



Cairo University

A TRAVELLING WAVES-BASED FAULT LOCATION SCHEME FOR MULTI-TAPPED OVERHEAD DISTRIBUTION SYSTEMS

By

Mahmoud Abd EL Fattah Mahmoud

A thesis submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

In

Electrical Power and Machines Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2017

A TRAVELLING WAVES-BASED FAULT LOCATION SCHEME FOR MULTI-TAPPED OVERHEAD DISTRIBUTION SYSTEMS

By

Mahmoud Abd EL Fattah Mahmoud

A thesis submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

In

Electrical Power and Machines Engineering

Under supervision of

Prof. Dr. Mahmoud Ibrahim

Gilany

Electrical Power and Machines Department

Faculty of Engineering,

Cairo University

Associate Prof. Dr. Doaa Khalil

Ibrahim

Electrical Power and Machines Department

Faculty of Engineering,

Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2017

TRAVELLING WAVES-BASED FAULT LOCATION SCHEME FOR MULTI-TAPPED OVERHEAD DISTRIBUTION SYSTEMS

By

Mahmoud Abd EL Fattah Mahmoud

A thesis submitted to the

Faculty of Engineering at Cairo University

In Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

In

Electrical Power and Machines Engineering

Approved by the

Examining Committee:

Prof. Dr. Mahmoud Ibrahim Gilany

Thesis main advisor

Associate Prof. Dr. Doaa Khalil Ibrahim

Member

Prof. Dr. Essam El-Din Abou El-Zahab

Internal Examiner

Prof. Dr. Nabil Hassan Mahmoud Abbasy

External Examiner

Faculty of Engineering, Alexandria University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2017

Engineer: Mahmoud Abd EL Fattah Mahmoud
Date of Birth: 24 / 11 / 1989
Nationality: Egyptian
E-mail: Mahmoud231@hotmail.com
Phone. : +201224763672
Address: Dokki – Giza – Egypt
Registration Date: 01 / 10 / 2012
Awarding Date: / / 2017
Degree: Master of Science
Department: Electrical Power and Machines Engineering



Supervisors: Prof. Dr. Mahmoud Ibrahim Gilany
Associate Prof. Dr. Doaa Khalil Ibrahim

Examiners: Prof. Dr. Mahmoud Ibrahim Gilany
Associate Prof. Dr. Doaa Khalil Ibrahim
Prof. Dr. Essam El-Din Abou El-Zahab
Prof. Dr. Nabil Hassan Mahmoud Abbasy
(Faculty of Engineering, Alexandria University)

TITLE OF THESIS: A TRAVELLING WAVES-BASED FAULT LOCATION SCHEME FOR MULTI-TAPPED OVERHEAD DISTRIBUTION SYSTEMS

Key Words: Characteristic Frequency, Distribution Network, Fast Fourier Transform (FFT), Fault Location, Clarke transformation, Travelling Waves.

Summary:

In this thesis, a digital protection technique is implemented for MV overhead distribution network using voltage signals only at MV substation. The proposed scheme utilize an automation system which depends on installing fault passage indicators at strategic points to identify the faulted section. The exact fault distance is determined through two phases. The first one is representing the network by a set of equations. Each equation belongs to specific path and fault type; as a relation between the distance between substation and fault point and the generated frequency observed at the substation. The other phase is the substituting by the obtained frequency in the appropriate equation.

The proposed scheme is extensively examined on a typical 22 kV distribution network. Different faults are simulated at different positions on main feeder and laterals to evaluate the accuracy of the proposed algorithm not only for various fault resistance, inception angle, and load level but also in case of changing in network topology. The final results demonstrate accurate fault location estimation for distribution systems.

ACKNOWLEDGMENTS

First of all, thanks to Allah who supported and strengthened me in all of my life and in completing my studies for the Master of Science (M.Sc.) degree.

