

An Analytical Framework for Power Quality Monitoring in Smart Power Microgrid

by

Sardar Ali

MS(IT), National University of Sciences and Technology, Pakistan, 2009

BS(IT), Kohat University of Science and Technology, Pakistan 2006

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ABSTRACT

Due to the high measuring cost, the monitoring of power quality is non-trivial. This work is aimed at reducing the cost of power quality monitoring in power network. Using a real-world power quality dataset, this work adopts a learn-from-data approach to obtain a device latent feature model, which captures the device behaviour as a power quality transition function. With the latent feature model, the power network could be modeled, in analogy, as a data-driven network, which presents the opportunity to use the well-investigated network monitoring and data estimation algorithms to solve the network quality monitoring problem in power grid. Based on this network model, algorithms are proposed to: 1) intelligently place measurement devices on suitable power links to reduce the uncertainty of power quality estimation on unmonitored power links, 2) estimate the power quality in unmonitored segments of a power network, using only a small number of measurement points, and 3) identify a potential malfunction device in the network.

The meter placement algorithms use entropy-based measurements and Bayesian network models to identify the most suitable power links for power meter placement. Experimental results show that the meter placement solution is efficient, and has the potential to significantly reduce the uncertainty of power quality values on unmonitored power links. After deploying power quality meters on selected links, for the unmonitored segments in the network, a maximum entropy (MaxEnt) based approach is presented to estimate power quality in smart grid. Compared to other existing methods such as Monte Carlo Expectation Maximization (MCEM), the MaxEnt based approach is much faster. Finally, using reading from our metered locations, we propose a prediction model that derive an acceptable device behaviour with the help of CBEMA curve to identify a potential malfunction device in the power grid. Our simulation results show that our prediction model accurately detect the malfunction devices and makes the device maintenance/replacement recommendations.

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DEDICATION

I dedicate this thesis to my parents *Subhania Bibi* and *Abdulkabir Khan*. For all those years, you dreamed for the best possible education I could get. I hope that this achievement will complete that dream.

Chapter 1

Introduction

1.1 Why Power Quality Monitoring?

Electrical power networks are one of the critical infrastructures of our society. Due to our high dependence on electricity, the issue of reliability in electric networks has become a core research interest in the area of smart grid [12]. Reliability evaluation of power grid, however, is challenging due to the existence of multiple electric utilities and the potential of cascading failures of power distribution systems [1]. One of the most influential factors impacting the reliability and energy saving of power networks is the power quality delivered to, and experienced by, critical electric equipment. Poor power quality, such as voltage sags/swells, harmonics, fast impulses etc, may lead to power outage and service interruptions. Service unavailability caused by power losses is a serious problem for many companies and organizations, e.g., it may result in a significant revenue loss for Internet service providers or even loss of lives in hospitals. To improve the reliability of power networks, organizations and large companies (e.g., Google data centers) adopt smart microgrid, and closely monitor the power quality in different segments of the microgrid. Hence, the monitoring of power quality is a crucial component of assessing and maintaining reliability in power grids.

Monitoring power quality, however, is not an easy task. Since the power measurement devices [4, 14] are expensive, it is financially impractical to monitor every segment of a power network. The overhead of interconnecting these power meters and developing the power management system further increases the cost. In addition, in many cases direct monitoring of power quality is difficult, e.g., it is hard to install smart meters after power lines were sealed in hard-to-reach areas in a building. We

identify various research challenges in power quality monitoring.

1.2 Open Challenges

In order to effectively monitor the power quality in the smart grid, this work is intended to tackle the following challenges:

1. Based on a limited small number of monitored points in a power network, how can we effectively estimate the power quality of other unmonitored segments of the network?
2. Given a fixed number of available power meters, which grid segments should be selected for monitoring such that power quality can be inferred as accurately as possible in the remaining unmonitored segments of the network? A relevant research problem is to devise a mechanism that calculate the optimal number of meters required to achieve an acceptable level of network reliability.
3. Based on readings from our meters locations in the power grid, how can we accurately detect a potential malfunction device?

As the first step to tackle the above challenges, the probabilistic calculation of power quality values on unmonitored links requires the behaviour (latent feature) of each device to be known. We represent the latent feature of a device as a transfer function which is usually estimated through physical modelling or through the assessment of historical power monitoring data. Using a real power quality dataset, we show that historical data can be used to capture the latent features of a device. Our device latent feature model is presented in Chapter 3.

With devices' latent features captured, we in the second step introduce a network model of the smart microgrid as a data-driven network, in analogy, where we represent the electrical components as network nodes, power links as data links, flow of power as data flow on the links, and the power flowing through links as numeric data. The power quality estimation problem can then be modeled as an optimization problem of missing data estimation in a data network. This problem transformation significantly simplifies the complexity of the power grid network; it also give us the opportunity to use the well-investigated network monitoring and data estimation algorithms to solve the network quality monitoring in power grids. Chapter 4 presents the proposed network model.

Finally, using our network model, we propose various algorithms to tackle the three challenges we identified in this section. In the next section, we detail the identified challenges and summarize the solutions we propose to solve each challenge.

1.3 Proposed Solutions

Power quality meters play an important role in the reliability evaluations of the power grids. In this thesis, we identify three research problems related to smart meter placement, power quality estimation on unmonitored segments, and detection of a malfunction device in the power grid. Summary of the our proposed solutions for the three research challenges is as follows:

1.3.1 Power Quality Estimation using Maximum-Entropy Approach

The reliability evaluation of enterprise-level power grid seems to be much simpler compared to the large-scale power grid which is notoriously difficult due to the existence of the multiple electric utilities and the cascading failures of power distribution systems [1]. Nevertheless, to tackle the practical challenges, the power quality and operational status of electric devices in the microgrid must be monitored and recorded. On the other hand, due to financial and other practical in-feasibilities, each device in the network cannot be monitored. We need to tackle the following challenge: *Based on a limited small number of monitored points in a power network, how can we effectively estimate the power quality of other unmonitored segments of the network?*

We propose to use a Maximum-Entropy (MaxEnt) [10] approach to power quality estimation. The basic idea of MaxEnt is that out of all probability distributions consistent with a given set of constraints, we should choose the one that has the maximum uncertainty to be the estimated power quality values. Intuitively, the principle of MaxEnt implies that we should make use of all the information that is given and avoid making (biased) assumptions about information that is not available.

The MaxEnt approach is built on the top of our network model which give us the opportunity to use existing data estimation techniques used in the data networks. The problem of estimating power quality is modeled in such a way where we effectively get the benefit of MaxEnt approach to correctly estimate the power quality values at unmonitored links. We solve the formulated MaxEnt problem and validate

its effectiveness and efficiency with a simulated microgrid system. Compared to other existing methods such as Monte Carlo Expectation Maximization (MCEM), the MaxEnt based approach is much faster. The proposed MaxEnt approach is presented in Chapter 5.

1.3.2 Intelligent Meter Placement using Conditional Entropy

Power quality meters are being deployed to monitor the power quality in the power grid network. Power quality meters are expensive devices [4, 14] and it is impractical to monitor the power quality at every segment in the power grid network. Instead, power quality in non-metered grid locations must be inferred given data obtained from the measured locations. The research question arise is *where to place the meters in the power grid network?*

We propose an iterative approach for identifying network segments suitable for power meter placement. During each iteration of the algorithm we identify in a greedy manner the network segment that suffers from the most unpredictable power quality given the meters deployed so far. We then deploy the next power meter at that location.

A relevant challenge here is to identify the optimal number of meters to reduce the uncertainty and hence the overall reliability of the network to an acceptable level. Formally, we tackle the problem of *how to devise a mechanism that calculate the optimal number of meters required to reduce the uncertainty of power quality in the power grid to an acceptable level?* We propose to model the above issue as an optimization problem to minimize the number of meters while maintaining the desired level of network reliability.

For above two problems, the detailed problem definitions, the proposed solutions, and results from an experimental study are presented in details in Chapter 6.

1.3.3 Detecting a Malfunction Device using Our Prediction Model

The main objective of this work is to reduce the cost of power quality monitoring while ensuring the reliability of the power grid network. The two research problems discussed above address how to accurately estimate the state of the network. This information could be used to avoid device failures. We need to propose a model that

could accurately detect any significant change in the normal behaviour of a device. By doing so, we would be able to raise an alarm and make recommendations for the device maintenance or possible replacement before the device significantly compromise the reliability (in terms of power quality) of the power grid. The research question arises is: *how to detect a potential malfunction device in the power network based on available PQ readings.*

To address the challenge, using the power quality readings from the monitored links, we propose a prediction model that accurately detects a malfunction device in the power network. The idea is to make recommendation for device maintenance/replacement based on the accumulative suffer time of the device using the standard mesures defined in the CBEMA curve. Our proposed solution and the simulation results of its accuracy evaluations are presented in Chapter 7.

1.4 Contributions

The proposed thesis work investigate various algorithms to tackle our three research challenges in the area of power quality monitoring in power grid. As the first step to tackle the above challenges, we represent a device latent feature model used to capture the behaviour of the devices in the power grid. With devices' latent features captured, we in the second step introduce a network model of the smart microgrid as a data-driven network. This problem transformation significantly simplifies the complexity of the power grid network; it also give us the opportunity to use the well-investigated network monitoring and data estimation algorithms to solve the network quality monitoring in power grids.

Our latent feature and network models are detailed in separate chapters in this document. Using the network model, we propose various algorithms to tackle the three challenges and make the following three major contributions:

1. **Power Quality Estimation:** A Maximum-Entropy (MaxEnt) approach to power quality estimation. The proposed solution is presented in Chapter 5.
2. **Intelligent Meter Placement:** An intelligent entropy-based algorithm and a Bayesian network based approach to solve the meter placement problem. The proposed meter placement algorithms and their detailed evaluations are presented in Chapter 6.

3. **Malfunction Device Detection:** We propose a prediction model to detect any potential malfunction device. The proposed model is based on CBEMA curve, using the inferred and actual PQ values by meters we placed using our intelligent meter placement algorithms. The proposed model with its simulation results is presented in Chapter 7.

1.5 Thesis Outline

The rest of the thesis is organized as follows. Chapter 2 provides review on power quality in smart grid and discusses the available literature related to our proposed work. The proposed device latent feature model is presented and evaluated on a real dataset in Chapter 3. Our network model of the power grid is presented in Chapter 4. Based on the proposed network model, we build various algorithms to address the identified research issues. The research issue of estimating power quality values on unmonitored links is investigated in Chapter 5. In Chapter 6, we propose algorithms that intelligently place the power meters on high information locations in the power grid. In Chapter 7, based on the known power quality values from our proposing algorithms, we present a prediction model that detects a potential malfunction device. The thesis is concluded and the possible future extensions are discussed in Chapter 8.

Chapter 2

Background and Related Work

Due to our high dependency on electric power, reliability of power networks has become critically important. A variety of hardware and software tools for measuring and monitoring the power quality are available. Before we detail the cutting-edge research work in the area, we discuss the most important causes of power quality problems as follows.

2.1 Main Causes of Power Quality Problems

2.1.1 Voltage Sags/Swells

The voltage sags are brief reductions in voltage while the voltage swells are brief increase in voltage level which may last from a cycle to a second. Voltage sags are caused by faults, sudden increases in loads or device impedance, short circuits or faults. Causes of voltage swells are an abrupt reduction in load on a circuit or a damage in neutral connection. Sag or swell is the largest cause of problems from the utility side. Sags or swells can occur in the power distribution network or at the point of use. These types of disturbances can lead to loss of production or electronic device failures. Measurement devices being used should be able to detect these events. A standard reference for measuring the power quality events largely used by industry is the Computer Business Manufacturers Association (CBEMA) also known as ITI Council profile curve [9]. Power quality monitoring devices use the ITI curve as a reference to highlight if the voltage events may result in any potential problem.

2.1.2 Harmonics

A harmonic is a periodic, an integer multiple wave of the fundamental frequency. They are caused by non-linear electric loads. Technically, voltage harmonics are caused by the combination of line impedance and current with a frequency other than the fundamental frequency. Harmonics in power grids are the main cause of power quality problems. A lot of harmonics in the power systems can cause malfunctioning or damage to the electric devices. Power quality measurement devices use the technique of Fourier Analysis to detect the magnitude and frequency of voltage harmonics.

2.1.3 Interharmonics

Interharmonics are distortions in the current or voltage waveforms. They are different from ordinary harmonics in that it refers to voltages or currents having frequency components that are not integer multiple of the fundamental frequency. They can be found in networks of all voltage classes. They can be found in networks of all voltage classes. They can affect power-line carriers, lighting, computer displays, heating of transformers and motors, mis-operation of electronic devices etc. However, due to their small amplitude and uncertain frequency, they are difficult to detect.

2.1.4 Transients

Transients (also known as *surges* or *spikes*) are momentary changes in voltage or current that last for a very short period of time. The interval is usually less than $1/16^{th}$ of a voltage cycle or about 1 milliseconds. The typical duration of voltage transients is 50 microseconds while the duration of current transients is 20 microseconds. Transients can come from external sources as well as from within the system. The external sources include lightning, switching of facility loads, poor or loose connections in the distribution system, opening/closing of disconnects, tap changing on transformers, environmental changes. The main culprits within the system causing transients include device switching, arcing, static discharge, and adding or removing loads. If left unchecked, transients can lead to device degradation over time.

2.1.5 Other Causes

As discussed earlier, the life time of electric/electronic devices is dependent on the electric power quality. There are many other causes which effect the power quality in

the electric network. In order to improve the reliability of the electric power network, the causes of the power quality problems need to be addresses. Some of the main other causes are as follows.

