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NGO MINH KHOA

A STUDY OF VOLTAGE DISTURBANCES
IN DISTRIBUTION NETWORK

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DISSERTATION IN BRIEF

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This dissertation has been finished at: Danang University of Technology, The university of Danang

Supervisor 1: Assoc, Prof. PhD. Dinh Thanh Viet
Supervisor 2: PhD. Nguyen Huu Hieu

Examiner 1: GS.VS.TSKH. Trần Đình Long
Examiner 2: PGS.TS. Vò Ngọc Điều
Examiner 3: TS. Lê Hữu Hùng

The dissertation will be defended at the Thesis Assessment Committee at Da Nang University Level at Room No:

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INTRODUCTION

1. The reason for choosing the dissertation

Nowadays, electrical equipment in modern industry uses more and more electronic devices, controllers (such as motor speed drive controllers, programmable logic controllers, etc.) with the involvement of the distributed generation using renewable energy sources (wind, solar, etc.) in distribution networks. These devices require high voltage quality in order to ensure their normal operation conditions.

2. The purposes of the research

- The dissertation researches about signal processing methods used in voltage disturbance analysis problems. Then a new method based on discrete wavelet transform (DWT) and linear adaptive neural network (ADALINE) is proposed in order to determine and classify accurately voltage disturbances which appear at a monitoring position in distribution network.

- The dissertation researches characteristics, effects, solutions and standards of voltage sag. Then the authors propose a research method of voltage sag effects to sensitive loads in distribution network based on modeling and simulating by using Matlab/Simulink software.

- Application of the proposed method in chapter 2 to determine voltage sag indices according to the IEEE Std. 1564-2014 standard and evaluate voltage quality for sensitive loads in Vietnam’s distribution networks.

- Application of voltage sag mitigation methods by using mitigation equipments at connection point between sensitive loads and distribution network.
3. Research methods

To build up the system to monitor, classify and mitigate voltage disturbances especially voltage sag/swell, the research method of the dissertation will study problems below:

+ *The background of signal processing methods in modern signal processing applied in power system are researched in this dissertation.*

+ *Highlights of characteristic identification methods of signals follow artificial intelligent are studying and then the efficiency of voltage disturbance classification system is improved.*

+ *Data in this work is gathered by simulating transient process in power system by Matlab/Simulink software, real data is also gathered to evaluate the proposed methods.*

4. The object and scope of research

*The research object:* The dissertation researches on voltage disturbances in distribution networks including types of short-term voltage variations (voltage sag, voltage swell, voltage interruption) and long-term voltage variations which impact on voltage quality in distribution network.

*The research scope:* The dissertation researches voltage disturbance classification methods aforementioned, and studies effects and determining indices of voltage sag in order to improve voltage quality for sensitive loads in distribution networks. In addition, this dissertation also studies voltage sag mitigation solutions in distribution networks.

5. The meaning of science and practice of the dissertation

*The meaning of science:* With the previous content, the dissertation results will have the meaning of science as following:
- A voltage disturbances classification method meets requirements on monitoring voltage quality in distribution network. The system can handle a large volume of input data collected from the monitoring locations on the grid.

- It shows that the necessity of voltage disturbances classification especially in the context of increasing the power electronic devices as well as distributed generation involved in distribution network.

- Discrete wavelet transform (DWT) method is an effective tool in signal processing, its detail and approximation coefficients are the typical characteristics of voltage disturbances.

- ADALINE shows ability for voltage amplitude identification comparing with traditional methods. ADALINE can also determine both the amplitude and phase angle of different frequency components of voltage disturbance signals.

The meaning of practice: The research problems in the dissertation will have the meaning of practice as following:

- Classification is an essential task in the management and operation of the power grid to deliver the best performance.

- With the huge data of real waveforms recorded by power quality monitoring equipment which are located at different points in distribution networks, and the considering period can be long (weeks, months, years). Therefore, we need a classification system to classify that data.

- The classification results will help the selection, design and installation of suitable equipment to prevent the consequences which voltage disturbances can cause impact on the electrical equipment customers and the electricity unit.
CHAPTER 1. VOLTAGE DISTURBANCE CLASSIFICATION OVERVIEW IN DISTRIBUTION NETWORK

1.1. Introduction

Voltage quality monitoring is a process of gathering, analyzing and describing the real data into useful information. Data collection process is usually done by continuously measuring the voltage as shown in Figure 1.1. Normally the process of analysis and evaluation is done in the traditional way, but with the recent advantages in the fields of signal processing and artificial intelligence has opened up many opportunities to be able to design and application intelligent systems use to automatically analyze and evaluate real data with human intervention [17]. The main goal of the data collection is to identify and control the disturbances. This can be done by detecting, analyzing and defining characteristic of different NLDA.