I would like deeply to express my thanks and gratitude to my supervisors; Prof. Dr. Mahmoud Gilany and Associate Prof. Dr. Doaa Khalil Ibrahim, Electrical Power and Machines Department, Faculty of Engineering, Cairo University for their faithful supervision, enormous efforts, and their great patience during the period of the research.

Finally, I would like to thank my family for their great inspiration, kind support, and continuous encouragement.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	i
TABLE OF CONTENTS	ii
LIST OF TABLES	v
LIST OF FIGURES	vi
LIST OF SYMBOLS AND ABBREVIATIONS	x
ABSTRACT	xv
CHAPTER (1): INTRODUCTION.....	1
1.1. Medium Voltage Distribution Networks	1
1.2. Distribution Network Configuration	1
1.2.1. The components of overhead radial distribution network	1
1.3. Protection in Distribution networks.....	3
1.3.1. Protection equipment in distribution network	4
1.3.1.1. Protective relays	4
1.3.1.2. Circuit breakers	4
1.3.1.3. Reclosers.....	4
1.3.1.4. Fuses	4
1.3.1.5. Sectionalizer	4
1.3.2. Fault location techniques	5
1.3.3. Protective relays versus fault locators	6
1.4. Present Fault Location Techniques.....	7
1.5. Research Efforts for Fault Location in Distribution Systems.....	8
1.6. Problem Statement.....	8
1.7. Thesis Objectives.....	10
1.8. Thesis Organization.....	10
CHAPTER (2): LITERATURE REVIEW ON FAULT LOCATION TECHNIQUES IN DISTRIBUTION SYSTEMS	12
2.1. Faults Nature and Types.....	12
2.1.1. Faults causes	12
2.1.2. Faults types.....	13
2.2. Benefits of Fault Location Estimation.....	14
2.2.1. Time and effort saving.....	14
2.2.2. Improving the system availability	15
2.2.3. Assisting future maintenance plans	15
2.2.4. Economic factor.....	15
2.3. Literature Survey for Fault Location Algorithms.....	15
2.3.1. Impedance-Based methods	15

2.3.2.	Travelling wave-Based methods	17
2.3.2.1.	Type A locators	18
2.3.2.2.	Type D locators	19
2.3.2.3.	Type E locators.....	20
2.3.3.	Recent travelling wave techniques	21
2.3.3.1.	Multi-end fault location algorithms	21
2.3.3.2.	Double-end fault location algorithms	24
2.3.3.3.	Single-end fault location algorithms.....	27
2.3.4.	Comparison of the main characteristics of recent travelling wave techniques	33
CHAPTER (3): BASIC CONCEPTS TO IMPLEMENT THE PROPOSED SCHEME.....		35
3.1.	Outlines of the Proposed Methodology	35
3.2.	Basic Concepts Related to the Proposed Scheme.....	36
3.2.1.	Distribution automation system.....	36
3.2.2.	Travelling waves on distribution line	40
3.2.2.1.	The line equations.....	40
3.2.2.2.	Propagation speed.....	42
3.2.2.3.	Reflection and refraction of travelling waves.....	43
3.2.3.	Phase and modal transformation.....	45
3.2.4.	Fourier analysis	46
3.2.4.1.	Discrete Fourier Transform (DFT)	50
3.2.4.2.	Fast Fourier Transform (FFT)	51
3.2.5.	Characteristic path frequency	55
3.3.	General Considerations in Tested Network Simulation and Proposed Scheme Calculations	57
3.3.1.	Transformer modeling	57
3.3.2.	Line modeling.....	58
3.3.3.	Curve fitting.....	59
CHAPTER (4): IMPLEMENTING THE PROPOSED FAULT LOCATION SCHEME AND TESTED CASE STUDY.....		61
4.1.	The Proposed Scheme Description.....	61
4.2.	Tested Case Study Description.....	65
4.3.	Implementing Calculations of the Proposed Scheme	67
4.3.1.	Distribution of FPI devices.....	67
4.3.2.	Generating equations	68
4.3.2.1.	Filter implementation	68
4.3.2.2.	Frequency resolution implementation	71
CHAPTER (5): EVALUATING THE PERFORMANCE OF THE PROPOSED FAULT LOCATION SCHEME AND ACHIEVED RESULTS		80

