HARMONIC REDUCTION OF A SINGLE-PHASE MULTILEVEL INVERTER USING GENETIC ALGORITHM AND PARTICLE SWARM OPTIMIZATION

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UNIVERSITI TUN HUSSEIN ONN MALAYSIA
HARMONIC REDUCTION OF A SINGLE-PHASE MULTILEVEL INVERTER USING GENETIC ALGORITHM AND PARTICLE SWARM OPTIMIZATION

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A thesis submitted in partial fulfilment of the requirements for the award of the Degree of Master of Electrical Engineering

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I dedicate this thesis to my beloved parents, supervisor, sisters, family and friends.
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My deepest appreciation goes to my family, especially to my mother for her unfailing love and prayers which have been supported me through the years. In addition, I would like to thank my sister for her encouragement and support throughout the years.
Inverter play important role in power system especially with it capability on reducing system size and increase efficient. Recent research trend of power electronics system are focusing on multilevel inverter topic in optimization on voltage output, reduce total harmonics distortion, modulation technique and switching configuration. Standalone application multilevel inverter is high focused due to the rise of renewable energy policy all around the world. Hence, this research emphasis on identify best topology of multilevel inverter and optimize it among the diode-clamped, capacitor clamped and cascaded H-bridge multilevel inverter to be used for standalone application in term of total harmonics distortion and voltage boosting capability. The first part of research that is identify best topology multilevel inverter is applying sinusoidal pulse width modulation technique. The result shown cascade H-bridge give the best output in both total harmonics distortion (9.27%) and fundamental component voltage (240 V_{rms}). The research proceed with optimization with fundamental switching frequency method that is optimized harmonic stepped waveform modulation method. The selective harmonics elimination calculation have adapt with genetic algorithm and particle swarm optimization in order to speed up the calculation. Both bio-inspired algorithm is compared in term of total harmonic distortion and selected harmonics elimination for both equal and unequal sources. In overall result shown both algorithm have high accuracy in solving the non-linear equation. However, genetic algorithm shown better output quality in term of selected harmonics elimination where overall no exceeding 0.4%. Particle swarm optimization shows strength in finding best total harmonics distortion where in 7-level cascaded H-bridge multilevel inverter (m=0.8) show 6.8% only as compared to genetic algorithm. Simulation for 3-level, 5-level and 7-level for each multilevel inverter at different circumferences had been done in this research. The result draw out a conclusion where the possibility of having a filterless high efficient invert can be achieve.
ABSTRAK

Inverter memainkan peranan penting dalam sistem kuasa terutamanya dengan keupayaan mengurangkan saiz sistem dan meningkatkan efisien. Kajian terhadap elektronik kuasa sistem amat giat dalam kategori optimisme kualiti voltan output, mengurangkan jumlah herotan harmonik, teknik modulasi dan konfigurasi suis. Aplikasi inverter berdikari difokuskan dengan galakan penggunaan tenaga boleh diperbaharui di seluruh dunia. Oleh itu, kajian ini fokus kepada mengenal pasti konfigurasi suis inverter yang paling sesuai untuk aplikasi inverter berdikari dari diode clamped, capacitor clamped dan cascaded H-bridge inverter bertingkap. Kajian mula dengan simulasi ketiga tiga inverter dengan mengaplikasi teknik sinusodal pusle width modulation. Keputusan menujukan bahawa cascaded H-bridge inverter merupakan terbaik berbanding dengan yang lain dengan jumlah herotan harmonik (9.27%) dan frekuensi asas komponen voltan (240 Vrms). Kajian diteruskan dengan optimisme cascaded H-bridge inverter dengan teknik optimized harmonic stepped waveform modulasi. Selective harmonics elimination terlibat dengan kalkulus matematik yang rumit. Genetik algoritma dan partikel swarm optimistik diperuntukkan untuk menyelesaikan kalkulus yang rumit. Dalam proses simulasi, genetik dan partikel swarm optimisme dibandingkan satu sama lain. Keputusan menujukan bahawa genetik algoritma menunjukkan superior atas partikel swarm optimistik secara keseluruhan(>0.4%). Tetapi, partikel swarm optimistik menujukan keupayaan mendapat output yang paling rendah jumlah heratan harmonik (6.8%). Semua simulasi dijalankan dengan cara dan spesifikasi berlainan dengan 3-level, 5-level dan 7-level. Kajian in akhir dengan konklusi bahawa filterless inverter mampu direalisasikan.
## CONTENTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE</td>
<td>i</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>vi</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>ivii</td>
</tr>
<tr>
<td>CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS AND SYMBOLS</td>
<td>xxiii</td>
</tr>
</tbody>
</table>