Figure 1.1. Voltage quality measurement and monitoring diagram.

Figure 1.2. The meaning of extracting characteristic input signal.
1.2. Voltage disturbance classification methods

There are many different methods to determine the characteristics and to classify voltage disturbances, however they can be classified into two main groups as follows:

+ **The traditional methods**: They are the methods commonly used in the protection relay and power quality monitoring devices in distribution network.
  
  - The root mean square (RMS) method
  - The fundamental voltage method
  - The peak voltage method

+ **The modern methods**: Because the traditional methods have weaknesses in detecting the voltage disturbance characteristics so we need to find out the modern methods to quickly and accurately detect voltage disturbances.
  
  - The short-time Fourier transform
  - The adaptive linear neural network (ADALINE)
  - The wavelet transform

1.3. Conclusion

Based on the content presented on the voltage disturbance classification method of in distribution network. It shows that there are many methods of classifying voltage disturbance, but each method has different advantages and disadvantages. Therefore finding a more suitable method to apply to the classification of voltage disturbance types to bring high efficiency in monitoring, operation distribution network.

Although classic methods has advantages but also exist certain disadvantage in determining the characteristics to classify the voltage disturbance types. Therefore the trend will study application of
methods of modern signal processing to determine parameters and accurate classification of voltage disturbance types. A review of existing methods for determining the characteristics and classification voltage disturbance shows that usually we have to combine modern methods to maximize efficiency as well as overcoming disadvantages each other in determining the characteristics and classification voltage disturbances. Hence using DWT and ADALINE combined to determine voltage disturbance characteristics.

CHAPTER 2. A METHOD FOR DETERMINING CHARACTERISTICS AND CLASSIFYING VOLTAGE DISTURBANCES IN DISTRIBUTION NETWORK

2.1. Introduction

Voltage disturbance monitoring becomes necessary in the management and operation in order to improve the quality of electricity supply to customers especially for modern industrial customers such as electronic manufacture, semiconductor material manufacture, computer data centers, etc. as shown in Figure 2.1.

![Figure 2.1. The necessary of voltage disturbance monitoring.](image)

2.2. Characteristics and classification of voltage disturbances

The monitoring system includes three modules as shown in Figure 2.3. Voltage disturbance characteristics as shown in Figure 2.4.
Figure 2.4. Definition of voltage disturbances according to 1159-2009 [32].

2.3. Background of wavelet transform

2.3.1. Wavelet transform (WT)

2.3.2. Discrete wavelet transform (DWT)

2.3.3 Mother wavelet selection

2.4. The proposed method

The algorithm of proposed method is shown in Figure 2.7. There are 3 main parts: (1) – This is the signal processing unit using low-pass filters and A/D conversion to get the voltage digital signal form. (2) - This component combines DWT and ADALINE to extract the characteristics of voltage signal that is: duration and magnitude of the event from the input voltage signal. (3) – This is voltage
disturbance classification unit from the characteristic extracted earlier to return the result of the types of voltage disturbance. The classification algorithm is shown in Figure 2.8.

![Figure 2.7. Characteristic determination and voltage disturbance classification](image)

### 2.4.1. Determine $J$ levels in DWT

DWT multi-resolution analysis transforms the original signal in time domain to time domain-frequency. Assuming voltage signal with sampling frequency is $f_s$, while the approximation coefficients ($A_j$) and detail coefficients ($D_j$) with different frequency bands.

### 2.4.2. Voltage amplitude estimate by ADALINE

ADALINE is a form of adaptive filter used to extract the signal in the noise environment using two-layer feedforward neural network, with N inputs and one output [66], [8]. ADALINE has many advantages as follows: online training based on the change in the input and output response; Self-adaptive algorithm is applied to train the network weights; Simple structure and easy integration of the hardware.

### 2.4.3. Voltage disturbance classification
2.5. The results of the proposed method

2.5.1. Signal mathematical model of voltage disturbances

To evaluate the effectiveness of the proposed method, voltage disturbance data is created by using mathematical equations:

\[
    u(t) = \begin{cases} 
    U_m \sin(\omega t + \varphi) & \text{if } t < t_s \text{ or } t > t_e \\
    U_{dis} \sin(\omega t + \varphi + \phi_{dis}) & \text{if } t_s \leq t \leq t_e 
    \end{cases}
\]  \( (2.27) \)

Using Matlab software to create signal samples by using (2.27) with a sampling frequency of 512 samples/cycle for the fundamental frequency of 50 Hz, with the voltage disturbance parameters within the limits according to IEEE Std. 1159-2009 standard.