5.1.	The Effect of Fault Resistance	80
5.2.	The Effect of Inception Angles	82
5.3.	Various Load Levels.....	84
5.4.	Change in Network Topology	85
5.5.	Change in Load Nature.....	86
5.6.	Scheme Response for Laterals Faults.....	87
CHAPTER (6): CONCLUSIONS AND SUGGESTED FUTURE WORK		
	89
6.1.	Conclusions	89
6.2.	Main Features of the Proposed Scheme	90
6.3.	Limitation of the Proposed Scheme.....	90
6.4.	Suggestions for Future Work.....	90
REFERENCES		91
PUBLISHED WORK		96
APPENDIX (A): MATLAB CALCULATION M-FILE		97
APPENDIX (B): EQUATIONS REPRESENT THE LATERALS OF THE TESTED NETWORK		98

LIST OF TABLES

Table 2.1: Occurrence percentage of fault types	13
Table 2.2: Main characteristics of the ten compared methods [38].....	17
Table 2.3: Main characteristics of travelling wave fault location techniques ..	34
Table 3.1: The response of the implemented FPI [45]	40
Table 3.2: Comparison between DFT and FFT algorithms [62]	54
Table 3.3: Constant values of SATTRAFO transformer model	57
Table 4.1: Clarke components used for each fault type.....	62
Table 4.2: Electrical parameters of the network	66
Table 4.3: Conductor parameter	66
Table 4.4: Loading data	66
Table 4.5: Transformers parameters	67
Table 4.6: Calculated transformers modeling data	67
Table 5.1: Locating SLG faults along main feeder at various value of fault resistance	81
Table 5.2: Locating DLG faults along main feeder at various value of fault resistance	82
Table 5.3: Locating SLG faults along main feeder at various inception angle	83
Table 5.4: Locating DLG faults along main feeder at various inception angle	84
Table 5.5: Locating SLG faults along main feeder at various load level	85
Table 5.6: Locating DLG faults along main feeder at various load level.....	85
Table 5.7: Locating faults along main feeder when the lateral 5 is disconnected	86
Table 5.8: New loading data at 0.8 power factor and 50 % of load 3	86
Table 5.9: Locating faults along main feeder when loads nature is changed ...	86
Table 5.10: Locating SLG faults at different laterals for different fault conditions	87
Table 5.11: Locating DLG faults at different laterals for different fault conditions	88

LIST OF FIGURES

Figure 1.1: Power system main components [1].....	1
Figure 1.2: 11 kV real Egyptian distribution rural network	2
Figure 1.3: 24.4 kV IEEE distribution 34 nodes test feeder	3
Figure 1.4: Pole transformer type	3
Figure 1.5: Typical 22 kV distribution network	9
Figure 2.1: Accumulated water on insulator surface	12
Figure 2.2: Fault types	14
Figure 2.3: Classification of fault location methods	15
Figure 2.4: Type A fault locator and its lattice diagram	19
Figure 2.5: Type D fault locator and its lattice diagram	19
Figure 2.6: Type E fault locator and its lattice diagram	20
Figure 2.7: Block diagram of an observer unit	22
Figure 2.8: Flowchart of the technique introduced in [16]	22
Figure 2.9: Block diagram of the technique introduced in [17].....	23
Figure 2.10: Block diagram of the technique proposed in [25]	24
Figure 2.11: Block diagram of the fault locator used in [19]	25
Figure 2.12: Lattice diagram of the technique proposed in [19]	26
Figure 2.13: Locator output at busbar R for the lattice diagram of the technique introduced in [19].....	26
Figure 2.14: Locator output at busbar S for the lattice diagram of the technique introduced in [19].....	26
Figure 2.15: Flowchart of the proposed technique in [20]	27
Figure 2.16: I_A+I_C module current travelling wave in [23]	28
Figure 2.17: Discrete wavelet transform results for [23].....	29
Figure 2.18: Flowchart of the technique proposed in [26]	30
Figure 2.19: Arial mode 1 of voltage signal during a fault.....	31
Figure 2.20: Generated mother wavelet from voltage signal in the proposed method of [27].....	31