### CHAPTER 1  INTRODUCTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Project background</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Problem statement</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Aim and objectives</td>
<td>4</td>
</tr>
<tr>
<td>1.4</td>
<td>Research scopes</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>Thesis outline</td>
<td>5</td>
</tr>
</tbody>
</table>

### CHAPTER 2  LITERATURE REVIEW
## 2.1 Power electronic system  
2.2 Power converter  
2.3 Voltage source inverter  
2.4 Multilevel inverter  
2.4.1 Diode-Clamped Multilevel Inverter  
2.4.2 Capacitor-Clamped Multilevel Inverter  
2.4.3 Cascaded H-Bridge Multilevel Inverter  
2.5 Total harmonic distortion  
2.6 Modulation technique  
2.6.1 Carrier-based pulse width modulation  
2.6.2 Third harmonics injection pulse width modulation method.  
2.6.3 Space vector pulse width modulation  
2.6.4 Harmonics Based Optimized harmonics stepped waveform modulation  
2.7 Selective harmonics elimination  
2.8 Previous research work on multilevel inverter

### CHAPTER 3 METHODOLOGY

3.1 Proposed multilevel inverter  
3.1.1 Multilevel topologies involved  
3.1.2 Sinusoidal pulse width modulation  
3.1.3 Simulation parameter  
3.2 Multilevel inverter optimization  
3.2.1 Optimized harmonics stepped waveform technique
3.2.2 Fourier series approach voltage output 35
3.2.3 Selective harmonics elimination calculation 40

3.3 Bio-inspired algorithm 42
3.3.1 Genetic algorithm 42
3.3.1 Particle Swarm optimization algorithm 47

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Topologies comparison 49
4.1.1 3-level multilevel inverter 49
4.1.2 5-level multilevel inverter 53
4.1.3 7-level multilevel inverter 55

4.2 Multilevel inverter optimization 58

4.3 Switching signal comparisons 58

4.4 Optimized harmonics stepped waveform (Genetic algorithm) 59
4.4.1 3-level with equal DC sources 59
4.4.2 5-level with equal DC sources 63
4.4.3 7-level with equal DC sources 68
4.4.4 3-level with unequal DC sources 71
4.4.5 5-level with unequal DC sources 75
4.4.6 7-level with unequal DC sources 79

4.5 Optimized harmonics stepped waveform (Particle swarm optimization) 84
4.5.1 3-level with equal DC sources 84
4.5.2 5-level with equal DC sources 89
4.5.3  7-level with equal DC sources  93
4.5.4  3-level with unequal DC sources  97
4.5.5  5-level with unequal DC sources  101
4.5.6  7-level with unequal DC sources  105
4.6  Overall discussion  109