Over/Undervoltage

When the RMS value of the voltage in a power system raises above 110% for a duration of greater then 1 minute, it is classified as an overvoltage. It happens when the system is either too weak to support the desired voltage or the voltage controls are sufficient. They are usually the result of switching off a large load. The overvoltage is usually protected using bulk capacitors.

An undervoltage is a decrease in the RMS voltage value when it falls under 90% of its original level for a duration of greater than 1 minute as classified by the CBEMA curve [9]. Its causes include overload circuits, load switching, and capacitor bank switching off. Undervoltages may result in premature shutdown of circuits, loss of important data, restart of electronic equipments.

Sustained Interruptions

It is a decrease in the voltage level to zero for a period of more than 1 minute as defined by IEEE standard [8]. They are often permanent in nature which requires manual intervention to restore the system. This type of interruptions are caused by permanent faults caused by storms, equipment failures, trees striking lines, and other environmental factors. If not tackled on time, these faults may result in a complete shutdown of the facility.

Voltage Unbalance

It is defined as the largest difference of the RMS voltage value (or phase angles) on a line from its average value. It is quantified in terms of ratios of the negative and zero components to the positive sequence. Voltage unbalance is usually caused by uneven distribution of voltage between the phases of an n-phase (usually 3-phase) system. It may also caused by mismatch of the impedance of a transformer, a blown fuse, or a bad capacitor. The problem may cause premature equipment aging, power supply ripple, insulation degradation, decrease in mean time between failures (MTBF).

Table 2.1: Electromagnetic Disturbance Phenomena Categories [6]

1. Conducted low-frequency phenomena	3. Conducted high-frequency phenomena
<ul style="list-style-type: none"> • Harmonics, interharmonics • signaling systems • Voltage fluctuations • Voltage dips and interruptions • Voltage unbalance • Power frequency variations • Induced low-frequency voltages • DC in AC networks 	<ul style="list-style-type: none"> • Directly coupled or induced voltages or currents • Unidirectional transients • Oscillatory transients
2. Radiated low-frequency field phenomena	4. Radiated high-frequency field phenomena
<ul style="list-style-type: none"> • Magnetic fields • Electric field 	<ul style="list-style-type: none"> • Magnetic fields • Electric fields • Electromagnetic fields
	5. Electrostatic discharge phenomena (ESD)
	6. High-altitude nuclear electromagnetic pulse (HEMP)

Frequency Variations

Frequency variation is the deviation of fundamental frequency from its nominal value. The size and duration of the frequency shift is dependent on the load characteristics. It is usually caused when a large load is disconnected or when a large power generator goes off-line. It can cause data loss, device crash/damage, or erratic operation in the electronic system.

2.2 Classification of Power Quality Disturbances

It is a known phenomena that when a power system is disturbed either by a short circuit, sudden increase in load, or any other relevant cause, the balance of energy is disturbed. During the disturbance, energy exchange between the electric and magnetic fields occurs which deviates the waveshapes of voltages and currents in the power system. This electromagnetic phenomena is standardized by two leading knowledge bodies in the field by standards: 1) IEC/TS 61000-2-5; and 2) IEEE Std. 1159-1995.

2.2.1 The IEC Classification

The International Electrotechnical Commission (IEC) classifies various phenomenas that cause electromagnetic disturbances through their standard IEC/TS 61000-2-5 [6]. These disturbances can reach the equipment either by conductive or radiative coupling pathways. When there is a physical pathway exists between the source of emission and the affected device, it is a conductive coupling. On the other hand, radiative coupling

Table 2.2: Categories and typical characteristics of power system EM phenomena [8]

Categories	Spectral Content	Duration	Voltage Magnitude
1. Transients			
(a) Impulsive			
i. Nanosecond	5-ns rise	< 50 ns	
ii. Microsecond	1- μ s rise	50 ns - 1 ms	
iii. Millisecond	0.1-ms rise	> 1 ms	
(b) Oscillatory			
i. Low frequency	< 5 kHz	0.3 – 50 ms	0 – 4 pu (per unit)
ii. Medium frequency	5 – 500 kHz	20 μ s	0 – 8 pu
iii. High frequency	0.5 – 5 MHz	5 μ s	0 – 4 pu
2. Short-duration RMS variations			
(a) Instantaneous			
i. Sag		0.5 – 30 cycles	0.1 – 0.9 pu
ii. Swell		0.5 – 30 cycles	1.1 – 1.8 pu
(b) Momentary			
i. Interruption		0.5 cycles – 3 s	< 0.1 pu
ii. Sag		30 cycles – 3 s	0.1 – 0.9 pu
iii. Swell		30 cycles – 3 s	0.1 – 1.4 pu
(c) Temporary			
i. Interruption		> 3 s – 1 min	< 0.1 pu
ii. Sag		> 3 s – 1 min	0.1 – 0.9 pu
iii. Swell		> 3 s – 1 min	0.1 – 1.2 pu
3. Long duration RMS variations			
(a) Interruption, sustained		> 1 min	0.0 pu
(b) Undervoltages		> 1 min	0.8 – 0.9 pu
(c) Overvoltages		> 1 min	1.1 – 1.2 pu
(d) Current overload		> 1 min	
4. Imbalance			
(a) Voltage		steady state	0.5 – 2%
(b) Current		steady state	1.0 – 30%
5. Waveform distortion			
(a) DC offset		steady state	0 – 0.1 %
(b) Harmonics	0 – 9 kHz	steady state	0 – 20 %
(c) Interharmonics	0 – 9 kHz	steady state	0 – 2 %
(d) Notching		steady state	
(e) Noise	broadband	steady state	0 – 1 %
6. Voltage fluctuations			
	< 25 Hz	intermittent	0.1 – 7 % (2.2 – 2 Pst)
7. Power frequency variations			
		< 10 s	\pm 0.10 Hz

occurs when there is no physical pathway but the emission propagates through electric and magnetic fields. Based on couplings and relative frequencies of the disturbances,

IEC classifies the electromagnetic phenomena into six categories as shown in Table 2.1.

2.2.2 The IEEE Classification

The Institute of Electrical and Electronics Engineers (IEEE) put efforts to standardize power quality terminology to allow the parties involved in to have standard and consistent terms. The IEEE standard 1159-1995 [8] provides a classification of power quality events. The various power quality events are classified in seven general categories. The classification is based on event characteristics such as spectral content, duration, and magnitude as shown in Table 2.2.

2.3 Related Work

Power quality is a crucial component of power system reliability. Poor power quality may lead to service interruptions. To improve the reliability of power grid networks, power quality measurement devices are being deployed to closely monitor the power quality on underlying power links. As discussed, it is not feasible to monitor every segments of the network. Instead we propose to 1) intelligently place the monitoring devices on selected network segments; and 2) estimate the power quality on unmonitored links base on the known information from the monitored links.

We also address the relevant research problems such as 1) how many meters are required to achieve the desired level of network reliability; 2) based on reading from the monitoring devices, how to accurately identify a malfunctioning device that degrades the power quality in the power system; and 3) based on user requirements, environmental and physical constraints, what is the best choice for a monitoring device to be used. Note that, we need to use devices of different capabilities for different scenarios. This section covers the research work relevant to our proposed solutions addressing the above identified problems. We classify the existing research (and available techniques) related to this work in the following categories.

2.3.1 Classification of Power Quality Events

There are many approaches of classifying the power quality events. Typically, power quality is assigned a label which is based on magnitude and duration of the electromagnetic phenomena (e.g., voltage sag or swell). Electrical utilities typically report

a System Average RMS Variation Frequency Index (SARFI) which is essentially a count of the number of times the magnitude and duration fall below (or above) a threshold. The IEEE and IEC also have their standards for classifying individual power quality events [6, 8]. These standards are detailed in Section 2.2. We use a discrete classification system in this work, similar to that described in the IEEE standard [8].

2.3.2 Power Reliability

The industry standard practices for electric power reliability in networks focus on measures such as Mean Time Between Failure (MTBF), reliability, and availability as defined by the IEEE Gold Book [7]. These measures are theoretical values, measured or calculated for components and networks operating under standardized conditions. They serve as methods for comparison but are not intended as predictive tools for networks that operate in realistic environments with varying temperature, humidity, load, and power quality.

Further, it is known that there exists a relationship between power quality and the lifetime and performance of components [9]. For an effective evaluation of power reliability, we need to accurately estimate power quality. [5], which motivates for the work we are proposing. The work proposed in [5] is relevant to our power quality estimation solution (see Chapter 5) where the authors propose an Expectation Maximization (EM) based algorithm to estimation the microgrid reliability. Although effective, the EM algorithm needs a long time to converge. We are thus motivated to find faster algorithms in power quality estimation.

2.3.3 Data Estimation Techniques

We use data estimation techniques to propose our power quality estimation solution (see Chapter 5). Here we give a short description of the EM and MaxEnt algorithms used in our work:

The Expectation Maximization (EM)

EM is a general approach to iterative computation of maximum-likelihood estimates when the observations can be viewed as incomplete data. Since each of the iteration of the algorithm consists of an expectation step followed by a maximization step, the

algorithm is named as the EM algorithm. The successive iterations always increase the likelihood and the algorithm converges at a stationary point.

Maximum Entropy (MaxEnt) Estimation

MaxEnt solves convex optimization problems of the form,

$$\begin{aligned} \text{maximize } g(\vec{x}) &= - \sum_{i=1}^n x_i \log x_i \\ \text{subject to } \mathbf{A}\vec{x} &\leq \mathbf{c}, \quad \mathbf{B}\vec{x} = \mathbf{1}, \end{aligned}$$

where $\vec{x} \in \mathbb{R}^n$ is the optimization variable, $A \in \mathbb{R}^{m \times n}$, and $B \in \mathbb{R}^{m \times n}$ are problem parameters; and $\mathbf{1}$ is a vector with all 1's.

2.3.4 Sensor Deployment

There is a great body of work on the optimal sensor deployment problem [11]. The meaning of sensors is broad, including any measurement/monitoring devices. In the context of power networks, optimal deployment of phasor measurement units (PMU) has been studied [16]. Nevertheless, we have not seen any work on studying optimal meter deployment problem in the context of network-wide power quality estimation.

2.3.5 Bayesian Inference

We use Bayesian inference to identify high information locations for deploying smart meters (detailed in Chapter 6). The Bayesian inference methods are helpful in providing the new estimates of the PQ values on non-monitored links given evidences are obtained from the metered locations. Bayesian inference is a general and well-investigated discipline which has applications in a wide range of fields. Several algorithms are available to address specific problem in this domain. For the problem of meter placement, several message passing algorithms could be used to help us determine the optimal meter placement. We chose the belief propagation or sum-product algorithm [13] since it is well understood, has been shown to work for general topologies [15] including tree networks, and has several software libraries available.

Chapter 3

Capturing the Latent Feature of Power Devices

3.1 Introduction

Power quality meters are expensive devices, which need to place on carefully selected links in the power network. In order to estimate the power quality values on unmonitored links, we use the known power quality values from events reported by meters placed on monitored links. The probabilistic calculation of power quality values on unmonitored links requires the behaviour (latent feature) of each device to be known. We represent the latent feature of a device as a transfer function, which is usually estimated through physical modelling or through the assessment of historical power monitoring data.

In this chapter, we first introduce a latent feature model to capture the behaviour of electric devices in the power network. Using a real power quality dataset, we then demonstrate that the historical data can be used to capture the latent features of a device. We use k -fold cross-validation technique to measure the accuracy of latent features we obtain using our dataset. Experimental evaluations show that the captured latent features are consistent.

3.2 The Latent Feature Model

The latent feature of a device is basically the behaviour of a device in the power network, which can be captured by monitoring the power quality at the input and

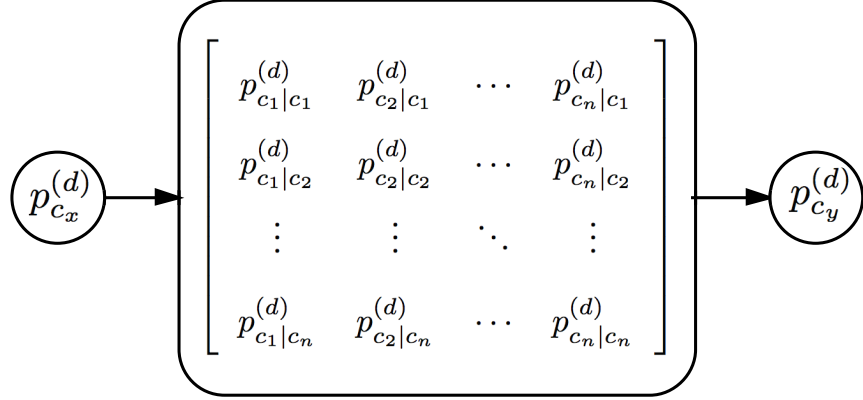


Figure 3.1: Latent feature model of a device d where the two circles represent the power quality meters at input and output of node d ; the matrix inside the node d represents the transfer function of the node.

