theorem, the sample frequency has to be set to at least $R > 2 \cdot B = 10000$ Hz. Hence, the sample frequency of the measurement device used to evaluate the scenario is set to 20000 Hz.

3.1.3 Transformation from Time- to Frequency Domain

TODO: better title

Since a great number of important characteristics of the power quality depends on measuring the frequency (and it's components) on a power line, the transformation form a signal recorded in the time domain to it's frequency parts shall be discussed. The most important method used for transformation is the Fourier transform. By using the Fourier analysis, a signal can be represented by its sinusoidal waveforms. In other words, the output of the Fourier analysis shows the amplitude and phase (cosine and sine components) at every frequency of the original signal. The conversation of a signal from the time- to the frequency-domain can be represented by the Discrete Fourier Transform (DFT). The input for the DFT is a signal of N points and can be calculated using the following formula[Sun01]:

$$X(k) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi}{N} nk}$$

Implementing the DFT directly results in an algorithm with a complexity of $\mathcal{O}(N^2)$. Therefore, efficient implementations (Fast Fourier Transform - FFT) are available that reduce the complexity to $\mathcal{O}(N \cdot log(N))$. The most common FFT algorithm is the Cooley-Tukey algorithm that uses the divide and conquer approach which can be found in listing 3.1[Mob07]. The results of this transformation are 'Bins' representing a sample of the spectrum with the frequency

$$f_i = \frac{R}{N} \cdot i$$

where i is the current Bin-index. Therefore, the output of the FFT has a limited resolution of the frequency. In the proposed scenario, the resolution (or the difference between two Bins) should be at least 0.5 Hz which can be represented as $\Delta f = f_n - f_{n-1} = 0.5$ Hz. Since $n \geq 0$ and $n < N$, we can choose an arbitrary n in this range.

$$n = 2, R = 20000Hz$$

$$\Delta f = f_n - f_{n-1} = f_2 - f_1$$

$$\Delta f = \frac{R}{N} \cdot 2 - \frac{R}{N} \cdot 1 = \frac{2 \cdot R - 1 \cdot R}{N} = \frac{R}{N}$$

$$\Rightarrow N = \frac{R}{\Delta f} = \frac{20000Hz}{0.5Hz} = 40000$$

When looking at the recursive algorithm, it can be seen that the algorithm works efficiently when N is a power of two. Hence we take the next greater power of two for N. $N = 2^{16} = 65536$, which results in a resolution $\Delta f = 0.305$ Hz.

For the sake of completeness, 'Window functions' have to be taken into account. The FFT works under the precondition that the signal is periodic in the examined window (N points). Due to measurement uncertainty and that in practice, the signal is not a perfect sine wave, errors occur in the output. To minimize the error, window function can be applied to the measurement data before FFT, which transforms the input signal to a periodic signal. Different window function (Hanning, Hamming, Blackman, etc.) exists to examine different aspects of the spectrum. Practice has shown that the Hanning-Window is useful in most situations and is also applied in the proposed thesis. Every sample $x[n]$ in the time domain is multiplied with $w[n]$, which has the following formula[Mey06]:

$$w[n] = 0.5 - 0.5 \cdot cos(\frac{2\pi n}{N})$$

Listing 3.1: Recursive Cooley-Tukey FFT algorithm

```
private void CalculateFFT(ref Complex[] signal)
{
      int n = signal.Length;

      if (n <= 1)
      {
            return;
      }

      //Divide
      Complex[] even = new Complex[n / 2];
      Complex[] odd = new Complex[n / 2];

      for (int i = 0; i < n / 2; i++)
      {
            even[i] = signal[2 * i];
            odd[i] = signal[2 * i + 1];
      }

      //Conquer
      CalculateFFT(ref even);
      CalculateFFT(ref odd);

      //Combine
      for (int i = 0; i < n / 2; i++)
      {
            double kth = -2 * i * Math.PI / n;
```

```
            Complex wk = new Complex(Math.Cos(kth), Math.Sin(kth));

            signal[i] = even[i] + wk * odd[i];
            signal[i + n / 2] = even[i] - wk * odd[i];
      }
}
```

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3.2 Cloud Computing

3.3 Internet of Things

CHAPTER 4

System Design

4.1 Requirements

4.2 System Overview

4.3 Hardware Architecture

4.4 Software Architecture

4.4.1 Synchronization

Synchronizing a distributed measurement system is essential. Although an not synchronized system delivers correct data that holds true for the point of measure, synchronizing theses systems allow to extract further knowledge out of the captured data. In the use case, selected for this thesis, power quality monitoring provides good arguments for synchronization. If somewhere in the power network an error occurs, it could be possible that this error is propagated throughout the network. Since the electric network and the infrastructure around it consists of resistive, inductive and capacitive load, a cascading of a fault is possible. With an adequate synchronization, it is possible to track the error propagation with a distributed measurement systems.