CHAPTER 5  CONCLUSION

5.1  Conclusion  114
5.2  Research contribution  115
5.3  Future work and recomendation  116

PUBLICATIONS  117

REFERENCES  118

APPENDIX A  126
APPENDIX B  129
VITA  130
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>3-level diode clamped multilevel inverter switching configuration</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>3-level capacitor clamped multilevel inverter switching configuration</td>
<td>17</td>
</tr>
<tr>
<td>2.3</td>
<td>Components comparison of multilevel inverter topologies</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>Literature on multilevel inverters</td>
<td>25</td>
</tr>
<tr>
<td>3.1</td>
<td>Simulation parameter</td>
<td>27</td>
</tr>
<tr>
<td>3.1</td>
<td>Particle swarm optimization parameter</td>
<td>47</td>
</tr>
<tr>
<td>4.1</td>
<td>3-level multilevel inverter analysis</td>
<td>53</td>
</tr>
<tr>
<td>4.2</td>
<td>5-level multilevel inverter analysis</td>
<td>56</td>
</tr>
<tr>
<td>4.3</td>
<td>7-level multilevel inverter analysis</td>
<td>58</td>
</tr>
<tr>
<td>4.4</td>
<td>3-level switching angles</td>
<td>60</td>
</tr>
<tr>
<td>4.5</td>
<td>3-level total harmonics distortion with respective modulation index</td>
<td>62</td>
</tr>
<tr>
<td>4.6</td>
<td>5-level switching angles</td>
<td>64</td>
</tr>
<tr>
<td>4.7</td>
<td>5-level total harmonics distortion with respective modulation index</td>
<td>66</td>
</tr>
<tr>
<td>4.8</td>
<td>7-level switching angles</td>
<td>68</td>
</tr>
<tr>
<td>4.9</td>
<td>7-level total harmonics distortion with respective modulation index</td>
<td>70</td>
</tr>
<tr>
<td>4.10</td>
<td>3-level switching angles (unequal)</td>
<td>72</td>
</tr>
</tbody>
</table>
4.11 3-level total harmonics distortion with respective modulation index (unequal) 74
4.12 5-level switching angles (unequal) 76
4.13 5-level total harmonics distortion with respective modulation index (unequal) 78
4.14 7-level switching angles (unequal) 80
4.15 7-level total harmonics distortion with respective modulation index (unequal) 82
4.16 3-level switching angles 85
4.17 3-level total harmonics distortion with respective modulation index 87
4.18 5-level switching angles 89
4.19 5-level total harmonics distortion with respective modulation index 92
4.20 7-level switching angles 94
4.21 7-level total harmonics distortion with respective modulation index 96
4.22 3-level switching angles (unequal) 98
4.23 3-level total harmonics distortion with respective modulation index (unequal) 100
4.24 5-level switching angles (unequal) 102
4.25 5-level total harmonics distortion with respective modulation index (unequal) 104
4.26 7-level switching angles (unequal) 106
4.27 7-level total harmonics distortion with respective modulation
4.28 Comparison of multilevel inverter on total harmonic distortion 111
4.29 Comparison of fundamental frequency voltage 112
4.30 Comparison between SPWM and OSHW method 112
4.31 Comparison between equal and unequal DC sources (Genetic algorithm) 113
4.32 Comparison between equal and unequal DC sources (Particle swarm optimization) 115
LIST OF FIGURES