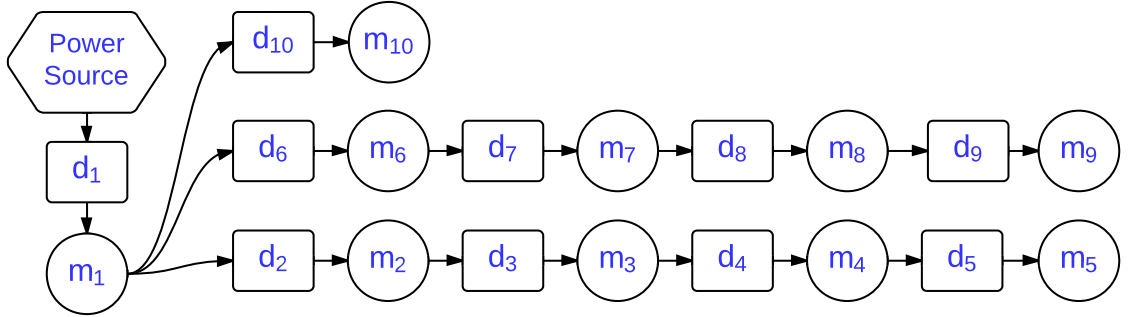


Figure 3.2: Graph network of power quality meters installed in a power network.

output links of the device. Based on these power quality readings (events), we model a device behaviour as a transfer function $f(d)$. A transfer function of a device is the matrix consisting of real values representing the probabilities that a power quality input c_x is mapped to another power quality c_y at the output link of a device d . Figure 3.1 shows a sample node (shown as a square box) whose input and output links are monitored (using power quality meters shown in circles) to capture the latent feature $f(d)$. Once the latent feature $f(d)$ is known, we can probabilistically estimate the power quality at links where no power meter is installed.

Table 3.1: Frequency table showing the number of events generated/reported by each power quality meter.

Meter ID	1	2	3	4	5	6	7	8	9	10
No. of Events	1705	629	756	764	777	282	309	181	44	657

Table 3.2: Frequency table showing the number of events classified as IEEE power quality class (c_i).

Power Quality Class	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
Number of Events	3056	738	1485	274	144	354	10	11	0	2	8	2	19	1

Table 3.3: Sample events from the dataset collected.

ID	Source	Duration	Magnitude	Severity	Phase	Type
119	5	0.02	292	3.19	V1	Transient
338	6	1.002	147	47.1	V3	Swell
763	1	0.07	84.4	1.03	V3	Sag

3.3 Power Quality Dataset

Our power quality dataset was collected at an enterprise power network for a period of four years. For privacy and security reasons, the physical network structure/diagram is omitted. Instead, we represent the topology/positions of the installed smart meters via a graph network as shown in Fig. 3.2. There are a total of 10 power quality meters (numbered from m_1 to m_{10}) installed. Each meter reported the power quality events (sag/swell, transient, etc.) to the data collection server via ethernet network. Table 3.1 shows the number of events reported by each power quality meter while the positions of the meters are shown in Fig. 3.2.

The original power quality events reported by our power quality meters carry detailed information where some of the reported attributes are not directly relevant to power quality monitoring. For instance, we have a large number of branch circuit monitors installed that log every 15 minutes. Second, due to the detailed information content, the size of the raw dataset was about 40 GB. In order to simplify the format and make the dataset concise and easy to analyze, we transform the reported events into a tabular form consisting of the power quality attributes we used. As a result, there are about 6000 power quality events recorded in the dataset. Sample events from the dataset are shown in Table 3.3 where: a) each row in the table represents a power quality event; b) the magnitude field represents a percentage of the nominal

Table 3.4: Sample events classification using IEEE Standard 1159 [8].

Source	Start Time	Duration	Magnitude	IEEE Event Class
4	733051.9385	0.00065	127	c_1
4	733052.9522	0.00754	146	c_2
8	733452.0117	0.00013	132	c_1
7	733462.7471	0.049	84	c_3
6	733488.8235	1.002	147	c_7
6	733569.0525	0.518	79	c_6
1	733572.9232	0.001	131	c_1
7	733589.9307	0.016	82	c_3
6	733724.0312	7105.48	30	c_{12}
3	733724.1134	0.01664	233	c_4

voltage that the sag or swell reached at its maximum (for instance the number 84 means that voltage is sagged to 84% of its nominal value, 147 means that it swelled up by 47% over its nominal value); c) the severity field is a calculated statistic that combines the magnitude, duration and class of an event to provide a ranking variable.

Using IEEE Standard 1159 [8], we classify the power quality events based on the fluctuation of the voltage for a predefined period. There are 14 different power quality classes defined in the standard, denoted from c_1 to c_{14} , respectively. Table 3.4 shows samples of the events we classify using the IEEE standard where the power quality class is shown in the last column of the table. The frequency of events belonging to the IEEE power quality class (c_1 to c_{14}) is shown in Table 3.2.

3.4 Learning Latent Feature ($f(d)$)

Using the real-world power quality dataset, we capture the device latent feature as follows:

- Since most of the PQ events are correlated, i.e., when there is a bad power quality event reported by a meter, the effect may be cascaded and a bad quality event may occur at other links (not necessarily at all links) as well. We identify these cascaded events based on timestamps of the events. When the time stamp is same (or varies by less than a second), we consider them correlated.
- For a cascaded event not occurring at a link, we set a nominal PQ value (PQ class c_{14}) at that link.

Table 3.5: A sample frequency table showing the number of events mapped from input power quality c_i to output power quality c_j at device d_8 .

		Output PQ (c_j)					
		1	2	3	4	6	14
Input PQ (c_i)	3	4	16	4	2	0	113
	5	0	0	0	0	0	1
	6	0	0	0	0	5	32
	7	0	0	0	0	0	2
	12	1	0	0	0	0	0
	14	47	48	13	24	2	2122

Table 3.6: A sample transfer function captured at device d_8 . Rows and columns having all values set to 0 are omitted.

		Output PQ (c_j)					
		1	2	3	4	6	14
Input PQ (c_i)	3	0.03	0.12	0.03	0.01	0	0.81
	5	0	0	0	0	0	1.00
	6	0	0	0	0	0.14	0.86
	7	0	0	0	0	0	1.00
	12	1.00	0	0	0	0	0
	14	0.02	0.02	0.01	0.01	0	0.94

- We put all the events in a 2-dimensional array $M(i, j)$ of events where the first dimension of the array represents an event i in the time series while the second dimension represents the corresponding event for each device j .
- The latent feature of a device d is a function giving the probability of an output PQ value at that device given an input value. For every device, we count the frequency of PQ mappings of input to output PQ values. This results in a 14×14 frequency table ($fr(d)$) for each device d . As an example, frequency table for device d_8 is shown in Table 3.5.
- Finally, the transfer function is calculated by dividing every element of the frequency table by sum of the row containing that element, i.e., $f(d, i, j) = fr(d, i, j) / \sum_{k=1}^{14} fr(d, i, k)$. Here, we slightly abuse the notation by using $f(d, i, j)$ to represent the value at the intersection of the i -th row and the j -th column in matrix $f(d)$. Hence, the transfer function is represented with a matrix. If every element in a row (say i -th row) of the frequency table is a 0, we assume

Table 3.7: Mean Square Errors (MSEs) in estimated and expected probabilities of the transfer functions.

		Subsets (k)						
		2	3	5	10	20	50	100
Device (d_j)	2	0.006	0.008	0.007	0.013	0.016	0.019	0.023
	3	0.011	0.011	0.014	0.016	0.02	0.025	0.028
	4	0.015	0.014	0.016	0.019	0.021	0.028	0.031
	5	0.01	0.01	0.012	0.015	0.018	0.023	0.027
	6	0.003	0.008	0.007	0.011	0.013	0.017	0.02
	7	0.019	0.018	0.023	0.019	0.021	0.023	0.024
	8	0.011	0.011	0.013	0.016	0.017	0.019	0.021
	9	0	0	0	0.002	0.007	0.013	0.018
	10	0.002	0.007	0.006	0.01	0.013	0.017	0.021

the same probability (i.e., $1/14$) for each element in that row in the transfer function, implying that no knowledge can be learnt from the dataset about the corresponding input event (c_i) on this device, and as such we assume the maximum uncertainty on its output events to avoid biased estimation. Table 3.6 shows a sample transfer function formulated from Table 3.5.

3.5 Cross-validation of $f(d)$

We use k -fold cross-validation technique to measure the accuracy of latent features we learnt. We partition the dataset (the 2-dimensional array M formulated above) into k random samples of equal size. Out of the k samples, we use $k - 1$ samples to generate a training transfer function and one sample to generate the test transfer function. The cross-validation is repeated k times where each of the k -samples is used exactly once for validation. The k results are then averaged to produce a single estimation for each device.

The Mean-Square Error (MSE) is used to measure the variation of the validation/test function (represented as $f_v(d)$) from its training function (represented as $f_t(d)$). The MSE is calculated as:

$$mse = \sum_{i=1}^{14} \sum_{j=1}^{14} |f_v(d, i, j) - f_t(d, i, j)| / (i \times j).$$

We use $k = 2, 3, 5, 10, 20, 50, 100$ in our experiments. As the value of k increases,

the number of events in the test data set reduces. For small value of $k = 2$, we divide the entire dataset in 2 sub-sets of equal size where one is used for training and the other is used for testing.

Table 3.7 shows the MSEs for all devices in the network at various sample sizes where it can be clearly seen that the values are slightly increasing with increase in the value of k . At $k = 100$, the largest value is 0.0285, i.e., in the worst case, the error between the trained and tested values is 2.8% on average. The small error values suggest that a device behaviour (latent feature) can be captured accurately with historical PQ data from power quality meters.

3.6 Conclusion

In this chapter, we proposed a device latent feature model which learns a device transfer function from real data. The device transfer function is needed to estimate the power quality values on unmonitored links in the power grid. In order to validate the proposed model, We used a real power quality dataset collected by Schneider Electric Inc. in a power grid in Canada. We demonstrated that the historical data can be used to capture the latent features of a device. The k -fold cross-validation technique was used to measure the accuracy of latent features we obtained using our dataset. Experimental evaluations showed that the captured latent features are consistent. The latent features learnt in this chapter are used by our meter placement algorithms proposed in Chapter 6.

Chapter 4

A Network Approach

4.1 Motivation

The power network has many logical and physical similarities with data networks. We model the power network as data-driven network which give us the opportunity to use the well-investigated network monitoring and data estimation algorithms to solve the network quality monitoring in power grids. The proposed network model is described in the next section.

4.2 The Model

We now model the power grid as a data-driven network, *analogically*, where electrical components are represented as nodes, power links as data links, and power flow as data flow. Hence the power grid can be viewed as a data network where we have nodes connected via data links and the data links transmit numeric data (i.e., power quality values/events in our case).

In order to classify flow of current as data (integer values), we divide the time into small slices where in each slice we classify the flow of power on any link as integer values. For the sake of generality, we represent these classes from c_1 to c_n . The power meters measure power quality continuously and assign a power quality class to each time slice according to the power quality in the interval. So in every time slice, we know power quality values in terms of integers on links where the power meters are installed.

In order to simplify our model, we treat the power flow through each node as a

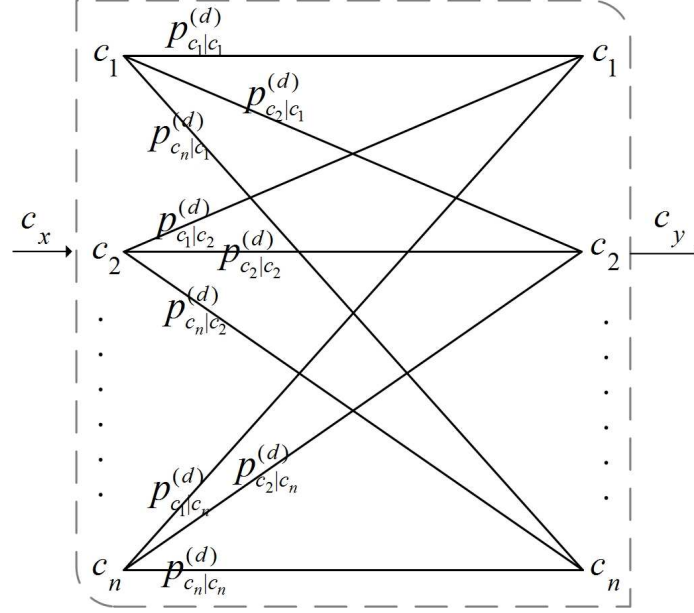


Figure 4.1: Power quality transition at each device d as a channel.

channel (shown in Figure 4.1). The input and output of this channel at each node comprises n power quality classes. The probability that a power quality c_x will be received as c_y at the output of the channel at each device d is represented by the symbol $p_{c_y|c_x}^{(d)}$. For each device d (or a subnet consisting of the concatenation of several devices), we call the $n \times n$ matrix consisting of the probability values $p_{c_y|c_x}^{(d)}$ the *power quality transition function*¹, or simply *transition function*. We represent the power quality transfer function $f(d)$ of a device d as a matrix as

$$f(d) = \begin{bmatrix} p_{c_1|c_1}^{(d)} & p_{c_2|c_1}^{(d)} & \cdots & p_{c_n|c_1}^{(d)} \\ p_{c_1|c_2}^{(d)} & p_{c_2|c_2}^{(d)} & \cdots & p_{c_n|c_2}^{(d)} \\ \vdots & \vdots & \ddots & \vdots \\ p_{c_1|c_n}^{(d)} & p_{c_2|c_n}^{(d)} & \cdots & p_{c_n|c_n}^{(d)} \end{bmatrix}, \quad (4.1)$$

where $p_{c_y|c_x}^{(d)}$ is the probability that the input quality c_x is received as c_y at the output of device d . Note that every row in the above matrix should sum to 1.