2.5.2. Electromagnetic transient software by Matlab/Simulink

Matlab/Simulink software is used as a tool for modeling IEEE 34 buses distribution network [77], some simulation cases are considered to simulate and voltage in a number of buses are kept to create a database for studies assessing the effectiveness of the proposed method.
2.5.3. Accuracy assessment of the method estimates the V-D-A

The time and amplitude estimation error:

\[ \Delta t = \left| dt - dt' \right| \]

\[ \varepsilon_u \% = \frac{\left| U_{890} - U'_{890} \right|}{U_{890}} \times 100 \]  \hspace{1cm} (2.34)

2.5.4. Application for the voltage waveforms

Figure 2.12. The voltage profile is in grid IEEE 34 when faults occurs at bus 836.

Figure 2.17. Case 1.

Figure 2.18. Case 2.
2.7. Conclusion

DWT is used in this dissertation to extract the typical characteristics of voltage disturbances: voltage sag, voltage swell and voltage interruption. Detail level 1 (D1) coefficients of DWT is very sensitive to sudden changes in the signal, so it is used to determine the beginning and end of the signal disturbance.

Using the number of analysis levels consistent with the sampling frequency of the signal voltage to generate approximately $A_J$ coefficients which contain only the fundamental frequency range desired. $A_J$ approximation coefficient is considered as input of ADALINE to estimate the amplitude of the voltage signal.

Modeling data to assess the effectiveness of the proposed method is done by mathematical modeling and simulation of electromagnetic transients using Matlab/Simulink software for IEEE 34 buses network. Short-circuits are simulated at several locations as well as the changes in value of the fault impedance and event duration to create database to evaluate the proposed method.
CHAPTER 3. DETERMINING VOLTAGE SAG INDICES FOR SENSITIVE LOADS IN DISTRIBUTION NETWORK

3.1. Introduction

3.2. Determining voltage sag indices in power systems

3.2.1. The method of sequence components

3.2.2. The method of six RMS voltages

3.3. Voltage sag indices according to IEEE Std. 1564-2014

3.3.1. The single event indices

3.3.2. The site indices

3.3.3. The system indices

3.4. Voltage sag indices according to IEEE Std. 1564-2014

Figure 3.7. The proposed method for determining voltage sag indices.
The proposed method for determining voltage sag indices in order to evaluate voltage quality in distribution network are implemented by using the proposed method in Chapter 2. The algorithm is shown in Figure 3.7. The inputs are database of voltage disturbance events which were gathered from different sources such as the power quality monitoring, fault record equipment, protection relay, intelligent measurement equipment, etc. The database is voltage signals sampled from events occurred at monitoring points.

3.5. Calculating voltage sag indices

3.5.1. Determining the single-event indices of voltage waveforms

The author uses voltage waveforms occurred in three-phase power systems to evaluate the proposed method in determining voltage sag characteristics and indices. The database of voltage waveforms are used from the sample sources in the power quality analysis program PQDiffractor [80]. From the sample database available in the program, the author chooses 3 voltage sag waveforms as shown in Figure 3.8(a), Figure 3.9(a) and Figure 3.10(a) to calculate voltage indices. Figure 3.8(b), Figure 3.8(b) and Figure 3.10(b) are the results of their RMS voltages. The single-event indices are also determined using the proposed method.

![Figure 3.8. The results of the single-event voltage sag (Sample 1).](image)

Kết quả các chỉ số theo sự kiện:

- Biến độ lõm áp: $U\% = 76.39\%$
- Thời gian tồn tại: $T = 4.9443$ chu kỳ
- Năng lượng mất: $E_{sv} = 3.1340$ s
- Mức độ nghiêm trọng: $S_e = 0.3922$ (p.u)
- Đührung lõm áp: $C_a$
- Điện áp đầu trang: $V = 0.7480$ (p.u)
- Hệ số thuận nghịch: $F = 0.9420$
3.5.2. Application for the tower Dang Minh, HCM city

3.5.2.1. The results of single-event indices

This dissertation uses the real database from events occurred and recorded by power quality monitoring PQube installed at the tower Dang Minh, HCM city. Figure 3.11 shows the results of severity, non-severity voltage sag and other events in July and August, 2015 at the tower Dang Minh.
3.5.2.2. The results of the site indices

![Graph showing SARFI indices]

*Figure 3.12. SARFI\textsubscript{Curve} indices according to type of curve of July, 2015.*

3.6. Conclusion

From the analysis results in this chapter, every type of voltage sag in three-phase power system is characterized by type, magnitude and duration time.

