THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

On Deep Machine Learning Based Techniques for Electric Power Systems

EBRAHIM BALOUJI

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Electrical Engineering
Chalmers University of Technology
Göteborg, Sweden, 2022

On Deep Machine Learning Based Techniques for Electric Power Systems

Ebrahim Balouji

Technical Report No. 5085
ISSN 978-91-7905-619-3
This thesis has been prepared using LaTeX.

Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Phone: +46 (0)31 772 1000
www.chalmers.se

Printed by Chalmers Reproservice
Göteborg, Sweden, January 2022

To my family.

Abstract

This thesis provides deep machine learning-based solutions to real-time mitigation of power quality disturbances such as flicker, voltage dips, frequency deviations, harmonics, and interharmonics using active power filters (APF). In an APF the processing delays reduce the performance when the disturbance to be mitigated is tima varying. The the delays originate from software (response time delay) and hardware (reaction time delay). To reduce the response time delays of APFs, this thesis propose and investigate several different techniques. First a technique based on multiple synchronous reference frame (MSRF) and order-optimized exponential smoothing (ES) to decrease the settling time delay of lowpass filtering steps. To reduce the computational time, this method is implemented in a parallel processing using a graphics processing unit (GPU) to estimate the time-varying harmonics and interharmonics of currents. Furthermore, the MSRF and three machine learning-based solutions are developed to predict future values of voltage and current in electric power systems which can mitigate the effects of the response and reaction time delays of the APFs. In the first and second solutions, a Butterworth filter is used to lowpass filter the dq components, and linear prediction and long short-term memory (LSTM) are used to predict the filtered dq components. The third solution is an end-to-end ML-based method developed based on a combination of convolutional neural networks (CNN) and LSTM. The Simulink implementation of the proposed ML-based APF is carried out to compensate for the current waveform harmonics, voltage dips, and flicker in Simulink environment embedded AI computing system Jetson TX2.

In another study, we propose Deep Deterministic Policy Gradient (DDPG), a reinforcement learning (RL) method to replace the controller loops and estimation blocks such as PID, MSRF, and lowpass filters in grid-forming inverters. In a conventional approach it is well recognized that the controller tuning in the differen loops are difficult as the tuning of one loop influence the performance in other parts due to interdependencies. In DDPG the control policy is derived by optimizing a reward function which measure the performance in a data-driven fashion based on extensive experiments of the inverter in a simulation environment. Compared to a PID-based control architecture, the DDPG derived control policy leads to a solution where the response and reaction time delays are decreased by a factor of five in the investigated example.

Classification of voltage dips originating from cable faults is another topic addressed in this thesis work. The Root Mean Square (RMS) of the voltage dips is proposed as preprocessing step to ease the feature learning for the developed LSTM based classifier. Once a cable faults occur, it need to be located and repaired/replaced in order to restore the grid operation. Due to the high importance of stability in the power generation of renewable energy sources, we aim to locate high impedance cable faults in DC microgrid clusters which is a challenging case among different types of faults. The developed Support Vector Machine (SVM) algorithm process the maximum amplitude and di/dt of the current waveform of the fault as features, and the localization task is carried out with 95% accuracy.

Two ML-based solutions together with a two-step feature engineering method are proposed to classify Partial Discharges (PD) originating from pulse width modulation (PWM) excitation in high voltage power electronic devices. As a first step, maximum amplitude, time of occurrence, area under PD curve, and time distance of each PD are extracted as features of interest. The extracted features are concatenated to form patterns for the ML algorithms as a second step. The suggested feature classification using the proposed ML algorithms resulted in 95.5% and 98.3% accuracy on a test data set using ensemble bagged decision trees and LSTM networks.

Keywords: Active Power filter, Deep Learning, Reinforcement learning, Cable faults, Voltage fluctuation, Flicker, Harmonics and Interharmonics, Machine Learning, phase locked loop, Partial Discharges, Voltage Dip.

List of Publications

This thesis is based on the following publications:

[A] **Ebrahim Balouji**, Özgül Salor, Muammer Ermis "Exponential Smoothing of Multiple Reference Frame Components With GPUs for Real-Time Detection of Time-Varying Harmonics and Interharmonics of EAF Currents" (Invited Paper). *IEEE Transactions on Industry Applications*, vol. 54, no. 6, pp. 6566-6575, 2018.

[B] **Ebrahim Balouji** , Özgül Salor, Tomas McKelvey, "Deep Learning Based Predictive Compensation of Flicker, Voltage Dips, Harmonics and Interharmonics in Electric Arc Furnaces," (Invited Paper) *Submitted to IEEE Transactions on Industry Applications.*

[C] **Ebrahim Balouji**, Karl Bäckström, Tomas McKelvey, "Deep Reinforcement Learning Based Grid-forming Inverter". *Submitted to Transactions on Smart Grid.*

[D] **Ebrahim Balouji**, Irene Y.H. Gu, Math H.J. Bollen, Azam Bagheri, Mahmood Nazari, "A LSTM-based Deep Learning Method with Application to Voltage Dip Classification " *IEEE 18th International Conference on Harmonics and Quality of Power (ICHQP)*, pp. 1-5, 2018.

[E] Navid Bayati, **Ebrahim Balouji**, Hamid Reza Baghaee, Amin Hajizadeh, Mohsen Soltani, Zhengyu Lin, Mehdi Savaghebi, "Locating high-impedance faults in DC microgrid clusters using support vector machines," *Applied Energy* Volume 308, 118338, ISSN 0306-2619, 2022.

[F] **Ebrahim Balouji**, Thomas Hammarström, Tomas McKelvey, "Classification of Partial Discharges Originating from Multi Level PWM Using Machine Learning" *IEEE Transaction on Dielectrics and Electrical Insulation.*(Accepted)

2022

Other published papers but not included in the thesis:

[G] **Ebrahim Balouji**, Karl Bäckström, Tomas McKelvey, Özgül Salor, "Deep Learning Based Harmonics and Interharmonics Pre-Detection Designed for Compensating Significantly Time-varying EAF Currents," (Invited Paper) *IEEE Transactions on Industry Applications*, vol. 56, no. 3, pp. 3250-3260, 2020.

[H] Azam Bagheri, Irene Y. H. Gu, Math H. J. Bollen, **Ebrahim Balouji** "A Robust Transform-Domain Deep Convolutional Network for Voltage Dip Classification" *IEEE Transaction on Power Delivery*, vol. 33, no. 6, pp. 2794-2802, 2018.

[I] **Ebrahim Balouji**, Thomas Hammarström, Tomas McKelvey, "Partial Discharge Classification in Power Electronics Applications Using Machine Learning" *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, pp. 1-5, 2019.

[J] **Ebrahim Balouji**, Karl Bäckström and Petri Hovila, "A Deep Learning Approach to Earth Fault Classification and Source Localization" *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2020, pp. 635-639, doi: 10.1109/ISGT-Europe47291.2020.9248944.

[K] Eva Lendaro, **Ebrahim Balouji**, Karen Baca, Azam Sheikh Muhammad and Max Ortiz-Catalan "Common Spatial Pattern EEG decomposition for Phantom Limb Paindetection" *EMBC Conference 2021 - Biomedical Engineering*, 2021

Acknowledgments

During the past years as a Ph.D students, I've enjoyed the help and company of many great people. First and foremost, there are no proper words to convey my deep gratitude and respect for my mentor and thesis supervisor Prof. Tomas McKelvey, for his continuous support, enthusiasm, kindness and encouragement during these years. It is a pleasure to work under his supervision. He helped me to think better and be a better researcher.

I would also like to deeply thank my co-mentors Prof. Thomas Hammarström, Prof. Özgul Salor Durna and Karl Bäckström for all of their supports and guidance. They have inspired me and helped me realize the power of thinking and reasoning.

During Ph.D life I was lucky to find wonderful friend who their support helps made me feel like I am in the right place. I would like to show my gratitude to: Kamran, Eva, Samar, Babak, Jacob L, Jacob K, Navid, Mohammad and Ahad.

I deeply thank my family for their unconditional trust, timely encouragement, and endless patience. It was their love that raised me up again when I got weary.

Acronyms

APF: Active Power Filter

AVR: Automatic Voltage Regulator

CNN: Convolutional Neural Network

DFT: Discrete Fourier transform

DL: Deep Learning

daq: Data Acquisition

DDPG: Deep Deterministic Policy Gradient

EAF: Electric Arc Furnace

ES: Exponential Smoothing

FFT: Fast Fourier Transform

GPU: Graphical Processing Unit

LSTM: Long Short-Term Memory

LP: Linear Prediction

LPF: Lowpass Filter

ML: Machine Learning

MSRF: Multiple Synchronous Reference Frame

PQ: Power Quality

PLL: Phase Lock Loop

PD: Partial Discharges

PED: Power Electronics Devices

PWM: Pulse Width Modulation

PCC:	Point of Common Coupling
RNN:	Recurrent Neural Network
RMS:	Root Mean Square
RL:	Reinforcement Learning
SVR:	Static Var Compensation
SSC:	Synchronous Static Compensator
SVM:	Support Vector Machine
TCR:	Tyristor Controller Reactors
UPS:	Uninterruptible Power Supply
VFD:	Variable Frequency Drives

Contents

Part I

Overview

CHAPTER 1

Introduction

1.1 Problem definition

Electric power systems are defined as a system comprised of electrical components to generate, transmit and distribute electricity to the utilities. By nature, electric power systems behavior is highly time-variant, nonlinear, and dynamic i.e. activation of circuit breakers, variation of load demands. Due to the above-mentioned features, a stable and robust behavior of electric power systems is challenging to be upheld and supported at all times. Besides, in the last two decades, the number of nonlinear loads and distributed generators has increased very rapidly due to the expansion of electric power systems, with new generation units such as solar panels,wind turbines, as well as the connection of more complicated and nonlinear loads, including electric arc furnaces (EAF), DC/AC drivers [1]. Furthermore, by developing and connecting more sensitive devices to the electric power system, the awareness of power quality (PQ) issues has increased [2]. PQ concerns the deviations from the ideal behavior of electric power systems as experienced by consumer devices and can be categorized into two main areas: PQ events and variations. Voltage dips, swell, transients, and interruption are examples of PQ events, and frequency deviations, harmonics, interharmonics, voltage fluctuations, and flicker are examples of PQ variations. According to [3]–[5], in the global range, 96% of the PQ problems in power systems are related to harmonics, voltage dips/fluctuation, flicker, and frequency deviation, which can cause significant damage to the system, and to utilities connected to the electric power system, leading to significant economical cost by the end [6]–[8]. Therefore, automatic countermeasures and compensation techniques should be developed for the problematic parts of the electric power systems. According to the IEC-61000-2-1 standard [9] harmonics are defined as spectral components of current or voltage waveform with a frequency equal to an integer multiple of the fundamental frequency. The same standard defines interharmonic as follows: between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. Voltage dips are short, temporary drops (due to cable faults in a majority of cases) in the voltage magnitude in the distribution or customer's electrical system as stated in IEC Standard 61000-4-30 [10]. Cable faults are defined as any break in the cables, short circuit among cables and the earth. The flicker phenomenon is an objectionable consequence of random or periodic fluctuations on the voltage waveform envelope, as defined in IEC 61000-4-15 standard [11]. These fluctuations is referred to as "light flicker" with the frequency range of 1 and 30 Hz.

Based on current literature on PQ analysis and compensation in medium and high voltage systems, real time mitigation of highly time varying PQ issues is still a challenging problem due to delays [12]–[18] see 1.1. These delays can be categorized into two main parts: (i) response time delay sources from the response time of control algorithms [19], [20], filters [21]–[23], and (ii) reaction time delays originating from hardware such as response time of sensors [24]–[26], processors [27], [28], data acquisition units [29], and boost inductors/ capacitor [20], [30] used in APFs and grid connected inverters/Converters.