The above model significantly simplify the network complexity of the power grid. Using this analytical model, in the next few chapters, we propose various algorithms for power quality monitoring and demonstrate that this model significantly helps sim-

¹For a device (or subnet) having multiple inputs/outputs, a power quality transition function is associated with each input/output pair.

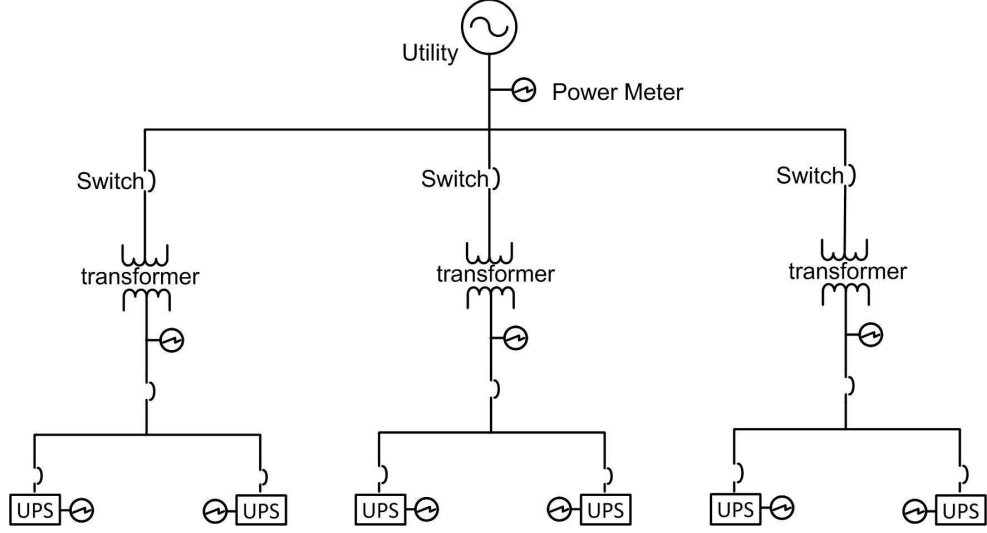


Figure 4.2: A simple view of power microgrid

plify things out there. A short summary of the proposing algorithms as applications of our analytical model is given in the next section.

4.3 Applications

We build various applications on top of the analytical framework we proposed in this Chapter. The applications are as follows.

4.3.1 Power Quality Estimation

Figure 4.2 shows a view of a power grid where there are different types of electrical devices connected to each other via power links. The smart meters are also installed on selected links. Moreover, every type of device has a power quality function which may be unknown. We want to estimate all the power quality functions based on the power quality values available on selected links where smart meters are installed.

In order to estimate the reliability of every device in the network, we need to estimate the power quality function $f(d_j)$ for each device d_j based on the quality function $f(s)$ of the subnet. It is clear that

$$f(s) = \prod_j f(d_j), \quad (4.2)$$

Our objective is to estimate $p_{c_y|c_x}^{(d_j)}$ (probability that power quality c_x will be mapped to power quality c_y at each device d_j). In order to solve the above research problem, we model the power network as data network which give us the opportunity to use the already proposed data estimation techniques to solve Eq. (4.2).

4.3.2 Intelligent Meter Placement

For the meter placement problem, we propose an iterative approach for identifying network segments suitable for power meter placement. During each iteration of the algorithm we identify in a greedy manner the network segment that suffers from the most unpredictable power quality given the meters deployed so far. We then deploy the next power meter at that location. Our proposed meter placement algorithms take advantage of our network model to calculate the uncertainty of the power quality values on various network segments.

Similarly, we use the same network model to solve the problem of getting the optimized number of meters required to achieve certain level of reliability. We formulate this problem as an optimization problem where the objective is to reduce the number of meters while maintaining an acceptable level of reliability. In order to calculate the reliability (the uncertainty of power quality) on power links, we use this network model which simplify the representation of the power network as a data network.

4.3.3 Detecting a Malfunction Device

Our third contribution is detecting a malfunction device in the power grid. Since the model we propose to detect a malfunction device uses our meter placement algorithms, the same concept of simplifying the power grid as a data network need to be used here as well. The proposed model is using the exact PQ values from the metered locations and inferred values from the non-metered locations in the network. A device is considered malfunction when it consistently behaving abnormal by generating significantly different PQ values than the expected ones. The acceptable behaviour is derived with the help of CBEMA curve.

Chapter 5

Fast Estimation of Power Quality

Summary: Power quality plays a critical role in the reliability of power networks. The monitoring of power quality, however, is a non-trivial task due to the high cost of measurement devices and the requirement on real-time responses. As a result, we need fast algorithms to estimate the power quality in various segments of a power network, using only a small number of measurement points. In this chapter, we propose a maximum-entropy (MaxEnt) based approach to estimating power quality in smart microgrid. Compared to other existing methods such as Monte Carlo Expectation Maximization (MCEM), the MaxEnt based approach is much faster.

5.1 Introduction

Power quality largely impacts the reliability and energy saving of power networks. Poor power quality such as voltage sags may lead to power outage and service interruptions. Service unavailability caused by power losses is a serious problem for many companies and organizations, e.g., it may result in a significant revenue loss for Internet service providers or even loss of lives in hospitals. To improve the reliability of power networks, organizations and large companies (e.g., Google data centers) adopt smart microgrid, and closely monitor the power quality in different segments of the microgrid.

Monitoring power quality, however, is not an easy task. Since the power measurement devices [4][14] (termed as smart meters in this thesis) are expensive, it is financially impractical to monitor every segment of a power network. The overhead of interconnecting these power meters and developing the power management system further increases the cost. In addition, in many cases direct monitoring of power

quality is difficult, e.g., it is hard to install smart meters after power lines were sealed in hard-to-reach areas in a building. In general, we need to tackle the following challenge: based on a limited small number of monitored points in a power network, *how can we effectively estimate the power quality of other unmonitored segments of the network?*

We propose to use a Maximum-Entropy (MaxEnt) [10] approach to power quality estimation. The basic idea of MaxEnt is that out of all probability distributions consistent with a given set of constraints (i.e., the known measure values in our case), we should choose the one that has the maximum uncertainty to be the estimated power quality values. Intuitively, the principle of MaxEnt implies that we should make use of all the information that is given and avoid making (biased) assumptions about information that is not available. We model the problem of estimating power quality in such a way where we can effectively get the benefit of MaxEnt approach to correctly estimate the power quality values at links where we do not have any measuring device installed. We solve the formulated MaxEnt problem and validate its effectiveness and efficiency with a simulated microgrid system.

5.2 Related Work

According to the IEEE Gold Book [7], the industry practices for electric power quality in networks focus on measures such as reliability, availability, and Mean Time Between Failures (MTBF). While it is known [9] that lifetime and performance of electrical components are dependent on power quality, none of the measures defined in the IEEE Gold Book accounts for power quality. Moreover, these measures serve as theoretical values for comparisons and are not intended to work in real environment (with varying temperature, humidity, load, and power quality) as predictive tools for networks. Further, the ITI curve report illustrates the relationship between power quality and the likelihood of damage to electric components. While considering the importance of both the magnitude and duration of power quality events in isolation, it does not consider its cumulative effects over time.

The EM algorithm is one of the most widely-used algorithms for estimation and has been applied in a variety of research areas. In [5], the authors investigate the power of EM algorithm in the estimation of microgrid reliability. Although effective, the EM algorithm needs a long time to converge. We are thus motivated to find faster algorithms in power quality estimation for smart microgrid.

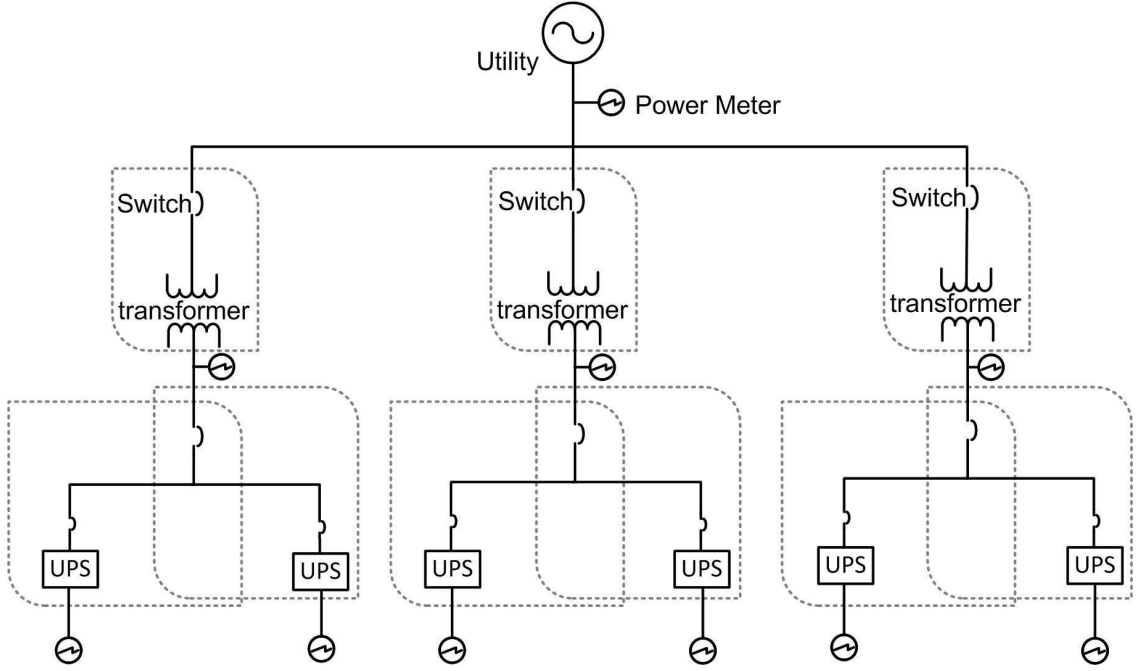


Figure 5.1: View of the power grid network under consideration. Subnets (within dotted lines) are formulated based on the positions of the power meters.

The measurement and monitoring of power quality are a vital part of today's smart grid. To classify power quality, a label is assigned to a power quality event, based on the feature of the event, e.g., the magnitude and duration of a voltage sag or swell. Typically, the power quality index, also known as System Average RMS Variation Frequency Index (SARFI), is reported as a count of the number of times the magnitude and duration fall below a threshold, standardized by the IEEE standard 1159-2009 [8].

5.3 Problem Formulation

Figure 5.1 shows a view of a power grid where there are different types of electrical devices connected to each other via power links. The smart meters are also installed on selected links. Moreover, every type of device has a power quality function which may be unknown. We want to estimate all the power quality functions based on the power quality values available on selected links where smart meters are installed. We divide the power grid network into small subnets where in every subnet we have two smart meters, i.e., one at the input as the first node and one at the output as the last node of the subnet as shown in Figure 5.1.

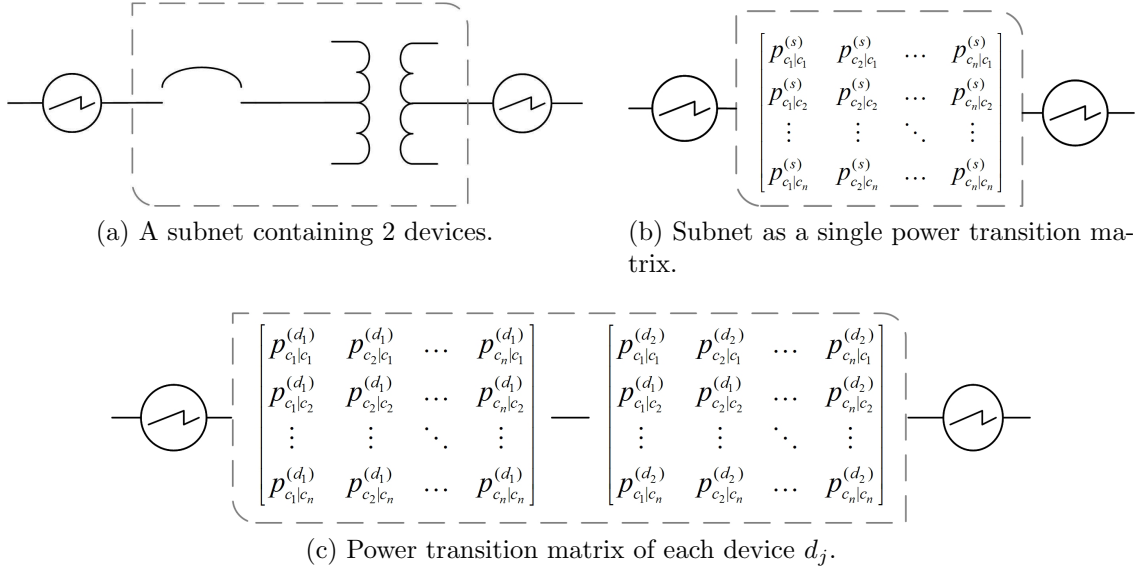


Figure 5.2: Subnet power transition matrix as a product of power transition matrices of individual devices.