When all events at single monitoring position are determined the characteristics and indices of the single-event then the site indices are also identified to evaluate voltage quality at the position. The site indices are used in this dissertation including: \textit{SARFI}\textsubscript{X}, \textit{SARFI}\textsubscript{ITIC}, \textit{SARFI}\textsubscript{SEMI}, voltage sag table, energy of voltage sags and severity of voltage sags.

In this chapter, a calculation program indices and statistic the voltage sag events are build-up in Matlab software. Applying the method which is proposed in Chapter 2 to calculate voltage sags and compare with the standard method according to IEEE Std. 1564-2014.

In order to evaluate the proposed method, a database of voltage sag waveforms are extracted from the power quality analysis program PQDiffractor to evaluate the proposed method. In addition, voltage sag events recorded at the tower Dang Minh, HCM city are also used to calculate the voltage sag indices.
CHAPTER 4. VOLTAGE SAG/SWELL MITIGATION FOR SENSITIVE LOADS IN DISTRIBUTION NETWORK

4.1. Introduction

4.2. The main characteristics of voltage sag

4.2.1. Voltage sag magnitude

Let we consider a 22 kV power system as shown in Figure 4.4. The influence of short-circuit power of grid source to voltage sag magnitude as shown in Figure 4.5.

![Figure 4.5. The influence of short-circuit power to magnitude.](image)

![Figure 4.6. The influence of cross area of power lines to magnitude.](image)

4.2.2. Time duration

4.2.3. Phase angle jump

4.3. The impacts of voltage sags

4.4. Voltage sag/swell mitigation methods

4.5. Voltage sag/swell mitigation using DVR

4.6. The proposed method of voltage sag impact study to the sensitive loads

The impact evaluation of voltage sag to sensitive loads in distribution network often implement by using physical models [12]. However the evaluation by using that method needs to have a real voltage sag source equipment, high cost and difficult implemention.
Therefore in this dissertation, the author proposes a method based on function modules in Matlab/Simulink software to determine characteristics of voltage sag and its effects to sensitive loads in distribution networks. The algorithm of the proposed method is shown in Figure 4.20.

![Figure 4.20. The proposed method for studying voltage sag impacts to sensitive loads.]

4.6.1. Voltage sag source module

4.6.2. Voltage sag characteristic determination module

4.6.3. Voltage sag impacts to AC-DC-AC conversion

+ Object description: Figure 4.24 shows the study model of voltage sag impacts to AC-DC-AC conversion [76].
The results: Voltage sag effects to the operation of AC-DC-AC conversion if it make the DC voltage of the conversion decreases below the minimum DC voltage ($U_{DC_{\text{min}}}$) then the conversion will be switch off the grid [14]. However each type of voltage sag will have the different impacts to the operation of AC-DC-AC conversion. Let’s suppose that $V=0.5$ (p.u), the impacts of voltage sag type A and C to the AC-DC-AC conversion operation respectively in Figure 4.25 and Figure 4.26.

Figure 4.25. The impacts of voltage sag type A to AC-DC-AC.

Figure 4.26. The impacts of voltage sag type C to AC-DC-AC.

The dependence of DC minimum voltage ($U_{DC_{\text{min}}}$) at output of the conversion depend on the characteristic voltage ($V$) and duration time of voltage sag types. This is shown in Figure 4.28 to Figure 4.34 respectively voltage sag types A, B, ..., G.
4.7. DVR application to mitigate voltage sag/swell

4.7.1. The proposed configuration of DVR

The configuration of DVR is used in this section is shown in Figure 4.35.

![DVR Configuration Diagram](image)

Figure 4.35. The configuration of DVR.

4.7.2. Control system of DVR

The block diagram of DVR control system uses the d-q-0 transform method shown in Figure 4.36.
Figure 4.36. The DVR control algorithm base on the d-q-0 transform.

4.7.3. The results of DVR to mitigate voltage sag/swell

The DVR model proposed in this study is modeled in Matlab/Simulink shown in Figure 4.37.

Figure 4.37. The DVR model to mitigate voltage sag/swell.

4.7.3.1. Voltage sag
Lets three-phase voltage sag has $U_{\text{sag}} = 0.5 \text{ pu}$ occurs at source side beginning at $t_s = 0.2 \text{ s}$ and ending at $t_e = 0.4 \text{ s}$. Three phase source voltages decrease to 0.5 p.u in duration 0.2 – 0.4 s shown in Figure 4.38(a). When voltage sag is detected, DVR will create compensation voltages series to source voltages with waveforms in Figure 4.38(b) to compensate voltage sag caused.