2.1   Illustrated square wave signal       9
2.2   Illustrated modified square wave signal     9
2.3   Illustrated pure sine wave signal     10
2.4   Voltage source inverter family         11
2.5   3-level diode clamped multilevel inverter topology    14
2.6   3-level capacitor clamped multilevel inverter topology 16
2.7   2-level cascaded H-bridge multilevel inverter topology 18
2.8   Classification of multilevel inverter modulation method 21
3.1   General block diagram of inverter system    27
3.2   Overall work flow chart                  28
3.3   3-level capacitor clamped multilevel inverter topology 29
3.4   3-level diode clamped multilevel inverter topology 30
3.5   3-level Cascade H-bridge multilevel inverter 30
3.6   SPWM phase disposition modulation        31
3.7   Comparison of modulation signal and carrier signal illustration 32
3.8   3-level optimized harmonics stepped waveform topology 34
3.9   n-level cascaded H-bridge multilevel inverter topology 35
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.10</td>
<td>Generalized staircase waveform of 5-level multilevel inverter</td>
<td>36</td>
</tr>
<tr>
<td>3.11</td>
<td>6 level quarter-wave symmetric waveform</td>
<td>38</td>
</tr>
<tr>
<td>3.12</td>
<td>Flow chart of genetic algorithm</td>
<td>43</td>
</tr>
<tr>
<td>3.13</td>
<td>Matlab constraint M-file</td>
<td>44</td>
</tr>
<tr>
<td>3.14</td>
<td>Matlab fitness M-file</td>
<td>45</td>
</tr>
<tr>
<td>3.15</td>
<td>Matlab optimization tool (Genetic Algorithm)</td>
<td>46</td>
</tr>
<tr>
<td>3.16</td>
<td>Particle swarm optimization flow chart</td>
<td>48</td>
</tr>
<tr>
<td>4.1</td>
<td>3-level cascaded H-bridge multilevel inverter system</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>Voltage output 3-level CC-MLI</td>
<td>50</td>
</tr>
<tr>
<td>4.3</td>
<td>Voltage output 3-level DC-MLI</td>
<td>51</td>
</tr>
<tr>
<td>4.4</td>
<td>Voltage output 3-level CHB-MLI</td>
<td>51</td>
</tr>
<tr>
<td>4.5</td>
<td>FFT analysis of 3-level CC-MLI output</td>
<td>52</td>
</tr>
<tr>
<td>4.6</td>
<td>FFT analysis of 3-level DC-MLI output</td>
<td>52</td>
</tr>
<tr>
<td>4.7</td>
<td>FFT analysis of 3-level CHB-MLI output</td>
<td>52</td>
</tr>
<tr>
<td>4.8</td>
<td>5-level cascaded H-bridge multilevel inverter system</td>
<td>53</td>
</tr>
<tr>
<td>4.9</td>
<td>FFT analysis of 5-level CC-MLI output</td>
<td>54</td>
</tr>
<tr>
<td>4.11</td>
<td>FFT analysis of 5-level DC-MLI output</td>
<td>54</td>
</tr>
<tr>
<td>4.12</td>
<td>FFT analysis of 5-level CHB-MLI output</td>
<td>55</td>
</tr>
<tr>
<td>4.12</td>
<td>7-level cascaded H-bridge multilevel inverter system</td>
<td>56</td>
</tr>
<tr>
<td>4.13</td>
<td>FFT analysis of 7-level CC-MLI output</td>
<td>56</td>
</tr>
<tr>
<td>4.14</td>
<td>FFT analysis of 7-level DC-MLI output</td>
<td>57</td>
</tr>
<tr>
<td>4.15</td>
<td>FFT analysis of 7-level CHB-MLI output</td>
<td>57</td>
</tr>
</tbody>
</table>
4.16 Switching signal of SPWM (a) and OHSW (b) 59
4.17 3-level switching angle versus modulation index 61
4.18 3-level fitness function value versus modulation index 62
4.19 Voltage output 3-level (m=0.85) 63
4.20 FFT analysis of 3-level output (m=0.85) 64
4.21 5-level switching angle versus modulation index 65
4.22 5-level fitness function value versus modulation index 65
4.23 Voltage output 5-level (m=0.8) 67
4.24 FFT analysis of 5-level output (m=0.8) 67
4.25 7-level switching angle versus modulation index 69
4.26 7-level fitness function value versus modulation index 69
4.27 Voltage output 7-level (m=0.8) 71
4.28 FFT analysis of 3-level output (m=0.8) 71
4.29 3-level switching angle versus modulation index (unequal) 73
4.30 3-level fitness function value versus modulation index (unequal) 73
4.31 Voltage output 3-level unequal DC (m=0.85) 75
4.32 FFT analysis of 3-level unequal DC output (m=0.85) 75
4.33 5-level switching angle versus modulation index (unequal) 77
4.34 5-level fitness function value versus modulation index (unequal) 77
4.35 Voltage output 5-level unequal DC (m=0.80) 79