Now, we consider every subnet as a single node which we call a black-box. For every black-box, we know the power quality values at the input as well as at the output. Based on this known power quality information, we calculate the power quality transition function by using some sample readings from the smart meters attached to both sides of every black-box. Figure 5.2 shows a sample subnet as a single node. We represent the calculated power quality function $f(s)$ of subnet s as a matrix as follows:

$$f(s) = \begin{bmatrix} p_{c_1|c_1}^{(s)} & p_{c_2|c_1}^{(s)} & \cdots & p_{c_n|c_1}^{(s)} \\ p_{c_1|c_2}^{(s)} & p_{c_2|c_2}^{(s)} & \cdots & p_{c_n|c_2}^{(s)} \\ \vdots & \vdots & \ddots & \vdots \\ p_{c_1|c_n}^{(s)} & p_{c_2|c_n}^{(s)} & \cdots & p_{c_n|c_n}^{(s)} \end{bmatrix}, \quad (5.1)$$

where $p_{c_y|c_x}^{(s)}$ is the probability that the input quality c_x is received as c_y at the output of the subnet s . Moreover, the value of $p_{c_y|c_x}^{(s)}$ can be easily calculated by measuring power quality values at the input and output smart meters of the subnet. Note that every row in the above matrix must sum to 1.

Figure 5.2(a) shows a subnet containing two devices. The power quality transition function (as a matrix) of the subnet is shown inside the black-box in Figure 5.2(b). Our objective is to correctly estimate the transition functions of every device d_j in

the subnet. These unknown functions are shown as matrices in Figure 5.2(c).

In order to estimate the reliability of every device in the network, we need to estimate the power quality function $f(d_j)$ for each device d_j based on the quality function $f(s)$ of the subnet. It is clear that

$$f(s) = \prod_j f(d_j), \quad (5.2)$$

which implies that

$$\begin{bmatrix} p_{c_1|c_1}^{(s)} & \cdots & p_{c_n|c_1}^{(s)} \\ \vdots & \ddots & \vdots \\ p_{c_1|c_n}^{(s)} & \cdots & p_{c_n|c_n}^{(s)} \end{bmatrix} = \prod_j \begin{bmatrix} p_{c_1|c_1}^{(d_j)} & \cdots & p_{c_n|c_1}^{(d_j)} \\ \vdots & \ddots & \vdots \\ p_{c_1|c_n}^{(d_j)} & \cdots & p_{c_n|c_n}^{(d_j)} \end{bmatrix} \quad (5.3)$$

Our objective is to estimate $p_{c_y|c_x}^{(d_j)}$ (probability that power quality c_x will be mapped to power quality c_y at each device d_j). We use the data estimation techniques to solve Eq. (5.3).

5.4 Power Quality Estimation using Entropy Maximization

Modeling the microgrids as data-driven networks helps us utilize the best available data estimation techniques to solve the power quality estimation problem. One of the most popular and widely-used data estimation techniques is EM algorithm. In a recent study [5], the authors successfully applied the EM algorithm to power quality estimation in microgrid. Although effective, the EM algorithm took a long time to converge. In this work, we propose to use a MaxEnt approach to estimating the power quality of unmonitored segments of the grid. Before we formulate the power quality estimation problem as a MaxEnt problem, first we give a short description of EM and MaxEnt algorithms:

- **The Expectation Maximization (EM):** EM is a general approach to iterative computation of maximum-likelihood estimates when the observations can be viewed as incomplete data. Since each of the iteration of the algorithm consists of an expectation step followed by a maximization step, the algorithm is named as the EM algorithm. The successive iterations always increase the likelihood and the algorithm converges at a stationary point.

- **MaxEnt:** MaxEnt solves convex optimization problems of the form,

$$\begin{aligned} \mathbf{maximize} \quad & g(\vec{x}) = - \sum_{i=1}^n x_i \log x_i \\ \text{subject to} \quad & \mathbf{A}\vec{x} \leq \mathbf{c}, \quad \mathbf{B}\vec{x} = \mathbf{1}, \end{aligned}$$

where $\vec{x} \in \mathbb{R}^n$ is the optimization variable, $A \in \mathbb{R}^{m \times n}$, and $B \in \mathbb{R}^{m \times n}$ are problem parameters; and $\mathbf{1}$ is a vector with all 1's.

Now, we model the power quality estimation problem as the MaxEnt problem to accurately estimate the power quality transition functions $f(d_j)$ with acceptable efficiency. Obviously, there are multiple possible power quality functions $f(d_j)$ which are consistent with Eq. (5.3). We consider only those solutions which not only satisfy Eq. (5.3) but are consistent with other design constraints, for instance: 1) every row in the matrix $f(d_j)$ must sum to 1 (or at least very close to 1); and 2) $p_{c_y|c_x}^{(d_j)}$ must not be negative. Other possible constraints are discussed later in this section.

The basic idea of using MaxEnt here is that out of all possible quality functions (probability distributions) consistent with the design constraints, we choose the one with maximum uncertainty. Intuitively, the principle of MaxEnt implies that we should make use of all the information (design constraints) that is available and avoid making (biased) assumptions about information that is not available. Our objective function becomes,

$$\mathbf{maximize} \quad g = - \sum_{j, x, y} p_{c_y|c_x}^{(d_j)} \log p_{c_y|c_x}^{(d_j)} \quad (5.4)$$

subject to following constraints:

1. All components of the estimated functions $f(d_j)$ must not be negative, that is,

$$p_{c_y|c_x}^{(d_j)} \geq 0 \quad (5.5)$$

2. Every row of $f(d_j)$ sum to 1. To allow negligible rounding errors, we introduce a small rounding error factor (ε_1) to be tolerated, i.e.,

$$\left| 1 - \sum_y p_{c_y|c_x}^{(d_j)} \right| \leq \varepsilon_1, \quad \forall x \quad (5.6)$$

3. The estimated functions $f(d_j)$ satisfy the condition $\prod_j f(d_j) = f(s)$. One may relax the condition by a small approximation error factor (ε_2) to adjust the rounding errors. This adjustment is necessary when we are interested in a close approximation of $f(s)$. This condition becomes,

$$\left| f(s) - \prod_j f(d_j) \right| \leq \varepsilon_2. \quad (5.7)$$

Note that we slightly abuse the notation for simplicity. We use $-$ above to represent an element wise minus of two matrices and $|\cdot|$ to change the values in the matrix to their absolute values. In addition, the symbol \leq means all values in the left matrix is no larger than ε_2 .

4. Every component of the estimated function $f(d_j)$ must not vary from its corresponding component of the “true” transition function $\acute{f}(d_j)$ by a factor ε_3 , i.e.,

$$\left| f(d_j) - \acute{f}(d_j) \right| \leq \varepsilon_3 \quad (5.8)$$

The meanings of the notations are the same as above.

Remark 1. *In practice, we do not know $\acute{f}(d_j)$. To avoid this problem, we can initially set $\acute{f}(d_j)$ as the transition function of the same type of device, which may be obtained via its specification or historical data of monitored devices of the same type. As time goes, this initial setting of $\acute{f}(d_j)$ should be updated with the optimal estimation function, i.e., $\acute{f}(d_j)$ is set to equal $f(d_j)$, and the updated $\acute{f}(d_j)$ is used for the next round of estimation. Such iterative updates capture the transition function of the (unmonitored) device, which may change over time.*

Remark 2. *Someone may argue that our solution may be biased toward the last constraint (i.e., Eq. 5.8). By ignoring the last constraint, we get many solutions consistent to the first three constraints and our objective function chooses the one having maximum uncertainty. Here, if we do not use constraint 4 (Eq. 5.8), we will be ignoring some known information about the transition functions of the unmonitored devices which may result in compromising the accuracy of the estimated transition functions. Further, in some rare cases, the last constraint may not be feasible when an obtained transition functions ($f(d_j)$) is different by an amount greater than ε_3 . In that case, we may ignore the last constraint or increase the value of ε_3 .*

Remark 3. *It is worth noting that the objective function (5.4) is a non-Shannon measure, because $\sum_{j, x, y} p_{c_y|c_x}^{(d_j)} = \sum_j \sum_x \sum_y p_{c_y|c_x}^{(d_j)} > 1$. Nevertheless, by maximizing this non-Shannon measure, we obtain a good estimation of transition functions as demonstrated in our experimental evaluation. This is not by coincidence, since the objective function could be considered as the sum of several Shannon entropy functions (i.e., Given x and j , $\sum_y p_{c_y|c_x}^{(d_j)} \log p_{c_y|c_x}^{(d_j)}$ is a Shannon entropy measure). In our case, we treat each entropy function with the same weight. If we have more knowledge regarding the distribution of input power quality events, assigning different weights to different entropy functions may lead to better estimation. We leave this exploration as future work.*

Remark 4. *This work focuses on a centralized processing and as such we assume that there exists an underlying communication system to support data collection to a central point. The implementation of this communication system is beyond the scope of this work. Further, the real-time issues of the monitoring and communication systems such as the data sampling and communication delay are ignored in the work.*

5.5 Performance Evaluation

We implement the proposed objective function and simulate a power microgrid using MATLAB. The view of the simulated network is shown in Figure 4.2 where only several network segments are monitored using smart meters. Our objective is to estimate the power quality values on network segment where no smart meter is installed. We use the same transition functions as in [5] as the ground truth. These power quality transition functions of various electrical components (switch, bus, ups, and transformer etc) in the smart grid are shown in Table 6.2.

We use non-linear constrained optimization algorithm named Sequential Quadratic Programming (SQP) to estimate the unknown power quality functions. Inputs to the algorithm are the known power quality functions for each subnet $f(s)$, error tolerance factors $\varepsilon_1 = \varepsilon_2 = 0.01$, and $\varepsilon_3 = 0.05$. The error tolerance is small enough for practical applications. The power quality matrix of each subnet is the product of the power transition functions (shown in Table 6.2) of the devices in that subnet. The simulated microgrid consists of subnets of two different sizes; one contain two devices (switch and a transformer) while the other containing four devices (switch, bus, switch, and UPS). Both of these subnets are shown in Figure 5.3. The power

Table 5.1: Transition Functions of Various Electrical Components [5]

		Output PQ				
		Class 1	Class 2	Class 3	Class 4	Class 5
Input PQ	Class 1	0.6	0.1	0.1	0.1	0.1
	Class 2	0.4	0.3	0.1	0.1	0.1
	Class 3	0.4	0.1	0.3	0.1	0.1
	Class 4	0.4	0.1	0.1	0.3	0.1
	Class 5	0.4	0.1	0.1	0.1	0.3

(a) Switch

		Output PQ				
		Class 1	Class 2	Class 3	Class 4	Class 5
Input PQ	Class 1	0.85	0	0	0	0.15
	Class 2	0.35	0.50	0.15	0	0
	Class 3	0.20	0.15	0.50	0.15	0
	Class 4	0.20	0	0.15	0.50	0.15
	Class 5	0.35	0	0	0.15	0.50

(b) Transformer

		Output PQ				
		Class 1	Class 2	Class 3	Class 4	Class 5
Input PQ	Class 1	1	0	0	0	0
	Class 2	0.1	0.9	0	0	0
	Class 3	0.1	0	0.9	0	0
	Class 4	0.1	0	0	0.9	0
	Class 5	0.1	0	0	0	0.9

(c) Bus

		Output PQ				
		Class 1	Class 2	Class 3	Class 4	Class 5
Input PQ	Class 1	1	0	0	0	0
	Class 2	0.8	0.2	0	0	0
	Class 3	0.8	0	0.2	0	0
	Class 4	0.8	0	0	0.2	0
	Class 5	0.8	0	0	0	0.2

(d) UPS

transition matrices of each subnet are calculated by multiplying the ground truth matrices of devices used in the corresponding subnet. Further, the simulation was performed on a desktop computer having Intel Dual-Core-i7 3.4 GHz processor with

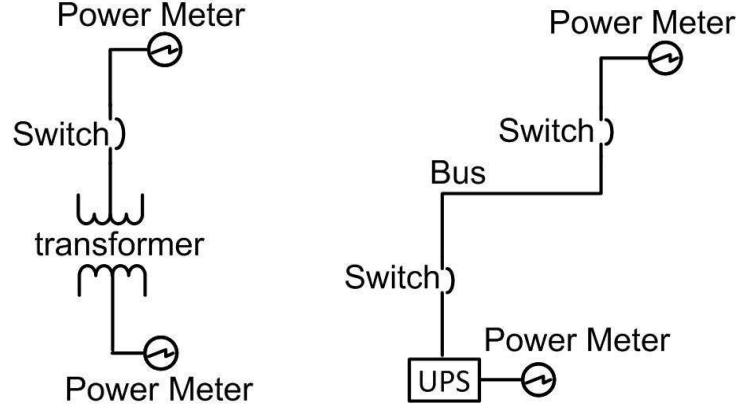


Figure 5.3: Two different kinds of subnets. The one at the left side containing two devices (switch, transformer) and the one shown at the right side containing four devices (switch, bus, switch, and UPS).

Table 5.2: Convergence time (in seconds) comparison of MaxEnt vs EM algorithms.

		MaxEnt	EM		
			Iteration 5	Iteration 10	Iteration 15
Subnet size	2	2.16	40.3	117.7	402.6
	4	3.42	118.32	366.9	981.01

Table 5.3: Mean Squared Error comparison of MaxEnt vs EM algorithms.

		MaxEnt	EM		
			Iteration 5	Iteration 10	Iteration 15
Subnet size	2	0.00020	0.00017	0.00013	0.00010
	4	0.00030	0.00025	0.00019	0.00014

4 GB physical memory.

Table 5.2 shows the convergence time comparison of both the EM and MaxEnt based solutions to power quality estimation. It can be seen that the convergence time of MaxEnt is much faster as compared to that of EM algorithm. We measure the estimation accuracy using Mean Squared Error (MSE), which is a statistical measure quantifying the difference between values implied by an estimator and the true values of the quantity being estimated. The results are shown in Table 5.3. From the results, we can see that both the methods give very close estimations of the power quality transition functions, i.e., the difference between the estimated and corresponding ground truth functions is negligible.