The testing equipment used in the proposed scenario support three different synchronization mechanisms. The radio based DCF77 time signal, the satellite based GPS signal and the Ethernet based SNTP protocol. The following section explains these three mechanisms in detail and evaluates which type suits most for this use case.

For the sake of completeness, two further synchronization modes exist. Distributed clock over EtherCAT and Q.sync. The first mode is part of the EtherCAT protocol that is implemented in the used modules, the second mode is a proprietary bus that connects multiple controllers. Since the different power quality measurement systems are spread across a wider geographical area, this two modes can't be used.

DCF77

DCF77 is a radio based time distribution services. It uses a long wave radio transmitter with a carrier frequency of 77.5 kHz. Due to the fact that the transmitter is located in Germany, it covers a maximum range (by using the proper detector) of approximately 2400 km, which is in fact whole Europe. Since DCF77 is driven by atomic clocks, the received radio signal is less accurate than the them[Eng12]. Every minute, the time information (and additional information like civil warnings[PHB04] and weather data[Eng12]) is transmitted amplitude modulated (AM) and phase modulated (PM) in Binary Coded Decimal (BCD). In the current message the information about the next second is transmitted, furthermore, the start of a minute can be detected. It is possible to detect leap seconds and the switch to daylight-saving time [PHB04]. Considering accuracy of the DCF77, the decoding mechanism is crucial. For the use in watches only the amplitude modulated signal is decoded which results in accuracy of +5ms up to +150ms. By using better antennas, this values can be enhanced to +5ms up to +15ms. To gain more accuracy, the phase modulated signal has to be decoded as well. This method results in an exactness of ±2ms[B.].

Since the signal of a DCF77 receiver cannot be connected directly to the measurement devices, the signal has to be converter inside the receiver to a suitable format. As an example of such a format, the "IRIG B003" standard is described in more details here. The Inter Range Instrumentation Group (IRIG) specifies various standards regarding transmitting time information over via a serial time code format. The name of the described standard refers to a format with 100 pulses per second (B), Pulse width code (0), no carrier (0) and Binary Coded Decimal - BCD, Straight Binary Second of Day - SBS (3). The date information is transmitted as a sequence of seconds, minutes, hours, days, years, control functions and time of day [Sec04]. Regarding the used testing equipment, DCF77 receivers can provide the IRIG B003 signal either straight as Transistor-Transistor Logic (TTL) signal into the measurement device, or over the RS-485 bus.

GPS

The Navstar Global Positioning System (GPS) is a satellite based time distribution service. In normal operation mode, it consists of 24 geometrical space slots with at least one operational satellite in it. Each satellite sends it's time information, generated by an atomic clock, and it's position to the receiver stations down on earth with a frequency of 1.57542 GHz. To control and observer the status of the GPS, the Operational Control System (OCS) is used to communicate with the satellites via ground antennas. The OCS is responsible for various tasks including telemetry, monitoring of different parameters and uploading of navigation data. Considering accuracy, GPS offers two services. On the one hand, the Standard Positioning Service (SPS) that is available to the civil public with less accuracy and on the other hand, the Precise Positioning Service (PPS) available to the military of the USA and it allies with high accuracy.[Dep08]. Due to this fact, the proposed system and the used testing equipment can only make use of the SPS.

After receiving the time information from one or more satellites, the data can be passed to the testing equipment. For this, the received information is transformed to the National Marine Electronics Association (NMEA) 0183 format. Since NMEA was designed as interconnection format of different devices used in the marine, the format consists of various sentences representing features of the connected devices. To use NMEA as protocol for transmitting time- and position data, the two sentences $GPRMC (Recommended Minimum Navigation Information) and $GPGGA (Global Positioning System Fix Data. Time, Position and fix related data for a GPS receiver) can be used. The data is transferred as ASCII text and can be decoded directly by knowing the format of the corresponding sentence. NMEA uses, like IRIG, a serial bus for communication[Nat02].

Beside NMEA, some GPS receivers are also able to provide information via the previously described IRIG B003 format.

SNTP

The Simple Network Time Protocol (SNTP), as a subset of the Network Time Protocol (NTP), provides time information in a network to clients. If a client wants to synchronize it's internal clock with a clock placed in the network (SNTP server), it has to send a message to this server. In the response, three timestamps are transmitted. The client timestamp when the message was sent, server time when the message was sent and server time when the message was received. With the information in this message and the timestamp when this message was received by the client, the exact time can be applied to the client[Joh04]. To synchronize a client's clock, the offset and delay of the client relative to the server is computed. By the used algorithm (especially because of the 64 bit integer arithmetic) a client has to be at least 34 years in the past and at most 34 years in future in order to get synchronized by the SNTP server[MDM+10].

Conclusion

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4.5 Network Architecture

4.6 Security Aspects / Threat-Modeling

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CHAPTER 5

Simulation

5.1 Tools

5.2 Important Points to consider

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5.3 Evaluation

5.4 Impact on System Design

CHAPTER 6

Implementation

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Evaluation

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