Among various types of cable faults in electric power systems, the cable faults occurring in DC lines are more challenging compared to AC power systems [31]. The AC waveform contains more frequency and amplitude information than the DC signal, which is only defined by the amplitude. Analyzing these pieces of information helped AC systems have a more advanced protection system to detect the location of AC cable faults and their location [32]–[35]. Therefore, detection of the location of DC cable faults requires further

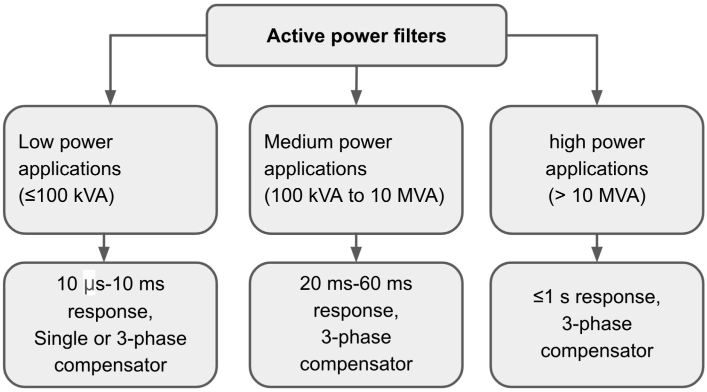


Figure 1.1: Classification of APF according to power rating and delays [12], [15]

attention.

Another problem in electric power systems is the failure of components that are caused by partial discharges (PD). PDs are among the most common issues in electric devices connected to high voltage electric power systems. PD is defined as a partial but not complete breakdown of dielectrics in insulation systems due to high voltage stress between conductors [36]. It usually occurs due to voids and flaws in high voltage insulation systems, and it can eventually lead to a full breakdown of the insulation if it is left undetected. The presence of PDs is considered a weakness in electrical devices and is in $70\% - 80\%$ the reason for the breakdown of high voltage electric devices of the cases [37]–[40]. For example, the existence of PD indicates an incipient insulation fault and can be regarded as an early warning sign of electrical insulation deterioration in electric power systems. Many studies analyze and classify PDs originating from sinusoidal shape waveforms. However, the most recent studies have reported a new type of PDs that originates from pulse width modulation (PWM) excitation in high voltage energy conversion units such as variable frequency/speed drives and inverters. These types of high voltage waveforms can also cause insulation deterioration, yet little or no research has addressed their fingerprints and root cause.

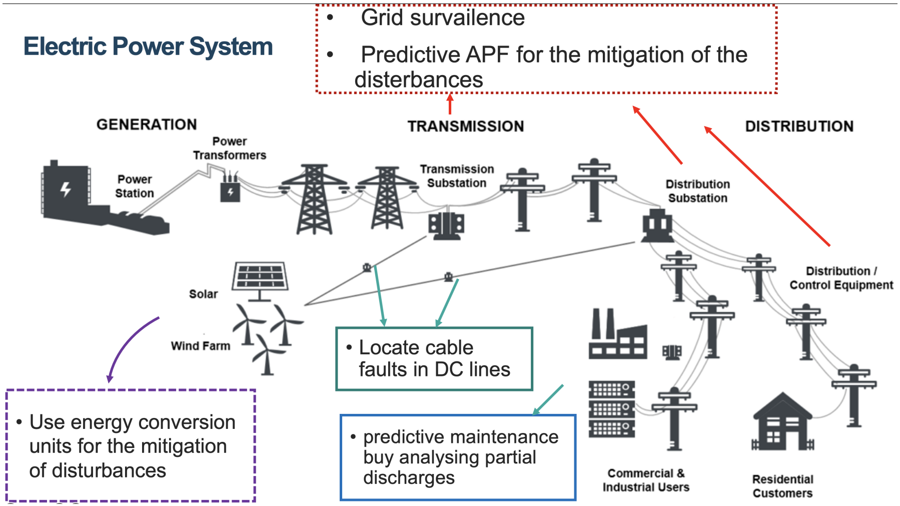


Figure 1.2: Overview of the electric power systems together with identified problems.

1.2 Aim and outline of thesis

Based on the current literature and discussion with industries, in this thesis we aim to look to electric power systems from generation to consumers and develop tools that provide complementary solutions to unsolved problems in this context (see Fig. 1.2). An outline of the thesis contents is:

- The delay in mitigating the PQ disturbances is the first problem identified to be solved. For this case, we aim to develop predictive APF which has almost no delay compared to trivial APF. The idea is to predict voltage and current to mitigate the settling time delays of components that are source of response and reaction time delays. In Chapter 2 the thesis gives an overview of the nature of PQ disturbances and the consequences of their occurrence in electrical power systems. Moreover, a brief introduction to existing methodologies for estimating and compensating the harmonics, interharmonics, flicker, and voltage dips will be discussed. We will also discuss the drawbacks and limitations of the existing APFs/inverters, and show how the proposed methods mitigate the problems. These studies are presented in paper A and B in detail and theirs summary and contribution are addressed in Chapter 2.

- For the case of mitigating disturbances by grid-forming inverters, we aimed to develop deep deterministic policy gradient (DDPG) a type of reinforcement learning (RL) based grid forming-inverter. The details of this approach is presented in paper C and Chapter 2 covers the overview of the RL-based inverter, the paper summary and contributions.

- We also give a brief background review on voltage dips and their classification methods, including our proposed solution. The details of these methods are given in paper D and the contributions and summary of the paper are addressed in Chapter 2.

- We also proposed an ML-based solution for the localization of the high impedance cable faults in DC lines. This study is presented in paper E, and the summary and short discussion on the existing methodologies are given in Chapter 2.

- In the case of analyzing the reasons for equipment failure in electric power systems, Chapter 3 of this thesis aims to propose solutions for the classification of PDs. This study targets the PDs originating from PWM excitation in power electronics devices such as APFs, inverters, and drives. This chapter includes an introduction to PDs and a literature review on existing methods for measuring and classifying the PDs originating from sinusoidal and DC waveforms. Moreover, the details of the proposed methods for measurement and classification of PDs originating from PWM excitation is given in paper F.

The summary of the defined problems and provided solutions is illustrated in Fig. 1.3. The path to provided solution is shown with red arrows and boxes.

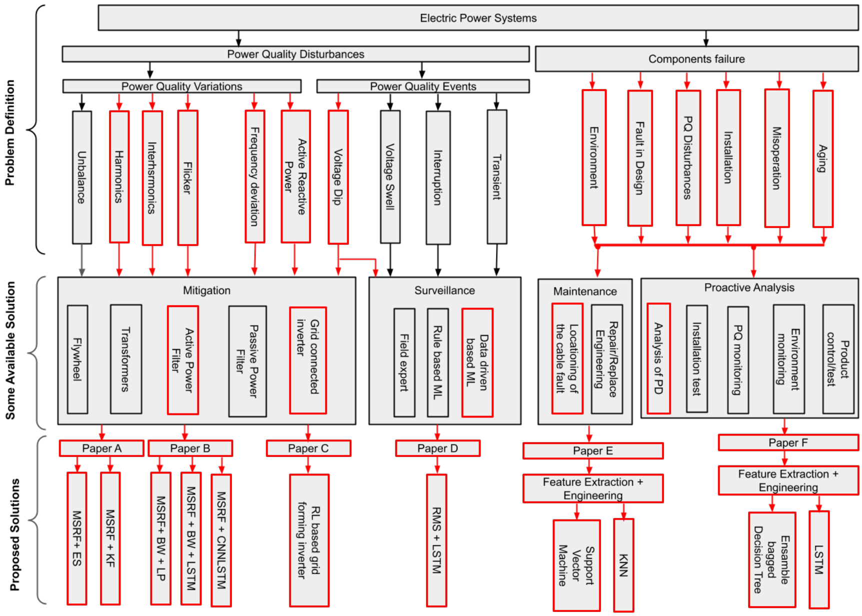


Figure 1.3: Overview of the defined problems and provided solutions in electric power systems together with some examples from the existing solutions.

CHAPTER 2

Prediction and Mitigation of PQ Disturbances

This chapter will give a brief introduction, possible causes, and consequences of the existence of the most common PQ disturbances in electric power systems. Furthermore, we will also address the available solution for mitigation and analysis of them. Finally, we briefly touch on the developed methodologies and contributions.

2.1 Harmonics and interharmonics

Voltage and current harmonics and interharmonics are originated due to the operation principle of nonlinear loads or generators. This results in voltage and current waveforms that differ from the sinusoidal shape with the fundamental frequency of the electric power systems. They can cause various problems impacting the quality of the electric power system in all generation, transmission, and distribution levels, including :

- reducing the performance of energy generation units (generators, inverters),
- heating in the transmission cables, winding of transformers and motors

which leads to insulation degradation, energy losses and reduced lifetime,

- cause of vibration and malfunctions on the motors,
- potential amplification of some harmonics due to parallel or series resonance in components such as capacitors which in turn can lead to frequency deviations and in severe cases can cause a blackout in electric power systems.

Power filters are used to mitigate harmonics and interharmonics caused by nonlinear components and loads in the power system. These filters can be categorized into two main classes: active and passive power filters. Passive filters are a combination of capacitors and inductors used to suppress harmonic currents. The passive filters have a limited capacity to mitigate time-varying harmonics and interharmonics originating from some nonlinear loads. APFs are the most well-known choice over classical passive filters due to higher efficiency and being capable of actively adapting to variations in the harmonics and interharmonics level in power system for mitigation purposes [41], [42]. Compensation is usually tackled by estimating the amplitudes and phases of the undesired frequency components (harmonics and interharmonics) in real-time and canceling them by supplying currents with the same amplitudes but opposite phase.

Harmonics and interhamonics estimation methods can be classified into two main classes, time-domain based and frequency domain based methods [13]. This classification is illustrated in more detail with some method examples from each domain in Table 2.1.

The frequency domain-based approaches, DFT, FFT, and RDFT, are discussed and implemented as harmonic estimation methods for APFs in [13]. RDFT and DFT are used to analyze, detect and compensate harmonics and resonance damping using APFs. Another RDFT based harmonics detection method is used for harmonic compensation in [43]. RDFT is used to generate the reference current signal for a single-phase shunt compensator in [44]. A method based on the estimation of overall phases of harmonics together with a sliding DFT is proposed by Hao et al. in [45] to improve the response time in selective harmonic compensation systems. A selective harmonic suppression methodology is developed for stability analysis of shunt active power filter (SAPF) in [46]. Sliding DFT is used in [47] to estimate harmonics and synchronize to act as an adaptive-harmonic compensator in PV systems.

Table 2.1: Overview of the most common PQ estimation methods used in APFs

Domain	PQ estimation method
Frequency domain	Discrete Fourier Transform(DFT)
	Fast Fourier Transform (FFT)
	Recursive Discrete Fourier transform (RDFT)
Time domain	Synchronous fundamental *dq* frame
	Synchronous individual harmonic *dq* frame
	Instantaneous power *pq* theory and variants
	Generalized integrator and variants

Generalized DFT is another method, which is shown to be a simple, fast, and flexible method to extract harmonics selectively [48]. In [49], recursive and nonrecursive versions of DFT are used to compute reference current waveforms for APFs. A DFT-based method in [50] is proposed to track frequencies and the corresponding amplitudes and phases. In [51], FFT methods are used to extract harmonics for single-phase shunt active filters as part of a multilevel inverter. A dominant harmonics elimination based on FFT is proposed in [52].

For time domain-based, a detailed investigation on the implementation of *pq* theory and synchronous reference frame (SRF), together with their modified version is conducted in [53]. In [13] a synchronous *dq* frame analysis, synchronous individual harmonic *dq* frame, instantaneous power *pq* theory and variants and Generalized integrator and variants are also implemented and discussed as a harmonic estimation method. The method has some drawbacks, such as implementing a Phase Lock Loop (PLL) to calculate the reference angle. In [54] a fast, selective harmonic current compensation method is developed with active power filter capabilities based on SRF and two degrees-of-freedom internal model controllers.