5.6 Conclusion

Reliability of power grid networks is critically important in today's life. Smart meters play an important role in estimating reliability of power networks but they are expensive devices and it is financially infeasible to install them on every link between devices in the power grid network. We propose a MaxEnt based model that accurately estimates power quality transition functions on unmonitored network segments. The experimental results show that 1) our MaxEnt based solution is much faster than the existing EM based solution to power quality estimation; and 2) the proposed solution accurately estimates the power transition functions. Finally, the MaxEnt based model opens a new scope of methods to quantitatively measure and solve the reliability problems in smart grid.

Chapter 6

Intelligent Meter Placement

Summary: Power quality is a crucial component of power grid reliability. Due to the high cost of measurement devices, the monitoring of power quality is non-trivial. As discussed earlier, this work is aimed at reducing the cost of power quality monitoring in power network. To realize our objective, we use our network model that represents the power grid network as a data-driven network. Using entropy-based measurements and Bayesian network models, we propose different algorithms to intelligently place measurement devices on suitable power links to reduce the uncertainty of power quality estimation on unmonitored power links.

The meter placement algorithms use entropy-based measurements and Bayesian network models to identify the most suitable power links for power meter placement. Experimental results show that the meter placement solution is efficient, and has the potential to significantly reduce the uncertainty of power quality values on unmonitored power links.

Further, we also formulate a model that estimates the required number of monitoring device in the power grid network to achieve a certain level of reliability. Our mathematical analysis show that the proposed model accurately calculates the required number of meters.

Nomenclature

$f(d)$	Device transfer function for a device d
$c_i^{(d)}$	Power quality of class i at device d
C_i	Set of $c_i^{(d)} \forall d$
$p_{c_y c_x}^{(d)}$	Probability that c_x will be mapped to c_y at device d
\hat{d}	Parent node of a node d
\tilde{d}	Child node of a node d
d_i	Inferred device

d_o	Observed device
F	Conditional transfer function of device d_o given d_i
$l_{out}^{(d)}$	Output link of device d
$l_{in}^{(d)}$	Input link of device d

6.1 Introduction / Motivation

Electrical power networks are one of the critical infrastructures of our society. Due to our high dependence on electricity, the reliability in electric networks has become a core research interest in the smart grid area [12]. Reliability evaluation of power grid, however, is challenging [1]. One of the most influential factors impacting the reliability and energy saving of power networks is the power quality delivered to, and experienced by, critical electric equipment. Poor power quality, such as voltage sags, may lead to power outage and service interruptions. Hence, the monitoring of power quality is a crucial component of assessing and maintaining reliability in power grid.

Monitoring power quality, however, is not an easy task. Since the power measurement devices [4, 14] are expensive, it is financially impractical to monitor every segment of a power network. The overhead of interconnecting these power meters and developing the power management system further increases the cost. Therefore, we need to intelligently place smart meters on selected power links to reduce the uncertainty of power quality estimation on unmonitored links in the power grid. The following core challenge needs to address: given a fixed number of available power meters, which grid segments should be selected for monitoring such that power quality can be inferred in the remaining unmonitored segments of the network.

We propose an iterative approaches for identifying network segments suitable for power meter placement. During each iteration of the algorithms we identify in a greedy manner the network segment that suffers from the most unpredictable power quality given the meters deployed so far. We then deploy the next power meter at that location.

The probabilistic calculation of power quality values on unmonitored links requires the behaviour of each device to be known. We use our latent feature model (proposed in chapter 3) to capture the device behaviour. With devices' latent features captured, we then use our network model to represent the smart microgrid as a data-driven network, in analogy, where we represent the electrical components as network nodes,

power links as data links, and flow of power as data flow on the links. This problem transformation significantly simplifies the complexity of the power network; it also presents the opportunity to use the well-investigated network monitoring algorithms to solve the meter placement problem. We then solve the meter placement problem by proposing the following algorithms:

- A simple entropy based algorithm,
- An intelligent Bayesian network based algorithm,
- A conditional entropy-based algorithm to solve the meter placement problem.

We also model the problem of calculating the number of required power meters as an optimization problem. The proposed optimization solution accurately estimate the required number of meters to achieve a certain level of reliability in the power grid network.

6.2 Related Work

This work is related to three categories of research and development: power quality classification, power reliability, and smart meter deployment.

On the first aspect, there are many approaches to the problem of classifying power quality events. Typically, quality is assigned a label based on the magnitude and duration of a voltage sag or swell. Electrical utilities typically report on indices such as System Average RMS Variation Frequency Index (SARFI) which is essentially a count of the number of times the magnitude and duration fall below a threshold. The IEEE also has a standard for classifying individual power quality events [8]. We use a discrete classification system in this work, similar to that described in the IEEE standard [8].

Regarding the second category, the industry standard practices for electric power reliability in networks focus on measures such as Mean Time Between Failure (MTBF), reliability, and availability as defined by the IEEE Gold Book [7]. The measures defined in [7] are theoretical values, measured or calculated for components and networks operating under standardized conditions. They serve as methods for comparison but are not intended as predictive tools for networks that operate in realistic environments with varying temperature, humidity, load, and power quality. It is known that there exists a relationship between power quality and the lifetime and performance of

components [9]. For an effective evaluation of power reliability, we need to accurately estimate power quality [5], which motivates the meter placement problem studied in this work.

On the third aspect, there is a great body of work on the problem of optimal sensor deployment problem [11]. The meaning of sensors is broad, including any measurement/monitoring devices. In the context of power networks, optimal deployment of phasor measurement units (PMU) has been studied [16]. Nevertheless, we have not seen any work on studying optimal meter deployment problem in the context of network-wide power quality estimation.

6.3 Meter Placement Problem Formulation

Before we formally illustrate our proposed algorithms for the deployment of power meters in the electric power grid, we detail our assumptions about the structure and function of the power grid network as follows:

1. *The power grid network is a tree-structured network where the electric current flows from root node to the child nodes.* Note that this is a reasonable assumption at any particular instance in time. While enterprise level power grids used in places such as hospitals and data centers often have two utility feeds available as well as an independent emergency power source, only one power source is typically used at one time. See the IEEE Gold Book [7] for further information on recommended practices in the design of critical power systems.
2. *The probability mass function (pmf) of power quality values at the input link to the root node is known.* In other words, the distribution of power quality at the input to the network, usually the utility feed, is known. This is also a reasonable assumption, since electrical utilities typically report on indices such as System Average RMS Variation Frequency Index (SARFI) which is essentially a count of the number of times the magnitude and duration falls below a threshold. Furthermore, there are often independent bodies that gather statistics on power delivery service reliability that can also be incorporated into an estimate of power quality distribution [2].
3. *The power quality transfer function $f(d)$ is known for every device d .* A device-specific power quality transfer function could be estimated for specific models

of electrical components through physical modeling or through the assessment of historical power monitoring data. Given a reasonable initial estimate, the transfer functions could be further refined through online learning techniques [5].

Given the assumptions listed above we can define a power meter placement algorithm as a process that takes as an input: the topology of the smart grid, an *a priori* estimate of the feed pmf , the power quality transfer function for each component, and the total number of meters M . The output of the algorithm is a set of L locations for deploying power meters.

6.4 Meter Placement Algorithms

6.4.1 A Simple Entropy-Based Approach

We propose to deployed the power quality meters on network segments where the power quality values are most uncertain. We measure the uncertainty of power quality on a link using Shannon's entropy measure. Therefore, the entropy formula to measure uncertainty at the output link of a device d becomes

$$H(d) = H(l_o^{(d)}) = - \sum_{i=1}^n p_{c_i}^{(d)} \log p_{c_i}^{(d)},$$

where $p_{c_i}^{(d)}$ is the probability of power quality c_i at the output link of device d .

In order to calculate $H(d)$, we need to know the power quality distribution function of link $l_o^{(d)}$. Starting from the root node of the tree-structured network, we traverse all the nodes (devices) in level-order fashion to calculate the distribution function $f_x(d)$ as $f_x(d) = f_x(\hat{d}) \times f(d)$. After calculating $f_x(d) = [p_{c_1}^{(d)} \ p_{c_2}^{(d)} \ \dots \ p_{c_n}^{(d)}]$ where $p_y(d) = \sum_{x=1}^n p_x^{(d)} \times p_{c_y|c_x}^{(d)} \ \forall \ y = 1, 2, \dots, n$.

The detail of our entropy-based meter placement algorithm is shown as Algorithm 1 where the power meters are placed on network segments having maximum uncertainty in power quality values. This simple algorithm is fast and useful when there is negligible impact of a link on any other link in the network. For instance, if a node always produces a power quality c_1 as output irrespective of the input quality (a stabilizer). Nevertheless, in most cases the network links are dependent on each other. Therefore, we need to consider the link dependency while calculating the uncertainty of a link, i.e., a meter reduces the entropy not only on the measured link, but also

Algorithm 1: A Simple Entropy-Based Algorithm

Input: distribution function of input link to device 1 i.e., $f_x^{(0)}$, transfer function $f(d)$, number of power meters M

Output: L (list of devices to be selected for meter placement)

begin

foreach (*device* d) **do**

$\hat{d} \leftarrow \text{getParent}(d)$;

 /* Note that device 1 (root of the tree) has no parent i.e., $\text{getParent}(1) = 0$ and $f_x(0)$ is given */

$f_x(d) \leftarrow f_x(\hat{d}) \times f(d)$;

$H(d) \leftarrow -\sum_{i=1}^n p_{c_i}^{(d)} \log p_{c_i}^{(d)}$;

 /* where $p_{c_i}^{(d)}$ is the i^{th} component of $f_x(d)$ vector */

end

 /* get N high entropy devices in vector H */

$L \leftarrow \text{getHighEntropyDevices}(H, N)$

end

on other links in the network. Further, based on our initial tests with the simple Algorithm 1, we conclude that it may create a poor allocation scheme for some cases. In the remainder of this section, we further investigate the problem and propose more robust methods to address the power meter placement problem.

In the next section, we look into the possibility of dependency of parent links on their child links. With the help of a Bayesian network model, we calculate the conditional uncertainty of all links in the grid conditioned on data from deployed meters.

6.4.2 Bayesian Network Based Approach

This section describes a Bayesian network based algorithm for selecting locations for placing power meters in a power grid. The approach uses Monte Carlo sampling and probabilistic inference approaches to identify locations in the power grid which exhibit unpredictable power quality events.

The problem is inherently challenging as the information received from a power meter flows not only the forward direction from the root nodes toward the leaf nodes, but also in reverse or upstream direction toward the root node (utility main) and back to all other nodes in the network.

To tackle the above challenge, we cast the problem as a Bayesian network and model the power grid using a factor graph. Several message passing algorithms could

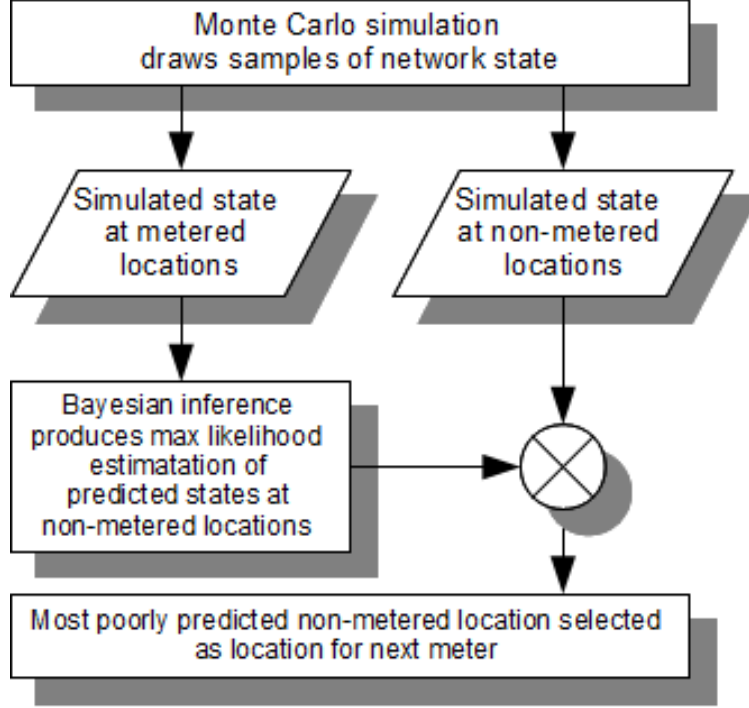


Figure 6.1: Data flow diagram of meter selection process during a single iteration of the greedy algorithm.

be used to help us determine the optimal meter placement. We chose the belief propagation or sum-product algorithm [13], since it is well understood and has been shown to work for general topologies [15] including tree networks.

MC Event Sampling

Given the transfer function $f(d)$, we use a Monte Carlo (MC) method to obtain a set of K samples at each node d . We first compute a *pmf* $f_x(d)$ for each node d using its transfer function $f(d)$ and the *pmf* of its parent node \hat{d} as $f_x(d) = f(d) \times f_x(\hat{d})$. Then, at each time slot $i \in \{1 \dots K\}$, we draw a sample $c_i^{(d)}$ from $f_x(d)$ at each node d . We repeat this at each node of the tree starting from the root and ending at the leaves. The result is a set of K simulated samples $C_i = \{c_i^{(1)}, c_i^{(2)}, \dots, c_i^{(N)}\}$ for each of the N links in the power network.