Figure 2.21: Improved estimation of the characteristic frequency in [28] (dotted line is the estimated frequency in step 1).....	32
Figure 3.1: The block diagram of the essential concepts related to the proposed scheme.....	35
Figure 3.2: The structure of the Chapter	36
Figure 3.3: The installed FPI on an overhead feeder	37
Figure 3.4: The installed FPI at strategic points on overhead feeders	38
Figure 3.5: Symantec diagram of distribution automation system	38
Figure 3.6: Response of installed FPIs during faults	39
Figure 3.7: The response of the implemented FPI [45]	39
Figure 3.8: Single phase line model.....	41
Figure 3.9: Reflection and refraction of travelling wave at a transition point..	44
Figure 3.10: Representation of a sine wave in time and frequency domain.....	46
Figure 3.11: Composing a nonsinusoidal signal by summing sinusoidals	47
Figure 3.12: Frequency spectrum of the nonsinusoidal signal of Figure 3.11 .	47
Figure 3.13: Continuous periodic waveform	48
Figure 3.14: Continuous aperiodic waveform	48
Figure 3.15: Discrete periodic waveform	48
Figure 3.16: Discrete aperiodic waveform.....	48
Figure 3.17: The general block diagram of DFT analyzer	49
Figure 3.18: Aliased Fourier transform of a waveform sampled at an inappropriate rate	49
Figure 3.19: Constructed signal of a waveform sampled at an appropriate rate	50
Figure 3.20: The frequency resolution of the frequency spectrum.....	51
Figure 3.21: The basic concept of FFT algorithm	52
Figure 3.22: Decomposing of 8-point signal to 8 signals	52
Figure 3.23: The basic butterfly computation [61]	53
Figure 3.24: Three stages in the computation of an N = 8-point DFT [61].....	53
Figure 3.25: Eight-point decimation FFT algorithm [62].....	54

Figure 3.26: Comparison between number of operations for DFT and FFT algorithms [56]	55
Figure 3.27: Tested distribution network shows some paths for generated travelling wave due to a fault at the end of line 10.....	56
Figure 3.28: The difference between interpolation and curve fitting	60
Figure 3.29: Straight and parabolic lines approximation.....	60
Figure 4.1: Flowchart for generating network equations during training phase	63
Figure 4.2: Flowchart of applying the proposed scheme in the operating phase	64
Figure 4.3: Tested distribution network to validate the proposed scheme	65
Figure 4.4: Tower configuration	66
Figure 4.5: Distribution of FPI devices on the tested network	68
Figure 4.6: 0 mode of voltage signals before using a filter	69
Figure 4.7: Frequency spectrum before using a filter	69
Figure 4.8: 0 mode of voltage signals after using a filter	70
Figure 4.9: Frequency spectrum after using a filter	70
Figure 4.10: Frequency spectrum for DLG fault at 9.7 km on main feeder at $\Delta F = 122$ Hz/bin	72
Figure 4.11: Frequency spectrum for DLG fault at 9.8 km on main feeder at $\Delta F = 122$ Hz/bin	72
Figure 4.12: Frequency spectrum for DLG fault at 9.9 km on main feeder at $\Delta F = 122$ Hz/bin	73
Figure 4.13: Frequency spectrum for DLG fault at 9.7 km on main feeder at $\Delta F = 61$ Hz/bin	73
Figure 4.14: Frequency spectrum for DLG fault at 9.8 km on main feeder at $\Delta F = 61$ Hz/bin	74
Figure 4.15: Frequency spectrum for DLG fault at 9.9 km on main feeder at $\Delta F = 61$ Hz/bin	74
Figure 4.16: Frequency spectrum for DLG fault at 2 km on main feeder	75
Figure 4.17: Frequency spectrum for DLG fault at 3.5 km on main feeder	75
Figure 4.18: Frequency spectrum for DLG fault at 5 km on main feeder	76