2.2 Voltage fluctuation and Flicker

Voltage fluctuations, and the corresponding light flicker due to them, are usually created by large power fluctuations at frequencies less than about 30 Hz. These fluctuations can be caused by large nonlinear loads such as EAFs, motors, and even reactive power compensator (a type of APF) and cycloconverters. Besides health-related issues, flickering lights can cause nuisance tripping of equipment because of the misoperation of relays and contactors. Fluctuations can also cause unwanted activation of uninterruptible power supplies (UPS) units to battery mode as well as problems with sensitive electronic equipment that requires consistent voltage (e.g., medical laboratories). Very large voltage fluctuation due to lack of power can also cause frequency deviations. Compared to harmonics compensation, a limited amount of research has been conducted on flicker compensation and mostly they are based on using active filters. The basic idea of the APFs/inverters is to dynamically inject a current (in shunt connection) or voltage (in series connection) of desired amplitude, frequency, and phase into the grid. The injected current/voltage will increase voltage amplitude at the PCC. With such a controllable injection of the current or voltage we can limit voltage variations. Some examples of using APF for the compensation of voltage fluctuations and flicker are:

- PV-Fed smart inverters for mitigation of voltage and Frequency Fluctuations in islanded microgrids [55],

- Energy-storage fed smart inverters for Mitigation of Voltage Fluctuations in islanded microgrids [56]

- voltage flicker mitigation studies with a current controlled PWM-based DSTATCOM [57],

- mitigation of arc furnace voltage flicker using an innovative scheme of adaptive notch filters [58],

- synthesis and evaluation of fast on-load multi-tap changers for flicker compensation in AC arc furnaces [59],

- selective interharmonic compensation to improve STATCOM performance for light flicker mitigation [60].

Almost all studies suggest using APF/inverter for the flicker and voltage fluctuation compensations. Therefore, the real-time compensation of time-varying fluctuation can be the issue that needs to be moderated.

2.3 Voltage dip

Voltage dips may be caused by various faults in the transmission and distribution networks, faults in the connected equipment, or high inrush and switching currents in the customer's installation. They can be relevant to many parts of the electric power system (generation, transmission, and distribution), albeit different performance parameters are needed for different stakeholders. Many types of electrical equipment are sensitive and can become damaged or malfunction by voltage dips including, but not limited, to variable frequency drives (VFD), motors, and PLCs. Therefore, such a phenomenon has to be analyzed and mitigated. This subsection will briefly introduce the classification and mitigation of voltage dips.

Classification of voltage dip

The most well-known solution to understand the characteristics of the voltage dips is their classification. They can occur repetitively within a short measurement interval due to the operation principle of the circuit breakers or self-recovering faults in cables. Having a classification can help to reduce downtime and contribute to fast repair of the electric power system. It can give clues for understanding, for example if the voltage dip is caused by a short connection of two phases (phase to phase fault) or short connection of one of the cables to the ground (single phase to ground) or overload effect on the system. Therefore we can find the responsible faulty phase fast and define the possible solution to mitigate it. This type of analysis can also help better grid planning and design. There are several comprehensive survey papers on the characterization of voltage dips and their challenges [61]–[63].

The literature can be roughly divided into two categories for extracting voltage dip features. The first category of methods (conventional ones) extracts features of different types of voltage dips by translating/converting human experts' knowledge into analytic models, methods, and algorithms. This category of feature extraction methods utilizes the hand-crafted feature extraction in the ML community [64]–[69]. The second category of methods is based on feature learning by using a large amount of training data where the features are extracted and modeled using deep learning-based methods such as CNN [70], [71], LSTM [72], and autoencoders [73], [74].

The benefit of deep learning-based methods is that they do not require several layers of explicit feature engineering methods, defining thresholds, and taking steps toward automatizing voltage dip event analysis and classification.

This thesis proposes deep learning-based methods that can learn and classify voltage dips using a large amount of voltage dip data. The details of both the proposed method and feature engineering together with experimental results are provided in paper *D* [75].

Location of faults in DC lines

Cable faults are damages to cables that affect the resistance in the cable. If allowed to persist, this can lead to high overcurrents and damage the electric power system. There are different types of cable faults. From a high-level perspective, they can be categorized into cable faults in DC and AC networks. Despite the advantages of DC networks such as no requirement for generator synchronization, the possibility of delivering more power, and no skin effect, dealing with cable faults in DC networks is more challenging thanks to their complications in the protection schema [76]. Plus, since the DC lines are mostly are underground or underwater, and it is more challenging to detect the fault in such conditions than the AC lines above ground. Compared to studies for the detection of cable faults in AC networks, there are limited amounts of research to detect cable faults in DC networks. Among the DC cable faults, detecting high impedance faults is the most challenging task because the observable pattern changes in the current shape are hard to detect. Thus the localization of high impedance DC cable faults is the target in this case of study. The primary focus of recent research work is offline techniques for the detection of the location of the DC cable faults [76]–[80]. Techniques widely used in industry are trace methods using acoustic or electromagnetic approaches [76], [77], which are time-consuming. Traveling-wave-based methods have also been developed using different algorithms [78]–[80]. However, when the system structure is complex (for example, meshed for multi-terminal connection), many reflections occur, influencing location results. Another drawback of the existing methods is that a detailed cable model is required for accurate fault location using the transient response to a high-frequency pulse. The majority of ML-based methods for the detection of cable faults are carried out for the AC networks [81]–[83]. Inspired by these contributions, we propose simple, effective ML-based methods to identify the location of cable faults in the DC network. The details of ML methods and feature engineering steps are presented in paper E.

Voltage dip mitigation

When a fault occurs, e.g., a short circuit between one phase lead and ground, it means that there is a power flow to the ground in one location. Therefore, the voltage level will drop, and as a consequence of such a problem, the other customers connected to the electric power system will experience a voltage dip event, which means a momentary lack of power. To prevent this issue a circuit breaker trips to disconnect the short circuit from the grid, and it is imperative for the electric power systems to be equipped with solutions to mitigate the effects of such a problem. There are several ways to mitigate voltage dips: (i) Upgrading the protection system to reduce the circuit breaker delays. (ii) Increasing the equipment immunity to voltage dips; The tolerance of the equipment satisfy based on the voltage-tolerance curve introduced by IEEE Std.1346-1998 [84]. (iii) Mitigation equipment at the interface where they can also be categorized into transformer based [85]–[87], motor generator based [88], and power electronics based [89]–[94].

The motor-based solution has low initial costs and enables long-duration ride through (several seconds) but can only be used in an industrial environment, due to its size, noise, and maintenance requirements. Transformer-based solutions are suitable for low-power and constant loads. However, this solution is a passive method, and it can suffer from delays in a dynamic environment.

Power electronics-based solutions such as APF and grid-supporting inverters are historically less costly, and they are more suitable for industrial customers with high PQ demands. The basic idea of these devices is to dynamically inject a current (in shunt connection) or voltage (in series connection) of desired amplitude, frequency, and phase into the grid. The injected current/voltage will increase voltage amplitude at the PCC. Such a controllable injection of the current or voltage limits voltage drop.

As indicated by the above summary, compared to available solutions such as motor, transformer, renovation of electric power system components, APF/ inverter installation is indeed a feasible long-term solution to reduce the impact of voltage dips.

2.4 Active power filters for compensation of harmonics, interharmonics, flicker, and voltage dips

One of the issues in implementing APF is the ability (i) to real-time measure and estimate (ii) to have fast hardware and control strategy to compensate the PQ disturbances. A large number of methods [13]–[18] have been developed to address these challenges. However, they usually suffer from delays that challenge fast response and mitigation of time varying PQ disturbances. The amount of delay can differ depending on the operating power level of APFs (see Fig. 1.1). Recall from the introduction chapter, the delays are categorized into response [15], [95]–[98] and reaction [96], [97], [99] time delays. The response time delay is the summation of the effect of the settling time delays of the component used in the software part of APFs and reaction time delay is the summation of settling time delays of physical components used in the hardware of APFs. The software and hardware part of a shunt APF with a feed-forward configuration is illustrated in Fig. 2.1. The delays of the software part includes the settling time delay of estimation methods [13], controllers, [19], [20], digital filters [21]–[23], and the delay of the hardware includes settling time delay of sensors [24]–[26], [100], processors [27], [28], data acquisition units [29], and boost inductors / capacitor [20], [30], [101] used in APFs. The choices of each component depend on power level, PQ disturbances, expenses of the components. For instance, if the PQ disturbance is highly time-varying (in the range of milliseconds), the components have to have a minimal response time, which is an irrelevant factor when dealing with the PQ disturbances that vary over hours.

As an example, we will investigate the Fig. 2.2 (a) illustrates the settling time of control algorithms that can be used in APFs.

Based on Fig. 2.2 (a), the settling time delay of control algorithm is defined as the time difference between initial state (t_1) and final state (t_2 or t_3) where the system's response has reached the desired stable situation. The acceptable settling time delay can be different from the case of PQ disturbances, aimed for the compensation. For example, in the case of compensating harmonics, a bit of a ripple ($\pm 5\%$ corresponding to t_2) can be acceptable as far as APF brings the level of harmonics to less than 2% [11], [102]. However, in the case of flicker compensation the settling time is t_3 (corresponding to $\pm 0.2\%$

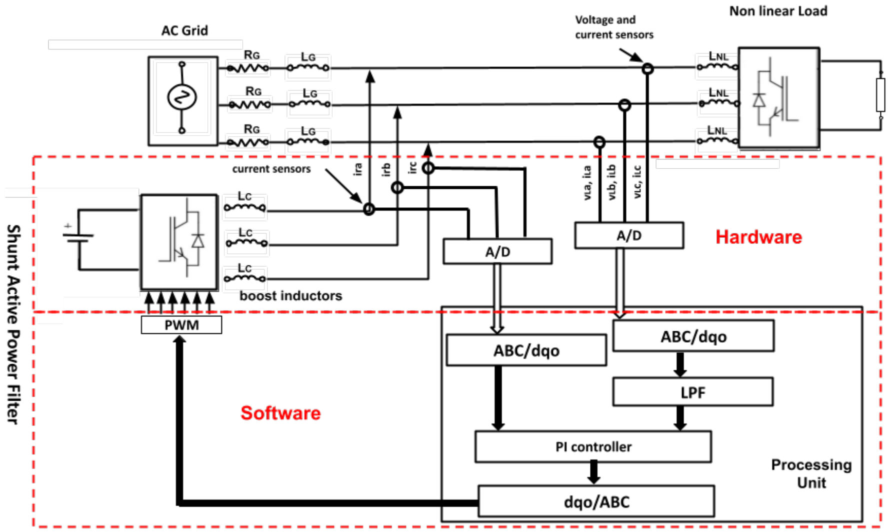
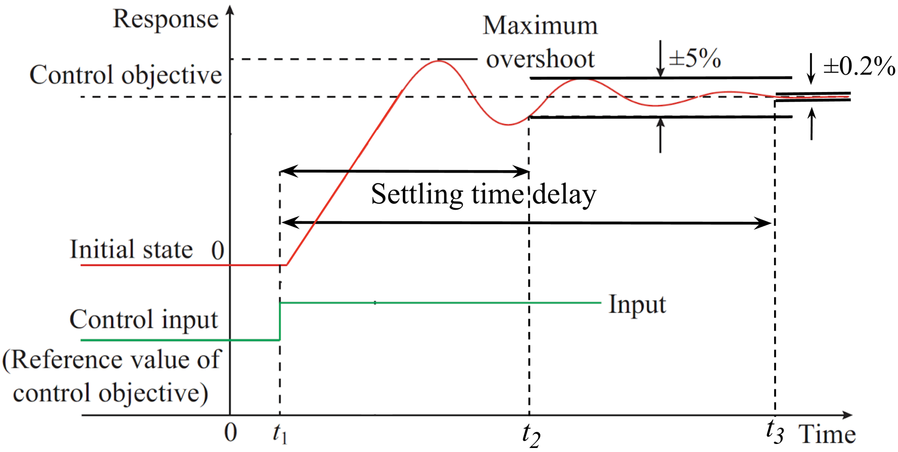