4.36 FFT analysis of 5-level unequal DC output (m=0.80) 79
4.37 7-level switching angle versus modulation index (unequal) 81
4.38 7-level fitness function value versus modulation index (unequal) 81
4.39 Voltage output 7-level unequal DC (m=0.80) 83
4.40 FFT analysis of 7-level unequal DC output (m=0.80) 83
4.41 3-level switching angle versus modulation index 86
4.42 3-level fitness function value versus modulation index 86
4.43 Voltage output 3-level (m=0.85) 88
4.44 FFT analysis of 3-level output (m=0.85) 88
4.45 5-level switching angle versus modulation index 90
4.46 5-level fitness function value versus modulation index 91
4.47 Voltage output 5-level (m=0.8) 93
4.48 FFT analysis of 5-level output (m=0.8) 93
4.49 7-level switching angle versus modulation index 95
4.50 7-level fitness function value versus modulation index 95
4.51 Voltage output 7-level (m=0.8) 97
4.52 FFT analysis of 3-level output (m=0.8) 97
4.53 3-level switching angle versus modulation index (unequal) 99
4.54 3-level fitness function value versus modulation index (unequal) 99
4.55 Voltage output 3-level unequal DC (m=0.85) 101
4.56 FFT analysis of 3-level unequal DC output (m=0.85) 101
4.57 5-level switching angle versus modulation index (unequal) 103
4.58 5-level fitness function value versus modulation index (unequal) 103
4.59 Voltage output 5-level unequal DC (m=0.80) 105
| 4.60 | FFT analysis of 5-level unequal DC output (m=0.80) | 105 |
| 4.61 | 7-level switching angle versus modulation index (unequal) | 107 |
| 4.62 | 7-level fitness function value versus modulation index (unequal) | 108 |
| 4.63 | Voltage output 7-level unequal DC (m=0.80) | 109 |
| 4.64 | FFT analysis of 7-level unequal DC output (m=0.80) | 110 |
| 4.65 | Overall harmonic elimination for equal and no equal DC source (Genetic Algorithm) | 114 |
| 4.66 | Overall harmonic elimination for equal and no equal DC source (Particle Swarm Optimization) | 115 |
# LIST OF SYMBOLS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>Carrier amplitude</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Modulation amplitude</td>
</tr>
<tr>
<td>fval</td>
<td>Fitness function value</td>
</tr>
<tr>
<td>$m$</td>
<td>Number of voltage level</td>
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<tr>
<td>P$_{\text{best}}$</td>
<td>Best fitness (PSO)</td>
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<tr>
<td>G$_{\text{best}}$</td>
<td>Global best (PSO)</td>
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<tr>
<td>V</td>
<td>Voltage</td>
</tr>
<tr>
<td>Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>AC</td>
<td>Alternate current</td>
</tr>
<tr>
<td>CC-MLI</td>
<td>Capacitor clamped multilevel inverter</td>
</tr>
<tr>
<td>CHB-MLI</td>
<td>Cascaded H-bridge multilevel inverter</td>
</tr>
<tr>
<td>CSI</td>
<td>Current source inverter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DC-MLI</td>
<td>Diode clamped multilevel inverter</td>
</tr>
<tr>
<td>DG</td>
<td>Distribution generation</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic algorithm</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-gate bipolar transistor</td>
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<tr>
<td>MG</td>
<td>Microgrid</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal–oxide–semiconductor field-effect transistor</td>
</tr>
<tr>
<td>PD</td>
<td>Phase disposition modulation</td>
</tr>
<tr>
<td>POD</td>
<td>Phase opposition disposition modulation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>PS</td>
<td>Phase shift modulation</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>OHSW</td>
<td>Optimize harmonic stepped waveform</td>
</tr>
<tr>
<td>SPWM</td>
<td>Sinusoidal Pulse Width modulation</td>
</tr>
<tr>
<td>SHE</td>
<td>Selective harmonic elimination</td>
</tr>
<tr>
<td>THD</td>
<td>Total harmonic distortion</td>
</tr>
<tr>
<td>VSI</td>
<td>Voltage source inverter</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Project background