Figure 4.19: Frequency spectrum for DLG fault at 8 km on main feeder	76
Figure 4.20: Frequency spectrum for DLG fault at 10 km on main feeder	77
Figure 4.21: Relation between fault distance along the main feeder and frequency in case of SLG faults.....	78
Figure 4.22: Relation between fault distance along the main feeder and frequency in case of DLG faults	79

LIST OF SYMBOLS AND ABBREVIATIONS

• Symbols

C	:	Capacitance of line per unit length.
F_0	:	Flux (Wb-turn) at steady state.
G	:	Conductance of line per unit length.
I_0	:	Current through magnetizing branch at steady state in (A).
I_m	:	Modal current.
L	:	Inductance of line per unit length.
L_p	:	Transformer inductance in primary winding in (mH).
L_{sec}	:	Inductance of the secondary side of SATTRAFO model.
R	:	Resistance of line per unit length.
R_m	:	Resistance in magnetizing branch in (ohm).
R_p	:	Resistance in primary winding in (ohm).
R_{sec}	:	Resistance of the secondary side of SATTRAFO model.
t_{r1}	:	Arrival instant of V_{r1} at busbar R.
t_{r2}	:	Detected instant of V_{r2} at busbar R.
t_{s1}	:	Arrival instant of V_{s1} at busbar S.
t_{s2}	:	Detected instant of V_{s2} at busbar R.
V_m	:	Modal voltage.
V_{prim}	:	Peak voltage of the primary side of SATTRAFO model.
V_{r1}	:	Generated travelling wave propagates towards busbar R.
V_{r2}	:	Reflection travelling wave of V_{r1} at fault point.
V_{s1}	:	Generated travelling wave propagates towards busbar S.
V_{s2}	:	Reflection of V_{r1} at remote busbar R.
V_{sec}	:	Peak voltage of the secondary side of SATTRAFO model.
Z_c	:	Surge impedance.
Δt_{1-0}	:	Time difference between the arrival time of zero mode and aerial mode.
Δt_f	:	Arrival time difference between substation detector and the detector at terminal of the faulted line.
Δt_m	:	Time differences between local maximum of signal coefficients.

Δt_{mp}	:	Arrival time difference between two the measuring points.
F_n	:	Nyquist frequency.
F_s	:	Sampling frequency.
V_r	:	Reflected wave.
V_{rp}	:	Root mean square voltage of the primary side of the transformer.
V_{rs}	:	Root mean square voltage of the secondary side of the transformer.
Z_T	:	Transformer impedance.
Z_{c2} & Z_{c1}	:	Characteristic impedances on the either side of transition point.
f_{im}	:	Improved value of characteristic path frequencies related to fault point.
f_p	:	Characteristic frequency corresponding to specific fault distance.
l_b	:	Distance between the two busbars S and R.
l_f	:	Distance between the substation and the end of the faulted line.
l_m	:	Distance between two measuring points.
n_p	:	Number of times required for a travelling wave to propagate along path (p) before get again the same polarity.
t_1	:	Instant that the first generated wave due to fault point is observed at locator in second.
t_2	:	Instant that the first reflected wave from the fault point is observed at locator in second.
t_A	:	Instant that the first generated wave is observed at terminal A in second.
t_B	:	Instant that the first generated wave is observed at terminal B in second.
t_C	:	Instant that the wave is generated by closing the circuit breaker in second.
t_R	:	Instant that the reflected wave is observed at terminal A in second.
v_0	:	Velocity of the zero mode.
v_1	:	Velocity of the first aerial mode.
v_τ	:	Transmitted wave.
ρ_{ri}	:	Current refection coefficient.
ρ_{rv}	:	Voltage refection coefficient.
\emptyset	:	Generated magnetic flux.