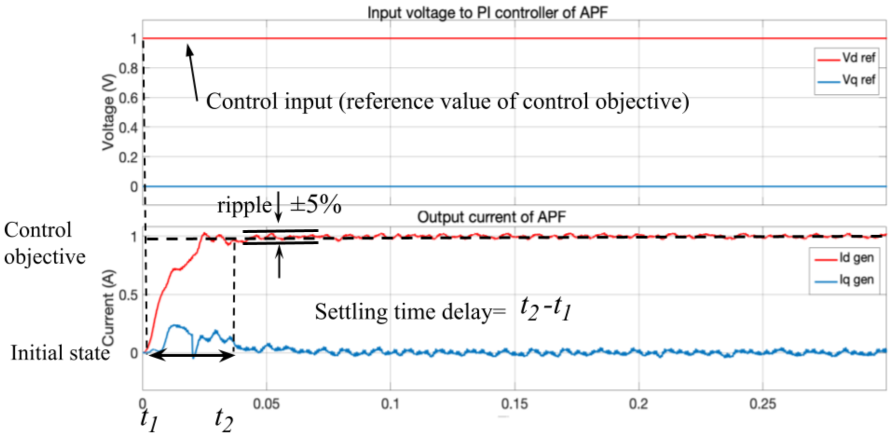
Figure 2.1: Diagram of a shunt APF in a feed-forward configuration.

ripple) [11], [103]. The accuracy of estimation of flickers is more important because choosing ±5% as an acceptable ripple can cause a voltage or current fluctuation and contribute to the problem rather than mitigation of it. We used a replica of the *dq* frame-based shunt APF proposed in Fig. 2.1 in the Simulink environment for generating these harmonics. An example of using the PI controller for compensating the third harmonic is shown in Fig. 2.2 (b). The PI controller is supposed to generate a stationary third harmonic. It can be seen that it takes almost 40ms for the controller to reach the final state where the acceptable ripple is 5%. Note that, in Fig. 2.2, the calculation of settling time delay is illustrated for estimation of *dq* component. It is also noteworthy to mention again that the settling time delay exists on all of the other components of APF (in software or hardware). Thus, when the PQ disturbances are time-varying, it is challenging for the APFs to follow the trend of changes in real-time and mitigate them.

Some approaches available in the literature have investigated methods to reduce the response and reaction time delays of APFs. To mitigate reaction time delay, the focus of studies is to develop faster equipment such as high-



(a)



(b)

Figure 2.2: (a) Overview of settling time delay of controllers in APFs. t_2 and t_3 are times that the control objective reaches an acceptable ripple range in final states (±5% for harmonics and ±0.2% for flickers). (b) calculating the settling time of the *PI* control algorithm of a shunt APF for mitigating the third harmonic.

frequency switches, faster sensors, and processing units. Some studies also have investigated the possibility of using different passive components. In the case of response time delay, the focus is to propose a faster control algorithms for APFs and the real-time estimation of the PQ disturbances. Taking all of these points into account, using in predictive methods in software can make it possible to mitigate the response and reaction time delays.

In this thesis, we propose two methods to mitigate the reaction and response time delays of APFs. In the first proposed method, parallel processing based on multiple synchronous reference frame (MSRF) analysis is used with exponential smoothing (ES) to reduce the reaction and response time delay. This study is presented in paper *A*. In the second method, we propose three ML-based solutions to predict the future samples of dq signals to be estimated with parallel processing-based MSRF methods. The results of this study are presented in paper *B*. The contributions of these studies will be summarized in the following two subsections.

2.5 Discussion on estimation and prediction of PQ disturbances

Recalling from the previous section, the critical point for mitigation of PQ disturbances is an accurate real-time compensation of these issues. The APF has delays and we predict the voltage and current to mitigate them. This section will discuss the proposed method for estimating and predicting PQ disturbances. In short, to predict the PQ disturbances, we decompose the voltage and current into different frequency components and then use ML for the prediction on each frequency component. For the decomposition task, we develop MSRF transformation, which consists of two synchronous reference frame (SRF) transforms shown with ABC/dqo in the same figure. The overall diagram of the MSRF is illustrated in 2.3 (blue dashed box). Each ABC/dqo block uses Park Transformation [104] with corresponding positive and negative frequency (w and $-w$) and converts three phase sets of voltage or current into dq^+/dq^- and o frame that rotates synchronously with the grid voltage vector.

The electric power system current can be defined as:

$$\begin{aligned} i_a(t) &= \sqrt{2} I_a \sin\left(2\pi f t + \Phi_a\right) \\ i_b(t) &= \sqrt{2} I_b \sin\left(2\pi f t + \Phi_b\right) \\ i_c(t) &= \sqrt{2} I_c \sin\left(2\pi f t + \Phi_c\right) \end{aligned} \tag{2.1}$$

where I_a, I_b and I_c are the amplitudes of each phase, f is the frequency and Φ_a, Φ_b and Φ_c are phase angles of the three-phase set. The Park Transformation of current is defined as:

$$\begin{bmatrix} i_d(t) \\ i_q(t) \\ i_o(t) \end{bmatrix} = \overbrace{\frac{2}{3}\begin{bmatrix} \cos(2\pi f t) & \cos\left(2\pi f t - \frac{2\pi}{3}\right) & \cos\left(2\pi f t + \frac{2\pi}{3}\right) \\ -\sin(2\pi f t) & -\sin\left(2\pi f t - \frac{2\pi}{3}\right) & -\sin\left(2\pi f t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}}^{Park's\ transformation\ matrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{2.2}$$

Such a transformation will result in the DC value of the desired frequency component in dq^+/dq^- and o frame superposed with other frequency components. To extract only the DC value of the desired frequency component, we use lowpass filter where it can be seen in Fig. 2.3 with LPF block. Thus with this style any three-phase time-varying signals which contain several frequency components, can be decomposed into their DC signals in dq^+/dq^- and o frames. This transformation is invertable and so given the components we can recover the three phase signal with MSRF $^{-1}$ shown in Fig. 2.3. Each dqo/ABC block in MSRF $^{-1}$ block, uses the inverse of Park transformation. The inverse Park Transformation is defined as:

$$\begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} = \overbrace{\begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix}}^{\text{Inverse Park's transformation matrix}} \begin{bmatrix} i_d(t) \\ i_q(t) \\ i_o(t) \end{bmatrix} \tag{2.3}$$

The summation of the output of dqo/ABC blocks on based on positive and negative frequency components(dq^+ and dq^-) and o frame will recover in sinusoidal version of the desired frequency component. For instance, if the a three phase current waveform of the electric power system is pure 50 Hz sinusoidal waveform with 1 A (see Fig. 2.4 (a)), the dq^+ and dq^- decomposition

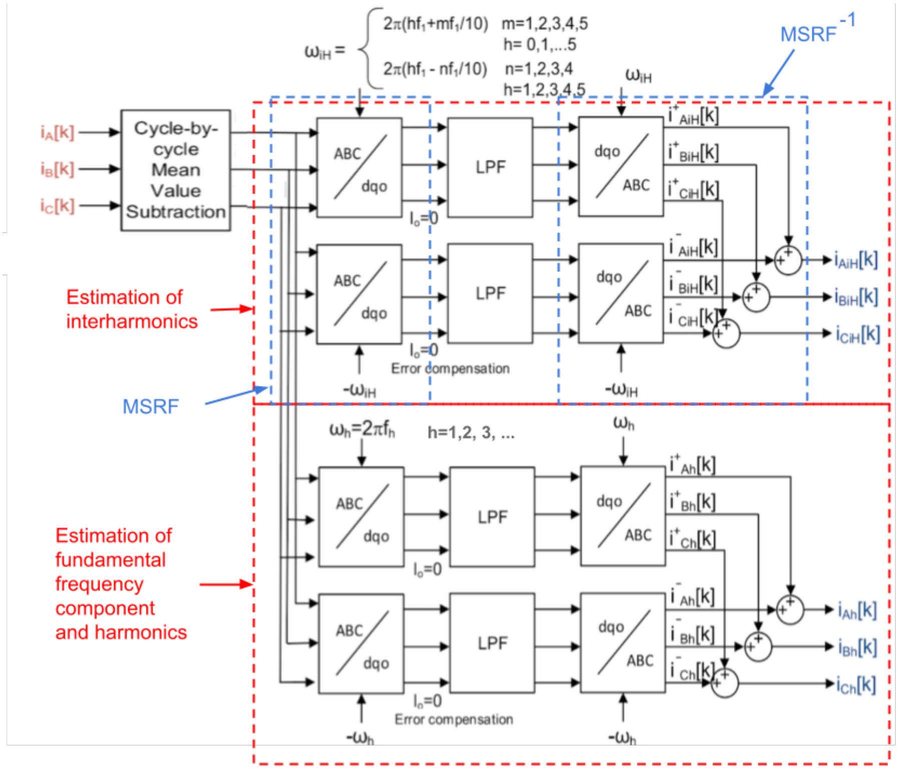


Figure 2.3: The block diagram of the proposed MSRF method.

of current using MSRF will be like Fig. 2.4 (b). zero sequence is shown with i_o in Fig. 2.4 (a). Note that for dq^+ $f = 50$ Hz and dq^-, $f = -50$ Hz. It can be seen that the frame rotation with 50 Hz speed will result in a DC waveform for components (i_d^+ and i_d^-) with 50 Hz in the original waveform.

As another example, if the original waveform with 50 Hz frequency and 1 A amplitude contains a 250 Hz frequency harmonic with 0.2 A amplitude (see 2.5 (a)), the transformation with $f = 50$ Hz in (2.2) will result positive d component as a DC signal superposed with an AC waveform (i_d^+ 2.5 (b)). We can also observe that the other positive and negative components appear as AC signals in the same figure. Using Butterworth lowpass filter will result in only the DC part of 50 Hz frequency components which is illustrated in Fig. 2.5 (c). Finally using the $MSRF^{-1}$ with $f = 50$ Hz resulted the AC waveform

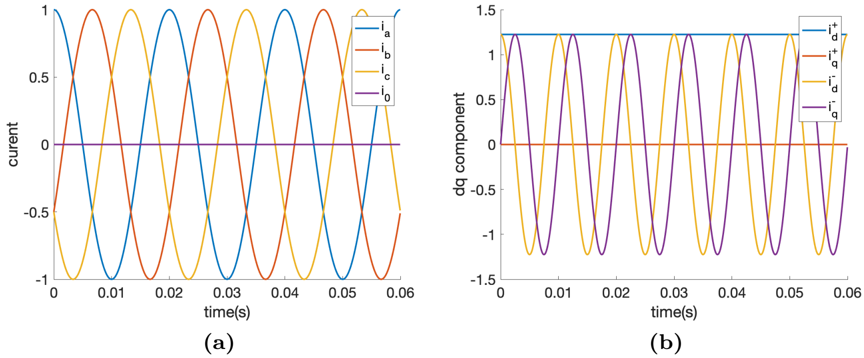
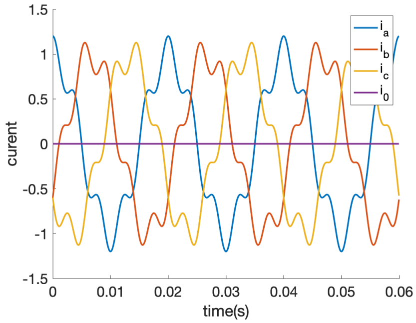


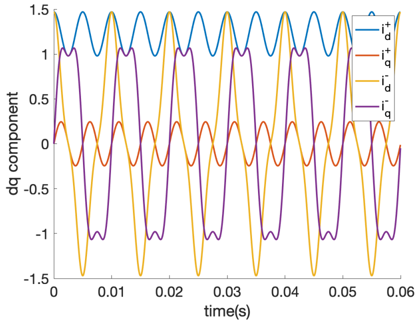
Figure 2.4: dq transform of a three phase current waveform (a) three phase current waveform with 1 A amplitude including the zero sequence. (b) dq^+ and $dq-$ transformation of three phase current waveform

of pure 50 Hz fundamental frequency component which is shown in 2.5 (d). In the case of estimating other 250 Hz frequency components, a similar procedure will be carried out by setting the f in MSRF and transforming it into $f = 50$ Hz for positive and $f = -50$ Hz for negative dq components. Thus, it can be seen that using MSRF transform can isolate the DC form of the different frequency components of three phase signal.