In conjunction with industrialization and increase of human population, resultant world energy demand continues to increase year by year. The population and energy consumption is increasing correspondingly with time which is also predicted to continue increasing in future [1]. This cause increasing demand of energy for future energy sustain [1]. The exploration in renewable energy show increasing trend in past decade. Examples of renewable energy sources (RES) such as sun, wind, geothermal, biomass which will not be exhausted. RES have advantage over traditional sources in less emission [2]. However, RES mostly experience problem related to inconsistent output. For example, solar energy are dependent source which differ by radiation and yet need to be covert form DC to AC. Renewable energy is always complemented with inverter which hold the key to generating high efficient and reliable power. To utilize the energy, inverters play an important role in energy conversion process.
Inverter can be classified into two main types that is voltage source inverter (VSI) and current source inverter (CSI). Each types have their own unique characterise which been listed in literatures [3-7]. From the literatures, a brief conclusion of VSI is more popular than CSI can be make [3]. In addition, VSI transformer-less inverter popular in renewable energy application due to overall size reduction. The most common use inverter is high power 2-level PWM inverter. However high power application ideally is require low switching losses.

In past decade, numberless of literature has proven multilevel inverter is a practical solution on resolving high switching losses problem exist in conventional inverter for high power application [8]. Research trend nowadays are more focusing on several multilevel inverter topologies for renewable energy sources application. Multilevel topologies inverter generate multilevel voltage source output which synthesize the staircase waveform form single or multiple low DC voltage source. The low input voltage source reduce the stress encounter by the switches with ability produce high output voltage source. Currently, cascaded H-bridge multilevel inverter (CHB-MLI) and it modified topologies is high grab attention due to the flexibility toward renewable energy.

Multilevel inverter system can be separate into two sector which is inverter topology system and switching strategy. Inverter topology system consist of the most part include switches power sources, topology configuration and filter system. Power source are mostly RE such as solar panel and wind turbine. For topology configuration, there are 3 main type which been frequently cited in literature that is diode clamped multilevel inverter (DC-MLI), capacitor clamped multilevel inverter (CC-MLI) and cascaded H-bridge multilevel inverter (CHB-MLI) [9-16]. Filter part is apply to remove harmonics and smoothen the inverter output quality.

The move on to next part that is switching strategy. This part manipulated the harmonics profile for the inverter output waveform. The conventional type are square wave. This type evolve into quasi-square wave which give better profile as compare to square wave. Current trend is pulse width modulation (PWM) which been widely
apply in currently VSI devices [17]. However, researcher explored other method on overcome the cons of PWM where different kind of add on method been apply in conjunction with PWM such as elective harmonic elimination (SHE). SHE consist of complex non-linear equation on resolving best switching timing. Hence, various calculation approach been tested to optimize the overall performance. The calculation method include newton-rapshon, Fourier transform, and even bio-inspired algorithm approach such as bee, ant, particle swarm, genetic, bat and others [18-23].

Multilevel inverter widely apply in power system area. The some of the power generated by renewable resources are capable on self-sustainable for the user or even excessive power can revert back to main grid. Hence, this research focus on the trend of self-sustainable type or so call standalone application.

1.2 Problem statement

At present, existing high power system using traditional multi-pulse converter which alone with bulky transform and filter system [24, 25]. The size of converter have given a limitation to the application of converter especially in small scale usage such as standalone application system. Beside of the sizing problem, traditional converter also have high switching loss and electromagnetic interference (EMI) problem according to the previous researches [26, 27]. In order to solve this problem, converter with smaller size and low switching loss criteria is needed. However in standalone system need to maintain or even performance better in term of harmonic distortions and voltage boosting capability. Hence, inverter are found to be the solution.

