

## TABLE OF CONTENTS

	<b>Page</b>
ACKNOWLEDGEMENT	iii
ABSTRACT (THAI)	iv
ABSTRACT	vi
LIST OF TABLES	ix
LIST OF ILLUSTRATIONS	x
<b>CHAPTER 1 Introduction</b>	<b>1</b>
1.1 Motivation	1
1.2 Harmonics	1
1.3 Literature Review	3
1.4 Purposes of the Study	6
1.5 Education/Application Advantages	6
1.6 Research Scope	6
1.7 Research Methodologies	6
1.8 Research Contributions	7
1.9 Thesis Organization	7
<b>CHAPTER 2 State Estimation and Harmonic State Estimation of Power System</b>	<b>8</b>
2.1 State Estimation	8
2.2 Harmonic State Estimation	12
2.2.1 Harmonic Measurement-State Variable Models	15
2.2.2 Harmonic State Estimation Algorithm	17
2.2.2.1 Measurements Vector; $Z(h)$	17
2.2.2.2 State Vector to be Estimated; $X(h)$	17
2.2.2.3 Measurement Noise (Uncertainty); $E(h)$	19
2.2.2.4 Gain or Measurement Matrix; $H(h)$	19
2.2.3 Solving the Harmonic State Estimation	20

2.2.3.1 Normal Equation	20
2.2.3.2 Singular Value Decomposition (SVD)	21
2.2.4 Observability Analysis	22
2.2.5 Load and Harmonic Source Identification	24
2.3 Bad Data Analysis	27
<b>CHAPTER 3 An Optimal Measurement Placement</b>	<b>28</b>
3.1 Introduction	28
3.2 Review of Measurement Placement Algorithms	29
3.2.1 Minimum Variance Approach	29
3.2.2 Modified Symbolic Observability	29
3.2.3 Genetic Algorithms	30
3.3 Proposed Measurement Placement Algorithm	31
<b>CHAPTER 4 Test Systems and Test Results</b>	<b>35</b>
4.1. Test Systems	35
4.1.1 Test System I: The New Zealand Test System	35
4.1.2 Test System II: The IEEE 14-Bus Test System	36
4.2 Test Results	38
<b>CHAPTER 5 Conclusions and Further Research</b>	<b>57</b>
5.1 Conclusions	57
5.2 Further Research	58
<b>REFERENCES</b>	<b>59</b>
<b>APPENDICES</b>	<b>62</b>
APPENDIX A Parameters of the IEEE 14-bus Test System	63
APPENDIX B Three Phase Transmission Line Parameters (TL) Program	74
APPENDIX C M-Files of the Proposed Measurement Placement Algorithm	79
APPENDIX D Singular Value Decomposition (SVD)	82
APPENDIX E Publications	88

## LIST OF TABLES

Table	Page
4.1 Measurement placement of the New Zealand test system	38
4.2 Measurement placement of the IEEE 14-bus test system	39
4.3 Fully measurement placement of the New Zealand test system	42
4.4 Fully measurement placement in dominant site of the IEEE 14-bus test system	42
4.5 Performance of the proposed algorithm to reduce the condition number	46
4.6 Validation of sequential elimination in the proposed algorithm	49
4.7 Measurement placement in case of the measurement matrix error using the 5 <sup>th</sup> harmonic order of Figure 4.7 of the IEEE 14-bus test system	50
A.1 Line parameters at fundamental frequency comparing between data from the IEEE 14-bus test system and data modeling from TL program	63
A.2 Line parameter at each harmonic frequency from TL program	64
A.3 Node-line incidence matrix ( $C_{NL}$ )	66
A.4 Line-branch incidence matrix ( $C_{LB}$ )	67
A.5 Non-zero elements of primitive admittance matrix ( $Y_{BB}$ ) for the 5 <sup>th</sup> harmonic	68
A.6 Node-node admittance matrix ( $Y_{NN}$ ) for the 5 <sup>th</sup> harmonic	69
A.7 Line-node admittance matrix ( $Y_{LN}$ ) for the 5 <sup>th</sup> harmonic	70
A.8 Harmonic source spectrum	72
A.9 The physical geometry of the IEEE 14-bus test system using TL program	72
A.10 Conductor types	73

## LIST OF ILLUSTRATIONS

Figure	Page
2.1 Illustration of SCADA system	9
2.2 A Framework for HSE	13
2.3 HSE and harmonic power flow	13
2.4 System-wide harmonic state estimation	14
2.5 Oriented graph of a power system	15
2.6 The solution process of HSE	18
2.7 Norton equivalent circuit for suspicious harmonic sources	25
2.8 Spectrum of harmonic current for an idealized six-pulse converter	26
2.9 Spectrum of harmonic current for an idealized twelve-pulse converter	26
3.1 Flowchart of proposed measurement placement algorithm	33
4.1 The New Zealand test system	36
4.2 The IEEE 14-bus test system	37
4.3 Example of measurement placement of the New Zealand test system	40
4.4 Example of measurement placement of the IEEE 14-bus test system	41
4.5 Fully measurement placement at Invercargill of the New Zealand test system	43
4.6 Reduced measurement point from Figure 4.5 using the proposed algorithm	44
4.7 Fully measurement placement at 3 sites of the IEEE14-bus test system	45
4.8 Reduced measurement point from Figure 4.7 using the proposed algorithm	45
4.9 The condition number at each iteration using sequential elimination of the New Zealand test system	47
4.10 The condition number at each iteration using sequential elimination of the IEEE 14-bus test system	48
4.11 Node harmonic voltage magnitude of the New Zealand test system	51
4.12 Node harmonic voltage angle of the New Zealand test system	51
4.13 Node harmonic injection current magnitude of the New Zealand test system	52
4.14 Node harmonic injection current angle of the New Zealand test system	52

<b>Figure</b>	<b>Page</b>
4.15 Line harmonic current magnitude of the New Zealand test system	53
4.16 Line harmonic current angle of the New Zealand test system	53
4.17 Node harmonic voltage magnitude of the IEEE 14-bus test system	54
4.18 Node harmonic voltage angle of the IEEE 14-bus test system	54
4.19 Node harmonic injection current magnitude of the IEEE 14-bus test system	55
4.20 Node harmonic injection current angle of the IEEE 14-bus test system	55
4.21 Line harmonic current magnitude of the IEEE 14-bus test system	56
4.22 Line harmonic current angle of the IEEE 14-bus test system	56
B.1 Example of tower for TL program	75
B.2 Image of conductor for TL program	76
B.3 The single phase $\Pi$ equivalent circuit for TL program	78