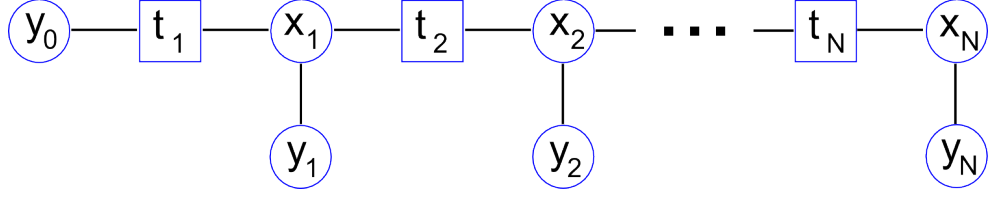


Figure 6.2: Power network modeled as a factor graph

Event Inference using Belief Propagation

The samples obtained by the MC simulation of power quality propagation contain consistent sets of power quality values at both metered and non-metered locations. We use Bayesian inference to infer the power quality at non-metered locations as a function of the simulated values observed at the metered locations and compare the resulting predictions to the simulated value seen at the non-metered locations. This process gives a relative indication of the predictive strength on each link of the network. Figure 6.1 shows a high-level description of this process.

To do the prediction, we first model the power network as a factor graph (Figure 6.2) and then use belief propagation to find the inferred values of power quality at the output of each node using the (simulated) evidence obtained from the power meters. The factor graph has conditional probability nodes t , equality nodes x , and evidence nodes y . The t nodes represent actual electrical devices with a known transfer function. The x nodes represent wired connections on our network for which we have already obtained a set of samples using MC sampling. These nodes are constrained so that all edges connected to them are equal. The y nodes represent locations where a power meter could be placed. The non-metered nodes are initialized to a uniform pmf and the metered nodes are set to a trivial pmf with a probability of 1 at the true power quality event and 0 everywhere else.

For each time slot t_i we infer the maximum likelihood power quality event that would appear at each node given the current meter configuration. We then estimate the error rate for each node in the network. If the inferred event differs from the event given by the MC sample we add $1/K$ for that sample. At each round of the algorithm we greedily choose to place a meter at the node with the highest error rate. We terminate the algorithm when all meters have been placed. See Algorithm 2 and Figure 6.1 for further details.

Algorithm 2: Monte Carlo Predicted Error Algorithm

Input: The topology T of power grid; the *pmf* of the input feed to first device i.e., $f_x(0)$; transfer functions $f(d)$; the number of power meters M to place; and the number of Monte Carlo samples to draw K

Output: L (list of links to be selected for meter placement)

```

begin
  foreach (power meter  $m$ ) do
     $\epsilon_l \leftarrow 0, \forall \text{ links } l \in T$ ;
    /*  $\epsilon_l$  is prediction error at link  $l$  */
    foreach (Monte Carlo Sample  $k$ ) do
       $L \leftarrow$  set of metered links  $\in T$ ;
       $L' \leftarrow$  set of non-metered links  $\in T$ ;
       $\hat{C}_k \leftarrow \text{predictPowerQuality}(L', L, T)$ ;
      /*  $\hat{C}_k$  is the  $k^{\text{th}}$  set of predicted power quality values while  $C_k$  is the  $k^{\text{th}}$  set of sampled values at all links */
      foreach (link  $l \in L'$ ) do
        if  $\hat{c}_k^{(l)} \neq c_k^{(l)}$  then
           $\epsilon_l \leftarrow \epsilon_l + 1/K$ ; /* add  $1/K$  to predicted error */
        end
      end
    end
     $\text{selectedLink} \leftarrow \max(\mathcal{E})$ ; /*  $\mathcal{E} = \{\epsilon_l\}$  i.e., set of  $\epsilon_l \forall l$  */
     $L.\text{add}(\text{selectedLink})$ ;
  end
end

function predictPowerQuality( $L', L, T$ ) :  $C_k$ 
begin
  init pmf  $\Psi = \{\psi_l\}, \forall \text{ links } l \in T$ ;
   $\Psi' \leftarrow \text{BeliefPropagation given evidence } L$ 
  foreach (link  $l \in L'$ ) do
     $c_k^{(l)} \leftarrow$  max probability power quality class inferred in  $\psi'_l$ ;
  end
   $C_k = \{c_k^{(l)}\}$ 
end

```

6.4.3 Conditional Entropy (CE) Based Approach

Since the PQ values on network segments are dependent on each other, we exploit the idea of conditional entropy to propose another new algorithm. Further, this approach is much faster than the Bayesian network (BN) based approach without compromising the accuracy. The idea here is to install each power meter under consideration on a

network segment i which results in maximum reduction in overall network entropy. We consider all possible placement points for every meter to be placed and choose a link which reduce the network entropy at maximum. Note that a reduction in network entropy is the sum of entropy reduction on the underlying link i and all other links whose entropy is minimized/reduced in effect of meter placement on a segment i . The one time matrix multiplications in this approach are much faster than our previous requirement of re-sampling the network state after every possible meter placement.

The CE based algorithm is efficient and scalable to large scale real-world networks. Both the BN and CE approaches are based on similar concepts of predicting the state of PQ values at unmonitored links given the current network configuration (positions of meters already placed). The CE based approach, which we will call MinEntropy, uses a heuristic to combine evidence but results in orders of magnitude faster running time.

Methodology

As discussed earlier in this paper, the uncertainty of power quality values on a link is dependent on the uncertainty of power quality values on other links (parents, childs, sibling nodes etc) in the network. Therefore, any new information about PQ values at a link increase our belief of the PQ values on other dependent links in the same network. Technically, the entropy of any link in the network is reduced by an amount of ≥ 0 by knowing the values of PQ on any other link in the network. We also know that, the entropy of a link given another link is always less than or equal to its original entropy i.e., $H(Y | X) \leq H(Y)$. Since every link $l_{out}^{(d)}$, if chosen for smart meter placement, influences the uncertainty of PQ values on other links, we consider the conditional entropy of all monitored links while placing power meter at a link $l_{out}^{(d)}$.

Now, the conditional entropy of a link $l_{out}^{(d_i)}$ (the output link of the inferred device d_i) given the smart meter is being installed on a link $l_{out}^{(d_o)}$ (the output link of the device d_o) is calculated using the formula

$$H(Y | X) = \sum_{x \in X} \left(p(x) \sum_{y \in Y} p(y | x) \log\left(\frac{1}{p(y | x)}\right) \right),$$

where X and Y are the distribution functions of the output links of d_o and d_i respectively. We write the above equation in terms of our power quality distribution vector

$f_x(d_o)$, device transition matrix $f(d_i | d_o)$ as:

$$H(Y | X) = - \sum \left(f_x(d_o) \times (F \otimes \log f(d_i)) \right),$$

where \times represents the cross product, the symbol \otimes represents the dot or componentwise product (also known as Hadamard product), and \log is a componentwise log operation. Further, the \sum operation is the summation of components of the resulting vector after \otimes and then \times operations, and F is the conditional transfer function representing $f(d_i | d_o)$. Depending on the positions of d_o and d_i , F is calculated in one of the three methods as follows:

1. **Observed device d_o is a parent of d_i :** Here, the conditional transfer function $f(child | parent)$ is simply the product of the normal transfer functions of devices between links $l_{out}^{(d_o)}$ and $l_{out}^{(d_i)}$, i.e.,

$$F = f(\check{d}_o) \times \dots \times f(d_i).$$

2. **Observed device d_o is a child of d_i :** We calculate the influence of a child device on a parent device. Note that the parent may not necessarily be the immediate parent. To calculate the entropy of parent given child using the general formula of conditional entropy, we need to first calculate the conditional transfer function F .

We use the concept of posterior probability (the Bayes theorem) to calculate F . This function is simply the product of the reverse transfer functions of devices all the way from child to parent. The reverse transfer function $f'(d)$ (consist of $p(parent | child)$ or $p(X | Y)$) is calculated as $p(X | Y) = \frac{p(X)p(Y/X)}{p(Y)}$. In our case, the function $f'(d)$ of a device d which list $p(x | y)$ in the xth row and yth column is calculated as:

$$f'(d) = \begin{bmatrix} f_x(\hat{d}) \\ f_x(\hat{d}) \\ \vdots \\ f_x(\hat{d}) \end{bmatrix} \otimes [f(d)]^T \oslash \begin{bmatrix} f_x(d) \\ f_x(d) \\ \vdots \\ f_x(d) \end{bmatrix}^T,$$

where \otimes is the componentwise product, \oslash is the componentwise division, and \hat{d} is the immediate parent of device d . Finally:

$$F = f'(d_o) \times f'(\hat{d}_o) \times \dots \times f'(\check{d}_i).$$

3. **Devices d_o , d_i belong to different sub-trees:** This is an interesting case where the devices d_o and d_i belong to two different sub-trees rooted by a device d_r . In this case, F is calculated in two steps. First, we calculate the conditional transfer function $f(d_r | d_o)$ of devices between links $l_{out}^{(d_o)}$ and $l_{out}^{(d_r)}$ using method 2. We then calculate the conditional transfer function $f(d_i | d_r)$ of devices between links $l_{out}^{(d_r)}$ and $l_{out}^{(d_i)}$ using method 1. Finally:

$$F = f(d_i | d_o) = f(d_r | d_o) \times f(d_i | d_r)$$

The MinEntropy Algorithm

Algorithm 3 illustrates our conditional entropy based solution to power meter placement. The idea here is to install each meter under consideration on a link i of the network which results in maximum reduction in overall network entropy. We consider all possible placement points for every meter to be placed and choose a link that reduce the network entropy to a minimum. Note that a reduction in network entropy is the sum of entropy reduction on the underlying link i and all other links whose entropy is minimized/reduced in effect of meter placement on link i .

In order to calculate the network entropy for every candidate link $l_{out}^{(d_o)}$, we first calculate the entropy of every link $l_{out}^{(d_i)}$ given $l_{out}^{(d_o)}$. These conditional entropies are efficiently calculated by multiplying $f_x(d_o)$ with transition functions of all devices on the path between links $l_{out}^{(d_o)}$ and $l_{out}^{(d_i)}$. We do not need to explicitly identify the path from $l_{out}^{(d_o)}$ to $l_{out}^{(d_i)}$ and we do not need to multiply the same transition functions again and again. The entropy calculation works in recursive fashion. Once we calculate the conditional entropy for a directly connecting neighbor of $l_{out}^{(d_o)}$, we then recursively calculate the entropies of neighboring links of that neighbor. Here, it should be noted that 1) every link trigger the neighboring links except the one who triggered the link itself. So no infinite recursion takes place and every link is accessed only once; 2) The product of transition functions calculated from $l_{out}^{(d_o)}$ to some $l_{out}^{(d_k)}$ is used to calculate the next product; 3) if a link is invoking its parent link, we use reverse transition function $f'(d)$ of that device. Otherwise, the normal transition function $f(d)$ is used. After every meter placement, the link entropies are updated. The same process is repeated until all smart meters are placed.

Algorithm 3: The MinEntropy Algorithm

Input: distribution function of input link to device 1 i.e., $f_x(0)$, transfer function $f(d)$, number of power meters N

Output: L (list of devices to be selected for meter placement)

begin

```

    foreach (power meter  $m$ ) do
         $maxReduction \leftarrow 0$ ;
         $selectedLink \leftarrow 0$ ;
        foreach (device  $d$ ) do
             $entReduction \leftarrow \text{calcNetworkEntropy}(d)$ ;
            if  $maxReduction < entReduction$  then
                 $maxReduction \leftarrow entReduction$ ;
                 $selectedLink \leftarrow d.outputLink$ ;
            end
        end
         $L.add(selectedLink)$ ;
         $updateEntropies(selectedLink)$ ;
    end

```

end

function $\text{calcNetworkEntropy}(d) : entRed$

begin

```

     $F \leftarrow \text{identityMatrix}(n)$ ;
    /*  $F$  is the combined transfer function i.e.,  $f(d_i | d_o)$  */
     $d_o \leftarrow d$ ;  $d_p \leftarrow d$ ;  $d_i \leftarrow d$ ;
     $entRed \leftarrow \text{recursiveConditional}(d_o, d_p, d_i, F)$ ;

```

end

function $\text{recursiveConditional}(d_o, d_p, d_i, F) : entRed$

begin

```

     $condEnt \leftarrow - \sum (f(d_o) \times F \otimes \log(F))$ ;
     $entRed \leftarrow \text{entropy}(d_i) - condEnt$ ;
    foreach (immediate child  $c$  of  $d_i$ ) do
         $F \leftarrow F \times f(c)$ ; /* child given parent link */
        /* for next recursive call,  $c$  is the inferred device and  $d_i$  is the previous device */
         $d_p \leftarrow d_i$ ;  $d_i \leftarrow c$ ;
        if ( $d_i \neq d_p$ ) then
             $entRed \leftarrow entRed + \text{recursiveConditional}(d_o, d_p, d_i, F)$ ;
        end
    end
     $d_p \leftarrow d_i$ ;  $d_i \leftarrow \text{getParent}(d_i)$ ;
    if ( $d_i \neq -1$  and  $d_i \neq d_p$ ) then
         $F \leftarrow F \times f'(c)$ ; /* parent given child link */
         $entRed \leftarrow entRed + \text{recursiveConditional}(d_o, d_p, d_i, F)$ ;
    end

```

end

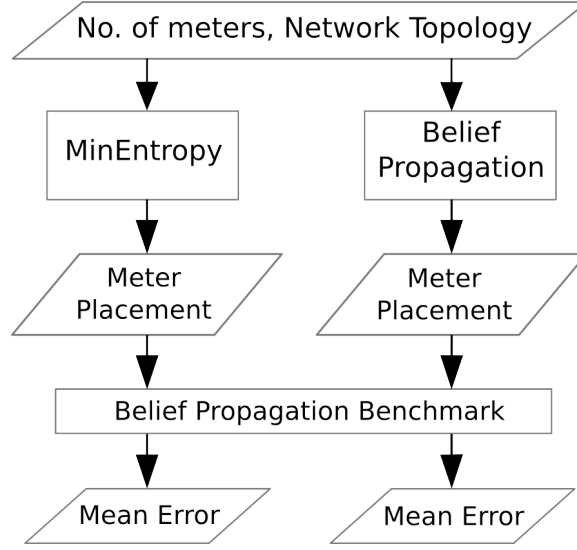


Figure 6.3: An overview of the meter placement evaluation process.