The single-phase voltage sag occurs in source side is considered in Figure 4.39. In this case, phase A occurs sag in duration 0.2-0.4 s shown in Figure 3.39(a). When voltage sag is detected the DVR will create compensation voltage on phase A shown in Figure 4.39(b). The results of load voltage is remained at nominal level in that duration as shown in Figure 4.39(c). Therefore the load is not effected by voltage sag at source side.

4.7.3.2. Voltage swell

Lets consider three-phase voltage swell with $U_{\text{swell}} = 1.5 \text{ p.u}$ occurs in source side beginning at $t_s = 0.2 \text{ s}$ and ending at $t_e = 0.4 \text{ s}$. 

Figure 4.38. Three-phase sag.

Figure 4.39. Single phase sag.
Three phase voltage at source side will increase to 1.5 p.u in that duration as shown in Figure 4.39(a). When voltage swell is detected, DVR will create the compensation voltage as waveform in Figure 4.41(b) to compensate voltage swell. The result of load voltage is remained at nominal level 1.0 p.u as shown in Figure 4.41(c) in that duration. Therefore the load is not effected by voltage swell in source side.

The single phase voltage swell at source side is considered as Figure 4.42. In this case, phase A is swell in duration 0.2 – 0.4 s as Figure 4.42(a). When voltage swell is detected then DVR will create voltage to compensate on phase A as shown in Figure 4.42(b). The results of load voltage is remained at nominal level as shown in Figure 4.42(c). Therefore load is not effected by swell in source side.

**Figure 4.41. Three-phase swell.**  
**Figure 4.42. The single-phase swell.**

### 4.8. Conclusion

This chapter proposed a method to study voltage sag impacts to sensitive loads in distribution networks based on modules and
function blocks in Matlab/Simulink software contribute in the research, evaluation of voltage sag impacts to the operation of sensitive loads in distribution networks.

Application of the proposed method to research voltage sag impacts to AC-DC-AC conversion operation. The simulation results are based Matlab/Simulink model which shows voltage sag events occurs in short-time duration but they can effect to the operation of the sensitive equipment.

Application of DVR to mitigate voltage sag/swell for sensitive loads in distribution networks. The configuration and control method based on the d-q-0 transform are proposed and modeled in Matlab/Simulink. Three-phase and single-phase voltage sag/swell are studied in this work to evaluate the proposed method.

CONCLUSION AND RECOMMENDATION

1. Conclusion

Based on research purposes, dissertation entitled “A study of voltage disturbances in distribution networks” has novel contributions in the field of voltage disturbance classification and mitigation research in distribution networks as following:

1. This dissertation proposes a voltage disturbance classification method in distribution network based on discrete wavelet transform (DWT) and adaptive neural network (ADALINE). The proposed method uses DWT to analysis the input voltage signal to J levels which is determined according to the sampling frequency of the input voltage signal. Therefore this transform will create an approximation coefficient at level J (A_j) which only contains the fundamental frequency. Then the detail coefficient (D_1) is very
sensitive with the changes in the input signal, therefore it is used to detect the beginning and ending time of the voltage disturbance.

2. Application of the proposed voltage disturbance classification method to identify voltage sag indices according to the IEEE Std. 1564-2014 standard for determining voltage sag indices including the single-event, the site and the system indices. Then the indices are used to evaluate the severity of each voltage sag event and each monitoring site for sensitive loads in distribution network.

3. A method to analysis voltage disturbance effects to sensitive loads especially voltage sag in distribution network. This method is used to analysis the effects of different voltage sag types from mathematic model, electromagnetic simulation software or real waveforms recorded by power quality monitoring equipment.

4. The control system of dynamic voltage restorer (DVR) is proposed to mitigate voltage sag/swell effects for loads which are sensitive to voltage disturbances especially voltage sag/swell in distribution network based on a-b-c to d-q-0 transform for voltage signal at source side.

2. Recommendation

Based on the research results of this dissertation, some tendencies in the future are proposed as follows:

1. **Researching voltage disturbance detection and classification with data connection through Internet.**

2. **Constructing voltage disturbance monitoring system at control centers in order to collect, analysis and evaluate indices on distribution network.**

3. **Selecting DVR location and capacity installed on distribution network to decrease harmfulness of voltage sag/swell.**
PUBLICATIONS OF THE AUTHOR


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