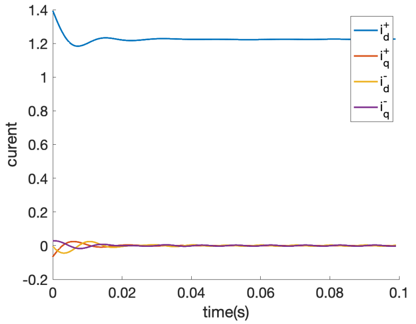
The benefit of using MSRF is that we can decompose a nonlinear waveform into a fundamental signal and other frequency components in a parallel fashion, thereby reducing the computation time. Also, we can represent each frequency component in a DC format which helps to observe the possible variation on the amplitude and phase of each frequency component in a smoother version. This makes it possible to do a prediction with a long enough horizon to mitigate the reaction and response time delay of the APFS. One example of these delays can be seen in Fig. 2.5 (c) and (d) originated from settling time delay of Butterworth filter in lowpass filtering of dqo components. For the prediction tasks, we used three methods, namely linear prediction, LSTM, and CNNLSTM. Linear prediction is a mathematical operation where future values of the lowpass filtered dqo components are estimated as a linear function of previous samples. Furthermore, LSTM consists of stateful operators that compute the future value based on the historical lowpass filtered dqo components a certain time ago. Finally, CNNLSTM architecture involves us-



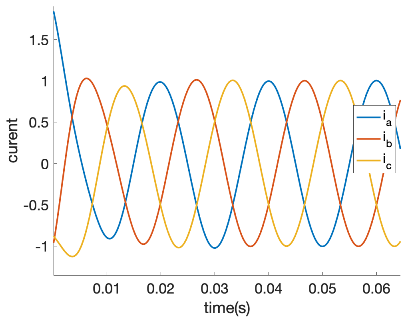
(a)



(b)



(c)



(d)

Figure 2.5: (a) A three phase set containing 5th harmonic. (b)*dqo* transform of a three phase current waveform with (c) filtered version of *dqo* components to extract the fundamental component of the there phase set. (d) $MSRF^{-1}$ version of filtered *dqo*

ing CNN layers for feature extraction on input data combined with LSTMs to support sequence prediction. In this thesis, the CNN layer is used to extract the filtered version of *dqo* components as the features and then LSTM tackles the prediction task by analyzing the extracted features sequentially. Note that the Butterworth filter is used only in linear prediction and LSTM methods. The details of the proposed MSRF and prediction methods are addressed in papers A and B respectively.

2.6 Mitigation of PQ disturbances by grid-connected inverters.

In the previous sections, we observe that the remaining concern with APF is their delays, and mitigation of disturbances requires several chains of analyses such as MSRFs, lowpass filters, PID controllers. Each step should be designed and tuned very carefully, which adds to the complexity of the proposed methods. Another issue with APFs is that they are an expensive and additional cost to electric power system train. Besides all the challenges mentioned above, one of the remaining issues in all methods is the choice of the PLL. The design of PLL requires filters and at least one control loop [105] and they need to be well-tuned. However, the settling time delay and estimation error are unavoidable. Subsequently, this will cause delays in estimating angle and frequency in the cases of phase angle jumps rapid or continuous variations in frequency level. Consequently, even if the amplitude is estimated in real-time, there will be a remaining error due to errors in instantaneous phase estimation.

As indicated by the above discussion, compared to available solutions in the literature and industry, by altering the topology of inverter's control units towards a fast response to disturbances in electric power system, we can develop a feasible long-term solution to avoid installing additional equipment such as APF, ease the computational and design complexity and costs. Such a solution can be obtained by using a RL based method. In the rest of this section, we will briefly discuss the conventional control methods used in inverters/APFs versus the proposed RL-based method.

2.7 Reinforcement learning based grid-forming inverter

Based on the literature study, we find that the control strategy of actuation parts of grid-connected inverters are based on classical control theory. These typologies are developed based on designing actions from well-specified estimation models of electric power systems. This can be a challenging task, especially when the behavior of the electric power system is nonlinear and time-varying. The nonlinearity of electric power systems is defined as unknown states in control theory caused by components and loads' operation conditions. A solution to gain understanding such situations can be to have a replica of the component of the electric power system in a simulation environment and an extensive experiments covering many scenarios and build their model based on the observation of the outcomes. Such a solution can be carried out using reinforcement learning (RL) based techniques which can find suitable control policies based on experiments in the simulation environments. Recently, different versions of this method have been used in several applications in electric power systems. A RL-based control of photovoltaics is carried out for control of power flow in the electric power system in [106], [107]. Epsilon greedy RL is used to control the connection and disconnection of photovoltaics to the electric power system [108]. DDPG RL-based method used for control of DAB converters for the reactive power flow control [109]. The RL-based method has also been used for designing and choosing the parameters of power electronic-based devices such as converters [110], [111]. All these methods contribute to solving various concerns in electric power systems. However, none of them are used for the control of grid-connected inverters. In this research work, we developed a DDPG based grid forming inverter to convert the energy from DC to AC and mitigate disturbances such as voltage fluctuations, voltage dips, and frequency deviations. In this approach, the system behavior is explored in many scenarios and an implicit model of them is based on the simulation outcome and simultaneously a control policy is learned. Utilizing the optained policy is helpful to cope and integrate into the non-linearity of the electric power systems and act faster to time-varying PQ events and variations minimized delays. The detail of the developed methods is given in paper C.

2.8 Contributions and paper summary

This section briefly presents the summary and contributions of the papers presented in this thesis. In all of the papers except paper E my contributions (in relation to the other authors) can be summarized as:

- Problem formulation (main)
- Solution idea (main)
- Code Implementation (main)
- Generating numerical results and Experiment design (main)
- Writing process (main)

In paper E my contributions were equal to the first author and the aforementioned tasks are equally distributed.

Paper A

In paper A, parallel processing-based MSRF analysis is used with exponential smoothing (ES) and Kalman filter, with a shorter response time than Butterworth filtering. The proposed methods reduce the settling time delay of estimating filtered *dqo* components to 1 ms and 3 ms using ES and Kalman filter, respectively. The possibility of adapting the window size of ES is optimized specifically to each harmonic and interharmonic frequency can increase the performance, however with the cost of extra manual effort. Parallel processing of all harmonics and inter harmonics is applied to the GPU framework, which lets the algorithm be close to real-time. Implementing MSRF in a parallel manner on a GPU decreased the computational time by almost a factor of 50. Therefore this study contributes to lowering both response and reaction time delay. The overall harmonics and inter harmonics system proposed has been tested on the EAF currents measured in the electricity transmission system.

Paper B

The studies in paper B propose three solutions for predicting harmonics and interharmonics to mitigate the delays in APFs in real-time harmonics filtering. The aim is to eliminate the reaction and response time delay of APFs originating from software and hardware parts. In the first approach, we used the Butterworth filter to estimate the *dq* components of the desired harmonics or interharmonics and then a linear prediction for the prediction of the future value of the filtered *dq* component. In the second solution, we developed an LSTM based prediction algorithm instead of a linear prediction. In the third solution, we proposed an end-to-end ML-based solution for filtering and predicting *dq* components. The ML method combines CNN and LSTM methods, where CNN has the role of filtering, and LSTM takes the prediction role. The LSTM based prediction increased the prediction accuracy and horizon up to two cycles of fundamental frequency (40ms) compared to the first and third solutions. We also proposed a novel data-driven regularization method to increase the prediction accuracy and horizon in the second and third solutions. To show the effectiveness and benefit of predictive methods for compensation of harmonics and inter harmonics, we designed a Simulink-based setup together with an embedded AI computing GPU (Jetson TX2) to design a predictive ML-based APF. The replica of an APF is built in a Simulink environment and prediction and estimation of harmonics are carried out on Jetson TX2. Implementing an ML-based active filter resulted in 96% efficiency compensating harmonics and interharmonics which is 36% higher than a trivial APF running in the same setup.

Paper C

Paper C aimed to mitigate the PQ disturbances such as frequency deviations, voltage dips, and continuous voltage fluctuation using RL based grid forming inverter. We use the DDPG method, the type of RL suitable for continuous states space, and model the grid and inverter's behavior. The control policy directly use the voltage and current waveforms as state-inputs and thereby bypass several estimation chains (SRF, MSRF, FFT) and lowpass filters used for conventional control algorithms such as PID. Furthermore, using the DDPG method eliminates the need for Ad hoc based tuning of parameters for coefficients of PID controllers and lowpass filter's cutoff frequency and order. The DDPG method mitigates the delays and measurement errors for the angle estimation. Such a model also helped reduce the settling time delay of the control system (15ms compared to 50ms) compared to a PID based solution. Another contribution with DDPG based grid-forming inverter is that the compensation efficiency of voltage fluctuations is improved by almost 2%. Additionally, the

DDPG method helped grid-forming inverter to have a fast reaction and accurate mitigation of frequency deviations originating from loads in the electric power systems.

Paper D

In this paper the topic of voltage dip classification is treated. The ML solution presented in paper D reduce the amount of preprocessing and learn the features within the learning process. Thus, instead of using several layers of preprocessing methods, we only used calculating RMS of voltage dips as a feature engineering step and LSTM networks as deep learning parts for the classification of the voltage dips. The proposed method resulted in 93.4% accuracy on test data set recorded from other countries. Furthermore, this method can be a suitable solution for classifying voltage dips in online applications for power systems. Using the deep learning-based method, Paper D has introduced the possibility of developing automatic feature learner algorithms rather than rule-based methods that need setting threshold values and preprocessing, which are standard methods available in literature and industry for voltage dip classification.

Paper E

Paper E proposes a feature engineering method and exploratory ML-based methods to detect the location of cable faults in DC networks. The contribution of such a method is that it needs only the current waveform recording and does not require any additional sensors. The proposed method eliminates the necessity of expensive and advanced equipment such as ships and scanners in underwater and underground cables. The proposed method is robust in noisy conditions. Finally, among the experimented ML methods, using Support Vector Machine (SVM) on suggested features resulted in detecting the location of high impedance cable faults with 5% average localization error.

CHAPTER 3

Classification of Partial Discharge Originating from PWM

3.1 Partial discharge analysis and classification

Partial Discharges can occur in different parts of electrical systems and equipment e.g. cables, transformers, motors, and can be caused by several factors, including shape and frequency of the high voltage signal, improper installations, aging, manufacturing defects, environmental and third-party damage. In recent years, by introducing more and more semiconductor devices in power systems such as (power electronic devices) PED, e.g., motor drives, inverters, and converters, the degradation due to PDs has become more common. Due to the voltage stress inflicted by pulse width modulation (PWM) switching techniques in PED devices, the PD characteristics are different from PDs occurring due to sinusoidal voltage exposure in terms of frequency, amplitude, and total charge amount. Detecting the presence and the magnitude of PD is a helpful tool to optimize the cost and the need to use electrical filters to smooth pulses generated by PWM and increase the lifetime of the insulation.