Table 6.1: Event Types

Type	Event Description
1	Good/normal power quality.
2	Below 70% of nominal voltage for more than 0.02 seconds or below 80% of nominal voltage for more than 0.5 seconds.
3	Below 70% of nominal voltage for more than 0.2 seconds.
4	Interruption of at least 1 second.
5	Interruption of at least 5 minutes.

6.5 Evaluations

We evaluate the two algorithms on a set of simulated networks. The evaluation process is depicted in Fig. 6.3 where each algorithm is given the same network topology to place a set of M meters. The devices considered are bus, switch, transformer and UPS. Power quality events are assigned a number from 1-5 in order of severity in accordance with [3] with 1 being a clean input. These are listed in Table 6.1 along with their descriptions. We used the transfer functions listed in Table 6.2 and assigned a prior on the utility feed of $[0.9947 \ 0.005 \ 0.0002 \ 0.00009 \ 0.00001]$. We use two different network topologies to test our algorithms. The first is a line network of 10 (and a variant of 50) devices. The second is a tree network with 16 devices. For each topology we choose 2 different device configurations, one with all identical devices and one with a mixture of different devices. For the BP algorithm, we collect $N = 10000$

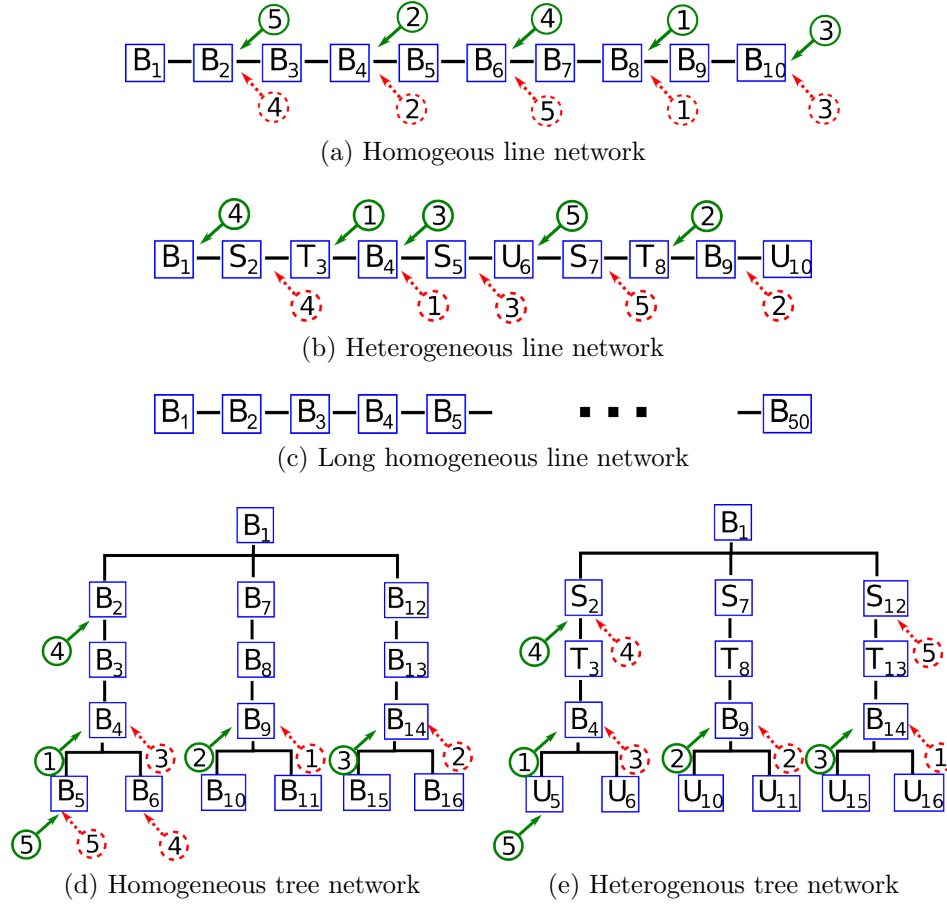


Figure 6.4: Networks used in our experiments. B=bus, S=switch, T=transformer , U=UPS. Ordered dotted circles correspond with the sequence of meters placed by BP while the solid circles show the meter placed by MinEntropy.

Table 6.2: Transition Functions of Various Electrical Components.

		Output PQ				
		1	2	3	4	5
Input PQ	1	0.9	0.1	0	0	0
	2	0	0.9	0.1	0	0
	3	0	0	0.9	0.1	0
	4	0	0	0	0.9	0.1
	5	0	0	0	0	1

(a) Bus

		Output PQ				
		1	2	3	4	5
Input PQ	1	0.7	0.1	0.1	0.05	0.05
	2	0	0.7	0.1	0.1	0.1
	3	0	0	0.7	0.2	0.1
	4	0	0	0	0.7	0.3
	5	0	0	0	0	1

(b) Switch

		Output PQ				
		1	2	3	4	5
Input PQ	1	0.85	0.15	0	0	0
	2	0.15	0.7	0.15	0	0
	3	0	0.15	0.7	0.15	0
	4	0	0	0.15	0.7	0.15
	5	0	0	0	0	1

(c) Transformer

		Output PQ				
		1	2	3	4	5
Input PQ	1	1	0	0	0	0
	2	0.8	0.2	0	0	0
	3	0.8	0	0.2	0	0
	4	0.8	0	0	0.2	0
	5	0.8	0	0	0	0.2

(d) UPS

samples for each device using MC sampling. For each network configuration we place $M = 5$ meters in order of importance.

Table 6.3: Results for each network configuration

Network Topology	Algorithm	Meter Placement Sequence	Mean Error Rate	Elapsed Time (seconds)
Line homogeneous	BP	9,5,11,3,7	0.041112	270
	MinEnt	9,5,11,7,3	0.041112	0.064
Line heterogeneous	BP	5,10,6,3,8	0.040215	281
	MinEnt	4,9,5,2,7	0.064040	0.064
Long line homogeneous	BP	28,14,42,21,7	0.076345	6122
	MinEnt	28,16,40,9,21	0.076479	8.5
Tree homogeneous	BP	10,15,5,7,6	0.057893	727
	MinEnt	5,10,15,3,6	0.056891	0.138
Tree heterogeneous	BP	15,10,5,3,13	0.063510	727
	MinEnt	5,10,15,3,6	0.071655	0.138

Figure 6.4 shows the meters placed by the two algorithms in various network topologies. The positions of the meters placed by both algorithms are essentially similar. The MinEntropy algorithm achieves much faster results, completing in less than a second in all cases (except the long 50-node network which takes about 8 seconds). On the other hand, the BP takes relatively much longer to complete. This is because BP compares individual samples on all links for every possible placement while the MinEntropy approach computes the conditional entropies at non-metered locations using probability mass functions instead using individual samples. Algorithm completion times for both BP and CE approaches are shown in Table 6.3.

The meter placements are then passed to the belief propagation benchmark to compare the accuracy of the two algorithms in terms of mean-square error (MSE), i.e., the mean error between the estimated and actual transfer functions on unmonitored links. We collect a set of known samples for a given meter configuration and infer the maximum likelihood power quality event that would appear at each unmonitored node using belief propagation. We then estimate the error rate for each node. If the inferred event differs from the event given by the MC sample, we add $1/N$ for that sample. The mean error rate across all nodes is taken as the final performance metric. As shown in Table 6.3, the MSEs are very small for both algorithms in all networks we tested. The BP algorithm gave slightly better estimations than MinEntropy in some cases at a cost of longer running times.

6.6 Conclusion

Power quality meters are expensive devices and it is financially infeasible to install them on every link in the power network. We proposed algorithms which intelligently place power meters on selected power links to reduce the cost of power quality monitoring. We formulate the problem of selecting suitable meter placements in power networks such that power quality can be best predicted. Two approaches were presented, one based on conditional entropy and one considering prediction error. Experiments in various simulation networks suggested that the conditional entropy based MinEntropy approach is much faster. Finally, the proposed solutions significantly reduce the uncertainty of power quality values on unmonitored power links.

Chapter 7

A Prediction Model

7.1 Motivation

As discussed in Chapter 1, the main objective of this work is to increase the reliability of power networks in terms of power quality. In order to monitor the power quality, power quality measurement devices are being deployed. Since power quality meters are expensive devices, we propose to intelligently place the power meters on selected segments in the power network. We then estimate power quality on unmonitored links based on the known values from monitored links. Since the power quality readings (exact readings from monitored links, estimated reading from unmonitored links) are available now, we can use this information to estimate the state of the network and identify any potential malfunctioning device. Our research problem becomes: *how to detect a potential malfunctioning device in the power network based on available PQ readings*. Next section briefly elaborate the proposed idea of detecting the potential malfunctioning devices in the power network.

7.2 The Model

7.3 Evaluations

Assume that one or more smart meters have continuously measured poor power quality. The power quality is indicated by some specific power quality index, for instance the System Average RMS Variation Frequency (SARFI) index . Based on the measured and estimated PQ values, we would like to know which device is most likely

to be malfunctioning. Here, we assume that we know the transform function of each device if the device is working properly. We call these transfer functions the regular transform functions of the devices. Now, a malfunctioning device is the one whose estimated transform function deviates significantly from its regular transform function.

We plan to first give a comprehensive mathematical model of the problem. We then devise a mechanism to calculate the deviation in transfer functions and finally we plan to propose an algorithm to efficiently identify any potential malfunctioning device in the power network. The proposed algorithm will be evaluated on various tree and bus structured network; specifically we will use the IEEE standard test networks for our simulations.

7.4 Conclusion

Power quality meters play an important role in the reliability of power networks. We plan to investigate the problem of identifying devices that degrade the power quality in the system. The proposed solution will be built on top of our already proposed work.

Chapter 8

Conclusion and Future Work

Bibliography

- [1] Réka Albert, István Albert, and Gary L. Nakarado. Structural vulnerability of the North American power grid. *Phys. Rev. E*, 69(2), Feb 2004.
- [2] AA Chowdhury, TC Mielnik, LE Lawion, MJ Sullivan, and A Katz. Reliability worth assessment in electric power delivery systems. In *Power Engineering Society General Meeting, 2004. IEEE*, pages 654–660. IEEE, 2004.
- [3] EPRI. Analysis of extremely reliable power delivery systems: A proposal for development and application of security, quality, reliability, and availability (sqra) modeling for optimizing power system configurations for the digital economy. *CEIDS*, 2002.
- [4] Fluke Corporation. Fluke Power Quality Analyzers. <http://www.fluke.com/fluke/usen/products/categorypqttop.htm>. [Online: accessed Aug. 2013].
- [5] Catherine Gamroth, Kui Wu, and Dimitri Marinakis. A smart meter based approach to power reliability index for enterprise-level power grid. In *Smart Grid Communications (SmartGridComm), 2012 IEEE Third International Conference on*, pages 534–539. IEEE, 2012.
- [6] IEC. Electromagnetic compatibility (emc) - part 2: Environment - section 5: Classification of electromagnetic environments. *IEC/TS 61000-2-5*, 1995.
- [7] IEEE. IEEE recommended practice for the design of reliable industrial and commercial power systems. *IEEE Std 493-2007 (Revision of IEEE Std 493-1997)*, pages 1–383, 2007.
- [8] IEEE. IEEE recommended practice for monitoring electric power quality. *IEEE Std 1159-2009 (Revision of IEEE Std 1159-1995)*, pages c1–81, June 2009.

- [9] ITI. ITI (CBEMA) Curve Application Note. Technical report, Information Technology Industry Council (ITI), October 2007.
- [10] Edwin T Jaynes. Information theory and statistical mechanics. *The Physical Review*, 106(4):620–630, 1957.
- [11] A. Krause and C. Guestrin. Optimizing Sensing from Water to the Web. *IEEE Computer Magazine*, August 2009.
- [12] Khosrow Moslehimi and Ranjit Kumar. A reliability perspective of the smart grid. *IEEE TRANSACTIONS ON SMART GRID*, 1(1), june 2010.
- [13] Judea Pearl. *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*. Morgan Kaufmann Pub, 1988.
- [14] Schneider Electric. PowerLogic Energy and Power Quality Meters. <http://www.schneider-electric.com>. [Online: accessed Aug. 2013].
- [15] Jonathan S Yedidia, William T Freeman, Yair Weiss, et al. Generalized belief propagation. *Advances in neural information processing systems*, pages 689–695, 2001.
- [16] W. Yuill, A. Edwards, S. Chowdhury, and S. P. Chowdhury. Optimal PMU placement: a comprehensive literature review. In *IEEE Power and Energy Society General Meeting*, Detroit, Michigan, July 2011.