Understanding the behavior and analyzing PDs is of great importance in automating the engineering of electric devices. Classifying and finding the root cause of PDs can also help to improve the isolation design of the electric devices and systems. Furthermore, it can also provide an advanced warning for pending insulation degregation, which needs to be repaired or replaced. Early detection and root cause identification of PDs followed by remedial action lead to simpler, lower-cost maintenance solutions. It is worth mentioning that classifying and analyzing PD can provide safety to people working in substations by minimizing arc flash hazards in medium voltage switch gears. Thus, many studies have addressed the topics of detecting, classifying, and analyzing the PDs occurring due to sinusoidal shape high voltage in electric power systems i.e. [37], [112]–[117]. Early contributions in methods for measuring and detecting of PDs can be found in [118]. Later these measurement studies have improved and methods for classification of different types of PD have been developed and introduced in [37]. Lutz has proposed a generalized solution to model and classifies PDs using rule-based approaches in [119]. Neural network-based solutions for classifying PDs have been reported [117], [120]. With the progress in detecting and classifying PDs, research studies have started to investigate different types of PD presence in electric devices and systems. Digital detection, grouping, and classification of PDs signals at DC voltage are developed in [121]. Chaotic analysis of PD is used to detect insulation defects in gas-insulated switchgear [122]. Detection of SF6 decomposition products by analyzing the PDs using SVM can be found in [123]. The feature engineering techniques together with ML-based methods are further used for analyzing PD in sinusoidal and DC electric power systems [124]–[129]. These studies show that that the characteristics of PDs have a very high correlation to the shape and frequency of the waveform. Also, due to the stochastic nature of PDs, the characteristics of the individual PD events originating from a particular PD class, e.g., an insulation failure, can differ in terms of amplitude and frequency, which makes the classification task very challenging. The large-scale introduction of new types of power conversion units to the electric power system, such as inverters and drives, leads to non-sinusoidal waveforms and new types of PDs with new characteristics arise. These PDs can also damage the insulation systems in electric power systems and have high importance to study, which have been less covered in the literature.

This thesis proposes a novel feature engineering and machine learning-based method to classify PDs originating from pulse width modulation (PWM) waveforms in energy conversion units and is reported in paper F.

3.2 Contributions and paper summary

Paper F

Paper F has addressed a study on classifying PDs that have occurred due to PWM in power electronic devices (PED). Such PDs have been less studied in the literature in the past but have gained more importance lately by the increasing number of PWM-based devices in today's power systems. One of the contributions of this study is the developed feature engineering method. Note that the characteristic of the same class of PDs originating from the same source (e.g., a cavity in the insulation with a certain high voltage excitation) has a random behavior in terms of amplitude and time of occurrence. Thus, the proposed method creates new patterns by concatenating features from several consecutive PDs. In addition to features described in the literature, e.g., max amplitude or frequency of PD occurrence, we extract more PD features, including the max amplitude of PD, the time duration of each PD, area under the PD curve, and time distance occurrence. The concatenated features from sequential PDs captures the temporal dependency between consecutive PDs. This extra information improves the performance of the classification task. Numerical results show that the deep learning LSTM architecture and ensemble bagged decision trees yield a 98.3% and 95.5% classification accuracy respectively on a representative PDs test data set.

In this paper my contributions (in relation to the other authors) can be summarized as:

- problem formulation (main)
- Solution idea (main)
- Code Implementation (main)
- Generating numerical results and Experiment design (main)
- Writing process (main)

CHAPTER 4

Conclusion

The thesis work initially started as a study to develop methods for mitigating and analyzing PQ disturbances such as harmonics, interharmonics, voltage dips. In the case study for mitigation of PQ disturbances, we discover that the APFs are the most common choice. However, in the case of dealing with highly nonlinear loads, fast estimation and reaction to the PQ disturbances is still a challenging issue, and they have response and reaction time delays. First, we find that the lowpass filtering process of *dqo* components using filters such as the Butterworth filter includes almost one cycle delay. Therefore we propose parallel programming-based MSRF together ES and Kalman filter as a faster and more accurate method than Butterworth filter. It has been illustrated that the proposed parallel processing-based algorithm and data-driven approaches such as ES and Kalman filter can reduce the response time delay and increase the estimation accuracy of harmonics and interharmonics.

To mitigate the rest of delays originating from other parts of APFs such as control algorithims, we proposed three ML-based predictor algorithms to mitigate response and reaction time delay. The first solution is to use linear prediction and Butterworth filter to lowpass filter and predict the future values of *dq* components of the MSRF method. This solution has managed to mitigate the delays originating from the Butterworth filter but still lags when the prediction horizon increases. The second solution is similar to the first one, but we used LSTM for the prediction task. We observed that the prediction accuracy with LSTM is higher than the linear prediction. It is also possible to increase the prediction horizon enough to mitigate both response and reaction time (lag of Butterworth filter, PI controller, data communication, and processing time). The final solution is an end-to-end deep learning solution where we used a combination of CNN and LSTM to lowpass filter and prediction task. The third solution resulted in a more accurate and extended horizon than the first solution but worse than the second solution.

The voltage dips classification took further attention because such analyses can help to find out the type of the faults and help to have automatized proactive maintenance and surveillance. We developed two DL-based classification methods to analyze cable faults that cause voltage dips. Hence, we calculated the RMS value of voltage dip, and LSTM networks are used as the classifier. This study is conducted to provide a solution with a minimal preprocessing step. We also observed that the developed method provides an automatized solution for classifying different voltage dips in online PQ monitoring systems. Using LSTM allowed classifying voltage dips while they are occurring even before the whole event ends.

This thesis aimed to develop a deep deterministic policy gradient (DDPG), a reinforcement learning-based method for controlling the grid-forming inverter that mitigates the variations in the amplitude and frequency of the fundamental frequency component. This method builds an implicit voltage model in an electric power system and eliminates the need for several chains of analysis to estimate the amplitude of grid voltage. Therefore, compared to classical PID-based approaches, by directly mapping the outcome of the performance of the inverter to the disturbances and maximizing the reward function, the delays in estimation and reaction to voltage fluctuations and frequency deviations are mitigated with an optimal data-driven control policy. The obtained results illustrate that, in the case of mitigation of voltage dips, the proposed method managed to reduce the response time of the inverter (resulting in reaction and response time delays) to 15 ms, which is a five-time improvement compared to the PID-based version. The DDPG based inverter also performed better in the case of mitigating the frequency deviations and variation in the voltage level of the electric power system in the example studied.

We also recognized that cable fault localization in the DC lines is one of the challenging topics in electric power systems. Hence, we proposed a feature engineering method and an exploitative study using several machine learning (ML) based methods to detect the location of the faults. The proposed method uses the current waveform recorded from the line and assembles a correlation between the extracted features (di/dt, impedance, and max of current) and the location of the fault to carry on the detection task. The proposed method has a lower cost, is more accurate, and is computationally less complex than the methods listed on the paper. Using the suggested features as a preprocessing step and support vector machine (SVM) as an ML-based method identified the location of fault with 5% average error in localization of cable faults.

Finally, we amid to study the leading cause for the failure of the electrical equipment, PD. Doing such analysis can help preventive maintenance and reduce considerable future costs. We classify PDs based on their origins, e.g., a cavity located in the insulations, the shape of PWM waveform in thems of its rising time. The classification of PDs has been studied by stacking the features extracted from PDs and forming sequences of PD information and two ML algorithms. The proposed classification algorithms on the features have resulted in the highest accuracy for LSTM architecture and ensemble on top of decision trees. We realized that using every feature of PDs can be valuable information to create understandable patterns from each PD type. The proposed feature engineering steps, together with ensemble bagged DT and LSTM methods, classify different classes of PDs with 95.3% and 98.5% accuracy, respectively. It can be concluded that the proposed method can be used as an online application to classify PDs originating from PWM of PEDs.

References

[1] H. Alhelou, “An overview of wide area measurement system and its application in modern power systems,” in *Handbook of Research on Smart Power System Operation and Control*, IGI Global, 2019, pp. 289–307.

[2] A. McEachern, “Designing electronic devices to survive power-quality events,” *IEEE Industry Applications Magazine*, vol. 6, no. 6, pp. 66–69, 2000.

[3] S. Bhattacharyya, J. M. A. Myrzik, and W. L. Kling, “Consequences of poor power quality - an overview,” in *2007 42nd International Universities Power Engineering Conference*, 2007, pp. 651–656.

[4] N. Chandrappa and S. Banerjee, “The next generation of power quality monitoring technology - helping industrial equipment stay healthy,” in *Analog Devices, Inc.*, 2017, pp. 1–4.

[5] Schneider, “Power quality: Measuring to manage,” *available at: https://blog.se.com/power- management- metering- monitoring- power -quality / 2015 /06/11/power-quality-measuring-to-manage/*, 2015.

[6] M. McGranaghan and B. Roettger, “Economic evaluation of power quality,” *IEEE Power Engineering Review*, vol. 22, no. 2, pp. 8–12, 2002.

[7] H. G. Beleiu, I. N. Beleiu, S. G. Pavel, and C. P. Darab, “Management of power quality issues from an economic point of view,” *Sustainability*, vol. 10, no. 7, p. 2326, 2018.

[8] B. Horia, G. Beleiu, I. Natalia, P., S. Gheorghe and C. Pompei, "Power quality problems and their solutions," 2019, Available at: `https://www.netlabindia.com`.

[9] "Electromagnetic compatibility EMC - part 2: Environment - section 1: Description of the environment - electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems," *IEC Standard-1000-2-1*, 2003.

[10] "Testing and measurement techniques-power quality measurement methods, 2003," *IEC Standard 61000-4-30:*, 2003.

[11] "Electromagnetic compatibility, part 3–3: Limits—limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current# 16a per phase and not subject to conditional connection," *IEC Standard 61000-3*, 2005.

[12] S. H. Qazi and M. W. Mustafa, "Review on active filters and its performance with grid connected fixed and variable speed wind turbine generator," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 420–438, 2016, ISSN: 1364-0321.

[13] L. Asiminoael, F. Blaabjerg, and S. Hansen, "Detection is key-harmonic detection methods for active power filter applications," *IEEE Industry Applications Magazine*, vol. 13, no. 4, pp. 22–33, 2007.

[14] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, 1999.

[15] M. El-Habrouk, M. Darwish, and P. Mehta, "Active power filters: A review," *IEE Proceedings-Electric Power Applications*, vol. 147, no. 5, pp. 403–413, 2000.

[16] Donghua Chen and Shaojun Xie, "Review of the control strategies applied to active power filters," in *2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies. Proceedings*, vol. 2, 666–670 vol.2.

[17] Y. Pal, A. Swarup, and B. Singh, "A review of compensating type custom power devices for power quality improvement," in *2008 Joint International Conference on Power System Technology and IEEE Power India Conference*, 2008, pp. 1–8.

[18] V. Gali, N. Gupta, and R. A. Gupta, "Mitigation of power quality problems using shunt active power filters: A comprehensive review," in *2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2017, pp. 1100–1105.

[19] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an lcl-filter-based three-phase active rectifier," *IEEE Transactions on Industry Applications*, vol. 41, no. 5, pp. 1281–1291, 2005.

[20] H.-H. Kuo, S.-N. Yeh, and J.-C. Hwang, "Novel analytical model for design and implementation of three-phase active power filter controller," *IEE Proceedings-Electric Power Applications*, vol. 148, no. 4, pp. 369–383, 2001.

[21] S. Golestan, M. Ramezani, J. M. Guerrero, and M. Monfared, "Dq-frame cascaded delayed signal cancellation- based pll: Analysis, design, and comparison with moving average filter-based pll," *IEEE Transactions on Power Electronics*, vol. 30, no. 3, pp. 1618–1632, 2015.

[22] S. Gomez Jorge, C. A. Busada, and J. A. Solsona, "Frequency adaptive discrete filter for grid synchronization under distorted voltages," *IEEE Transactions on Power Electronics*, vol. 27, no. 8, pp. 3584–3594, 2012.

[23] O.-y. Hua, B. Le-ping, and Y. Zhong-lin, "Voltage sag detection based on dq transform and mathematical morphology filter," *Procedia Engineering*, vol. 23, pp. 775–779, 2011, PEEA 2011, ISSN: 1877-7058.

[24] C. Xianghu, Z. Xiangjun, D. Feng, and L. Ling, "Novel pcb sensor based on rogowski coil for transmission lines fault detection," in *2009 IEEE Power Energy Society General Meeting*, 2009, pp. 1–4.

[25] A. Vadula and D. Li, "Current sensing delay in three-phase inverter," in *2018 IEEE Electronic Power Grid (eGrid)*, 2018, pp. 1–5.

[26] A. Nomura, "Choosing the right current sensor to observe the current waveform of switching devices," *available at: https:// https://eepower.com/technical-articles/choosing-the-right-current-sensor-to-observe-the-current- waveform-of-switching-devices/*, 2019.

[27] S. Fukuda and S.-I. Sugawa, "Adaptive signal processing based control of active power filters," in *IAS '96. Conference Record of the 1996 IEEE Industry Applications Conference Thirty-First IAS Annual Meeting*, vol. 2, 1996, 886–890 vol.2.

[28] H.-P. To, F. Rahman, and C. Grantham, "Time delay compensation for a current-source active power filter using state-feedback controller," in *Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005.*, vol. 2, 2005, 1213–1219 Vol. 2.

[29] B. C. Baker, "Tutorial: Basics of choosing and designing the best filter for an effective data-acquisition system," *Planet Analog Magazine*, 2006.

[30] S. Rahmani, N. Mendalek, and K. Al-Haddad, "Experimental design of a nonlinear control technique for three-phase shunt active power filter," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 10, pp. 3364–3375, 2010.

[31] J. Yang, J. E. Fletcher, and J. O'Reilly, "Short-circuit and ground fault analyses and location in vsc-based dc network cables," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 10, pp. 3827–3837, 2012.

[32] R. Razzaghi, G. Lugrin, H. Manesh, C. Romero, M. Paolone, and F. Rachidi, "An efficient method based on the electromagnetic time reversal to locate faults in power networks," *IEEE Transactions on Power Delivery*, vol. 28, no. 3, pp. 1663–1673, 2013.

[33] Y.-J. Shin, E. Powers, T.-S. Choe, *et al.*, "Application of time-frequency domain reflectometry for detection and localization of a fault on a coaxial cable," *IEEE Transactions on Instrumentation and Measurement*, vol. 54, no. 6, pp. 2493–2500, 2005.

[34] S. Mo, D. Zhang, Z. Li, and Z. Wan, "The possibility of fault location in cross-bonded cables by broadband impedance spectroscopy," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 4, pp. 1416–1423, 2021.

[35] E. Balouji, K. Bäckström, and P. Hovila, "A deep learning approach to earth fault classification and source localization," in *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2020, pp. 635–639.

[36] "High-voltage test techniques-partial discharge measurements, 3," *IEC Standard 60270*, 2000.

[37] F. Kreuger, E. Gulski, and A. Krivda, "Classification of partial discharges," *IEEE Transactions on Electrical Insulation*, vol. 28, no. 6, pp. 917–931, 1993.

[38] Y. HE, A. Nilsson, and F. Carlsson, "Failure causes of distribution network components," *Traffic*, vol. 9, pp. 0–5, 2011.

[39] T. D. Schütte and E. J. P. Santos, "Understanding the breakdown mechanism of bushings and implementing appropriate life-cycle oriented maintenance strategies," in *Proceedings of the 2010 Electric Power Quality and Supply Reliability Conference*, 2017, pp. 1–27.

[40] M. Lehtonen, "Fault rates of different types of medium voltage power lines in different environments," in *Proceedings of the 2010 Electric Power Quality and Supply Reliability Conference*, 2010, pp. 197–202.

[41] E. A. Cano-Plata, A. J. Ustariz-Farfan, and O. J. Soto-Marin, "Electric arc furnace model in distribution systems," *IEEE Transactions on Industry Applications*, vol. 51, no. 5, pp. 4313–4320, 2015.

[42] R. Collantes-Bellido and T. Gomez, "Identification and modelling of a three phase arc furnace for voltage disturbance simulation," *IEEE Transactions on Power Delivery*, vol. 12, no. 4, pp. 1812–1817, 1997.

[43] S. Srianthumrong and S. Sangwongwanich, "An active power filter with harmonic detection method based on recursive DFT," in *8th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.98EX227)*, vol. 1, 1998, 127–132 vol.1.

[44] M.-S. Karbasforooshan and M. Monfared, "An adaptive recursive discrete fourier transform technique for the reference current generation of single-phase shunt active power filters," in *2016 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC)*, IEEE, 2016, pp. 253–259.

[45] H. Chen, H. Liu, Y. Xing, and H. Hu, "Enhanced DFT-based controller for selective harmonic compensation in active power filters," *IEEE Transactions on Power Electronics*, 2018.

[46] Y. Zhang, K. Dai, X. Chen, Y. Kang, and Z. Dai, "Stability analysis of sapf by viewing DFT as cluster of bpf for selective harmonic suppression and resonance damping," *IEEE Transactions on Industry Applications*, 2018.

[47] E. Z. Bighash, S. M. Sadeghzadeh, E. Ebrahimzadeh, and F. Blaabjerg, "Adaptive-harmonic compensation in residential distribution grid by roof-top pv systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 4, pp. 2098–2108, 2018.

[48] H. Liu *et al.*, "Fast and flexible selective harmonic extraction methods based on the generalized discrete fourier transform," *IEEE Trans. on Pow. Elec.*, vol. 33, no. 4, pp. 3484–3496, 2018.

[49] J. M. Maza-Ortega, J. A. Rosendo-Macıas, A. Gomez-Exposito, S. Ceballos-Mannozzi, and M. Barragan-Villarejo, "Reference current computation for active power filters by running DFT techniques," *IEEE Transactions on Power Delivery*, vol. 25, no. 3, pp. 1986–1995, 2010.

[50] F. Cupertino, E. Lavopa, P. Zanchetta, M. Sumner, and L. Salvatore, "Running DFT-based PLL algorithm for frequency, phase, and amplitude tracking in aircraft electrical systems," *IEEE Transactions on industrial Electronics*, vol. 58, no. 3, pp. 1027–1035, 2011.

[51] M. Y. Lada, N. I. Zolkifri, J. A. M. Gani, M. R. M. Nawawi, and G. C. Kim, "Reduction of harmonic using single phase shunt active filter based on FFT method for cascaded multilevel inverter," 2016.

[52] T. D. Reddy and M. Barai, "A novel configuration to eliminate dominant harmonic frequency (dhf) by using FFT in series active filters," in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, IEEE, 2016, pp. 1–5.

[53] G. D. Marques, "A comparison of active power filter control methods in unbalanced and non-sinusoidal conditions," in *IECON '98. Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society (Cat. No.98CH36200)*, vol. 1, 1998, 444–449 vol.1.

[54] D. Campos-Gaona, R. Pena-Alzola, J. L. Monroy-Morales, M. Ordonez, O. Anaya-Lara, and W. E. Leithead, "Fast selective harmonic mitigation in multifunctional inverters using internal model controllers and synchronous reference frames," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 8, pp. 6338–6349, 2017.

[55] M. S. Pilehvar and B. Mirafzal, "Pv-fed smart inverters for mitigation of voltage and frequency fluctuations in islanded microgrids," in *2020 International Conference on Smart Grids and Energy Systems (SGES)*, 2020, pp. 807–812.

[56] ——, "Energy-storage fed smart inverters for mitigation of voltage fluctuations in islanded microgrids," in *2020 IEEE Electric Power and Energy Conference (EPEC)*, 2020, pp. 1–6.

[57] J. Sun, D. Czarkowski, and Z. Zabar, "Voltage flicker mitigation using pwm-based distribution statcom," in *IEEE Power Engineering Society Summer Meeting,*, vol. 1, 2002, 616–621 vol.1.

[58] A. El-Nady and A. Noureldin, "Mitigation of arc furnace voltage flicker using an innovative scheme of adaptive notch filters," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1326–1336, 2011.

[59] C. Cagigal Olay, S. Monteso Fernández, A. H. Bayo, J. C. C. Rodríguez, and S. Martínez García, "Synthesis and evaluation of fast onload multitap changers for flicker compensation in ac arc furnaces," *IEEE Transactions on Power Delivery*, vol. 29, no. 6, pp. 2519–2527, 2014.

[60] L. Feola, R. Langella, I. Papič, and A. Testa, "Selective interharmonic compensation to improve statcom performance for light flicker mitigation," *IEEE Transactions on Power Delivery*, vol. 33, no. 5, pp. 2442–2451, 2018.

[61] M. F. McGranaghan, D. R. Mueller, and M. J. Samotyj, "Voltage sags in industrial systems," *IEEE Transactions on industry applications*, vol. 29, no. 2, pp. 397–403, 1993.

[62] R. A. Flores, "State of the art in the classification of power quality events, an overview," in *10th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.02EX630)*, vol. 1, 2002, 17–20 vol.1.

[63] Y. Wang, M. H. Bollen, A. Bagheri, X.-Y. Xiao, and M. Olofsson, "A quantitative comparison approach for different voltage dip characterization methods," *Electric Power Systems Research*, vol. 133, pp. 182–190, 2016.

[64] S. Z. Djokic, J. V. Milanovic, D. J. Chapman, M. F. McGranaghan, and D. S. Kirschen, "A new method for classification and presentation of voltage reduction events," *IEEE Transactions on Power Delivery*, vol. 20, no. 4, pp. 2576–2584, 2005.

[65] M. H. Chia and A. M. Khambadkone, "Subcycle voltage dip classification using matrix pencil method with ellipse fitting algorithm," *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1660–1668, 2014.

[66] A. M. Stanisavljevic, V. A. Katic, B. P. Dumnic, and B. P. Popadic, "Overview of voltage dips detection analysis methods," in *2017 International Symposium on Power Electronics (Ee)*, 2017, pp. 1–6.

[67] M. R. Alam, K. M. Muttaqi, and T. K. Saha, "Classification and localization of fault-initiated voltage sags using 3-D polarization ellipse parameters," *IEEE Transactions on Power Delivery*, pp. 1–1, 2019.

[68] V. Ignatova, P. Granjon, and S. Bacha, "Space vector method for voltage dips and swells analysis," *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 2054–2061, 2009.

[69] E. Styvaktakis, M. H. Bollen, and I. Y. Gu, "Expert system for classification and analysis of power system events," *IEEE Transactions on power delivery*, vol. 17, no. 2, pp. 423–428, 2002.

[70] D. Li, F. Mei, C. Zhang, H. Sha, and J. Zheng, "Self-supervised voltage sag source identification method based on CNN," *Energies*, vol. 12, no. 6, p. 1059, 2019.

[71] E. Balouji and O. Salor, "Classification of power quality events using deep learning on event images," in *2017 3rd International Conference on Pattern Recognition and Image Analysis (IPRIA)*, IEEE, 2017, pp. 216–221.

[72] H. Wang, L. Qi, Y. Ma, J. Jia, and Z. Zheng, "Method of voltage sag causes based on bidirectional LSTM and attention mechanism," *Journal of Electrical Engineering and Technology*, pp. 1–11, 2020.

[73] K. Chen, J. Hu, and J. He, "A framework for automatically extracting overvoltage features based on sparse autoencoder," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 594–604, 2018.

[74] C. O'Donovan, C. Giannetti, and G. Todeschini, "A novel deep learning power quality disturbance classification method using autoencoders.," in *ICAART (2)*, 2021, pp. 373–380.

[75] E. Balouji, I. Y. H. Gu, M. H. J. Bollen, A. Bagheri, and M. Nazari, "A LSTM-based deep learning method with application to voltage dip classification," in *2018 18th International Conference on Harmonics and Quality of Power (ICHQP)*, 2018, pp. 1–5.

[76] J. Yang, J. E. Fletcher, and J. O'Reilly, "Multiterminal dc wind farm collection grid internal fault analysis and protection design," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2308–2318, 2010.

[77] L. Xu and L. Yao, "Fault ride-through of hvdc connected large offshore wind farms," in *Wind Energy Conversion Systems: Technology and Trends*, S. Muyeen, Ed. London: Springer London, 2012, pp. 415–430, ISBN: 978-1-4471-2201-2.

[78] M. Baran and N. Mahajan, "Dc distribution for industrial systems: Opportunities and challenges," *IEEE Transactions on Industry Applications*, vol. 39, no. 6, pp. 1596–1601, 2003.

[79] M. E. Baran and N. R. Mahajan, "Overcurrent protection on voltage-source-converter-based multiterminal dc distribution systems," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 406–412, 2007.

[80] F. Blaabjerg and J. Pedersen, "A new low-cost, fully fault-protected pwm-vsi inverter with true phase-current information," *IEEE Transactions on Power Electronics*, vol. 12, no. 1, pp. 187–197, 1997.

[81] D. Akmaz, M. S. Mamiş, M. Arkan, and M. E. Tağluk, "Transmission line fault location using traveling wave frequencies and extreme learning machine," *Electric Power Systems Research*, vol. 155, pp. 1–7, 2018, ISSN: 0378-7796.

[82] Z. Al-Hamouz, "Wavelet-based extreme learning machine for distribution grid fault location," English, *IET Generation, Transmission and Distribution*, vol. 11, 4256–4263(7), 17 Nov. 2017, ISSN: 1751-8687.

[83] M. Majidi, M. Etezadi-Amoli, and M. Sami Fadali, "A novel method for single and simultaneous fault location in distribution networks," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3368–3376, 2015.

[84] "IEEE recommended practice for evaluating electric power system compatibility with electronic process equipment," *IEEE Standard 1346-1998*, 1998.

[85] P.-T. Cheng, W.-T. Chen, Y.-H. Chen, C.-L. Ni, and J. Lin, "A transformer inrush mitigation method for series voltage sag compensators," *IEEE Transactions on Power Electronics*, vol. 22, no. 5, pp. 1890–1899, 2007.

[86] Y.-H. Chen, C.-Y. Lin, J.-M. Chen, and P.-T. Cheng, "An inrush mitigation technique of load transformers for the series voltage sag compensator," *IEEE Transactions on Power Electronics*, vol. 25, no. 8, pp. 2211–2221, 2010.

[87] K. P. Basu and S. A. Hafidz, "Mitigation of single-phase voltage sag and swell with zigzag transformer," in *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, 2008, pp. 2369–2373.

[88] H. Awad, J. Svensson, and M. Bollen, "Mitigation of unbalanced voltage dips using static series compensator," *IEEE Transactions on Power Electronics*, vol. 19, no. 3, pp. 837–846, 2004.

[89] A. Sannino, M. Miller, and M. Bollen, "Overview of voltage sag mitigation," in *2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.00CH37077)*, vol. 4, 2000, 2872–2878 vol.4.

[90] A. Sannino, J. Svensson, and T. Larsson, "Power-electronic solutions to power quality problems," *Electric Power Systems Research*, vol. 66, no. 1, pp. 71–82, 2003, Power Quality, ISSN: 0378-7796.

[91] M. Bongiorno and J. Svensson, "Voltage dip mitigation using shunt-connected voltage source converter," *IEEE Transactions on Power Electronics*, vol. 22, no. 5, pp. 1867–1874, 2007.

[92] M. Bongiorno, *Control of voltage source converters for voltage dip mitigation in shunt and series configurations*. Chalmers Tekniska Hogskola (Sweden), 2004.

[93] R. Weissbach, G. Karady, and R. Farmer, "Dynamic voltage compensation on distribution feeders using flywheel energy storage," *IEEE Transactions on Power Delivery*, vol. 14, no. 2, pp. 465–471, 1999.

[94] A. Visser, J. Enslin, and H. de T Mouton, "Transformerless series sag compensation with a cascaded multilevel inverter," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 4, pp. 824–831, 2002.

[95] T. Fang, Q. Zhou, F. Ding, X. Wu, Z. Li, and H. Tang, "Response time of reactive power based on different definitions and algorithms," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 2, pp. 440–449, 2021.

[96] ABB, "Active filters-pqfi-pqfm-pqfs improving power quality for efficiency and reliability," 2018.

[97] ——, "Power quality voltage stabilisation for industrial grids and wind farms with statcom," 2013.

[98] Siemens, "Reactive-power compensation and active filter," 2011.

[99] G. Bonifacio, A. Lo Schiavo, P. Marino, and A. Testa, "Comparative analysis of shunt active filters in nonideal operating conditions," in *Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441)*, vol. 1, 2000, 226–231 vol.1.

[100] S. Ziegler, R. C. Woodward, H. H.-C. Iu, and L. J. Borle, "Current sensing techniques: A review," *IEEE Sensors Journal*, vol. 9, no. 4, pp. 354–376, 2009.

[101] Y. Jin, T. Fang, and K. Yao, "An improved time-delay compensation scheme for enhancing control performance of digitally controlled grid-connected inverter," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2019, pp. 2772–2776.

[102] "Electromagnetic compatibility (emc)—part 4-7: Testing and measurement techniques—general guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto," *IEC Standard 61000–4*, 2002.

[103] M. A. Laughton and M. G. Say, *Electrical engineer's reference book.* Elsevier, 2013.

[104] C. J. O'Rourke, M. M. Qasim, M. R. Overlin, and J. L. Kirtley, "A geometric interpretation of reference frames and transformations: dqo, clarke, and park," *IEEE Transactions on Energy Conversion*, vol. 34, no. 4, pp. 2070–2083, 2019.

[105] S. Golestan, M. Monfared, F. D. Freijedo, and J. M. Guerrero, "Advantages and challenges of a type-3 pll," *IEEE Transactions on Power Electronics*, vol. 28, no. 11, pp. 4985–4997, 2013.

[106] D. Cao, J. Zhao, W. Hu, *et al.*, "Deep reinforcement learning enabled physical-model-free two-timescale voltage control method for active distribution systems," *IEEE Transactions on Smart Grid*, pp. 1–1, 2021.

[107] R. El Helou, D. Kalathil, and L. Xie, "Fully decentralized reinforcement learning-based control of photovoltaics in distribution grids for joint provision of real and reactive power," *IEEE Open Access Journal of Power and Energy*, vol. 8, pp. 175–185, 2021.

[108] H. Liu and W. Wu, "Two-stage deep reinforcement learning for inverter-based volt-var control in active distribution networks," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2037–2047, 2021.

[109] Y. Tang, W. Hu, D. Cao, *et al.*, "Artificial intelligence-aided minimum reactive power control for the dab converter based on harmonic analysis method," *IEEE Transactions on Power Electronics*, vol. 36, no. 9, pp. 9704–9710, 2021.

[110] T. Dragičević, P. Wheeler, and F. Blaabjerg, "Artificial intelligence aided automated design for reliability of power electronic systems," *IEEE Transactions on Power Electronics*, vol. 34, no. 8, pp. 7161–7171, 2019.

[111] X. Li, X. Zhang, F. Lin, and F. Blaabjerg, "Artificial-intelligence-based design (AI-D) for circuit parameters of power converters," *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2021.

[112] A. Contin, A. Cavallini, G. Montanari, G. Pasini, and F. Puletti, "Digital detection and fuzzy classification of partial discharge signals," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 9, no. 3, pp. 335–348, 2002.

[113] N. Sahoo, M. Salama, and R. Bartnikas, "Trends in partial discharge pattern classification: A survey," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 12, no. 2, pp. 248–264, 2005.

[114] A. Krivda and E. Gulski, “Neural networks as a tool for recognition of partial discharges,” in *1993 International Conference on Partial Discharge*, 1993, pp. 84–85.

[115] H. Ma, J. C. Chan, T. K. Saha, and C. Ekanayake, “Pattern recognition techniques and their applications for automatic classification of artificial partial discharge sources,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 2, pp. 468–478, 2013.

[116] E. Lalitha and L. Satish, “Wavelet analysis for classification of multi-source PD patterns,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 7, no. 1, pp. 40–47, 2000.

[117] H.-G. Kranz, “Diagnosis of partial discharge signals using neural networks and minimum distance classification,” *IEEE transactions on electrical insulation*, vol. 28, no. 6, pp. 1016–1024, 1993.

[118] D. Train, A. Mercier, and D. Thorne, “The detection of partial discharges in high voltage potential transformers in service,” *IEEE Transactions on Power Apparatus and Systems*, no. 6, pp. 1909–1916, 1974.

[119] L. Niemeyer, “A generalized approach to partial discharge modeling,” *IEEE transactions on Dielectrics and Electrical insulation*, vol. 2, no. 4, pp. 510–528, 1995.

[120] L. Satish and B. Gururaj, “Partial discharge pattern classification using multilayer neural networks,” *IEE Proceedings A (Science, Measurement and Technology)*, vol. 140, no. 4, pp. 323–330, 1993.

[121] S. Wenrong, L. Junhao, Y. Peng, and L. Yanming, “Digital detection, grouping and classification of partial discharge signals at dc voltage,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 6, pp. 1663–1674, 2008.

[122] J. Koo, S. Jung, C. Ryu, S. Lee, and B. Lee, “Identification of insulation defects in gas-insulated switchgear by chaotic analysis of partial discharge,” *IET Science, Measurement and Technology*, vol. 4, no. 3, pp. 115–124, 2010.

[123] J. Tang, F. Liu, X. Zhang, X. Liang, and Q. Fan, “Partial discharge recognition based on SF6 decomposition products and support vector machine,” *IET Science, Measurement & Technology*, vol. 6, no. 4, pp. 198–204, 2012.

[124] M. M. A. Salama and R. Bartnikas, “Fuzzy logic applied to PD pattern classification,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 7, no. 1, pp. 118–123, 2000.

[125] A. Hirata, S. Nakata, and Z. .-. Kawasaki, “Toward automatic classification of partial discharge sources with neural networks,” *IEEE Transactions on Power Delivery*, vol. 21, no. 1, pp. 526–527, 2006.

[126] K. Lai, B. Phung, and T. Blackburn, “Application of data mining on partial discharge part i: Predictive modelling classification,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 17, no. 3, pp. 846–854, 2010.

[127] H. Janani and B. Kordi, “Towards automated statistical partial discharge source classification using pattern recognition techniques,” *High voltage*, vol. 3, no. 3, pp. 162–169, 2018.

[128] M. Karimi, M. Majidi, H. MirSaeedi, M. M. Arefi, and M. Oskuoee, “A novel application of deep belief networks in learning partial discharge patterns for classifying corona, surface, and internal discharges,” *IEEE Transactions on Industrial Electronics*, vol. 67, no. 4, pp. 3277–3287, 2019.

[129] R. Zemouri, M. Lévesque, N. Amyot, C. Hudon, O. Kokoko, and S. A. Tahan, “Deep convolutional variational autoencoder as a 2D-visualization tool for partial discharge source classification in hydrogenerators,” *IEEE Access*, vol. 8, pp. 5438–5454, 2020.