Inverter play important role in regaining quality AC current to the consumer. Multilevel inverter have been done individually research according to the literatures for capacitor clamped [28, 29], diode clamped [30], cascaded H-bridge [31] and other topologies [32-34]. Each research show the related topology to be suitable for standalone application but there has been no comparative research between each other.
Among the topologies comparison, modulation strategies also hot topic of research in inverter fields. Several literature found to be having difficulty in resolving high non-linear equation of getting best switching timing [35-39]. The mathematical approach have reach a limit in increasing calculation speed of the complex equation. Due to all the problem mention in this section, the proposed solution will be presented in next section.

1.3 Aim and objectives

The aim of this research is to analyse the performance of multilevel inverter topologies for a standalone application. Hence following objectives had been listed to ensure objective achieved.

a) To compare the performance of multilevel inverter topologies with sinusoidal pulse width modulation in term of total harmonics distortion and the voltage boosting capability.

b) Apply proposed switching method to optimize the multilevel inverter with purpose to reduce total harmonic distortion and switching frequency.

c) To compare the capability of inverter system in adapting to balanced and unbalanced voltage sources with different bio-inspired algorithm for switching angle calculation.

1.4 Research scopes

Multilevel inverters are basically classified into three main categories which are capacitor clamped multilevel inverter, diode clamped multilevel inverter and cascaded H-bridge multilevel inverter. This research objective is to identify the most suitable topology in a single phase standalone application. The three topologies are the fundamental idea of the other latest modified topology. Hence, the scope has been narrowed into focusing only on these three multilevel inverter topology.
In simulation environment, topology construction and algorithm calculation is realised with the aid of Matlab/Simulink software. The overall specification for the simulation are listed as below. Total voltage input will always be 240 V, output voltage modulated to 50 Hz and the sampling time is $1 \times 10^{-6}$ s. MOSEF switches model is used. Hence, Matlab R2015a is used throughout the research with the aid of other software such as Microsoft Excel.

For the optimization of selected topology, optimized harmonic stepped waveform is proposed to be applied. The simulation input remain total 240 V and the sampling time is $1 \times 10^{-6}$ s. The calculation of selective harmonics elimination in this research is focus on comparison on genetic algorithm and particle swarm optimization. Both method under same simulation model with them own specification mention in methodology respectively.

In addition, three levels of multilevel inverter are applied in the research that is 3-level, 5-level and 7-level multilevel inverter. In this research, main key point is total harmonic distortion (THD), switching frequency, voltage boosting capability and the capability in adapting unequal sources.

### 1.5 Thesis outline

The thesis is doing performances analysis of multilevel inverter for standalone application. The literature studies of the project stated in chapter 2. Chapter 3 is the methodology of simulation topology and modulation method are discussed. Chapter 4 is where the result and analysis of the simulation are presented. Lastly chapter 5 is the conclusion and recommendation of the research.
2.1 Power electronic system

In current decade, power electronics is been focused by researchers in several industrial fields such as renewable energy, energy conversion, electrical vehicles and storage system. Power electronic is a system with aim to perform efficient energy condition, conversion and control form certain sources to a desired output condition. This technology is a combination of electrical and electronics component with goal in achieving high efficient, high availability, high reliability, small size, light weight and low cost [40]. Power conversion is one of the main key on power electronics. Hence, power electronic equipment can be classify into four main type that is AC to AC conversion, DC to AC conversion, AC to DC conversion and DC to DC conversion [41]. In this research, DC to AC conversion is been emphasize which so call as inverter.
Power electronic device with rectifiers is been introduce in 1890 by Dobrowlsky. However, the evolution invention in semiconductor which overcome the short of rectifiers had urged evolution for power electronics fields. In the last of 1950s, semiconductor industry invention, thyistor had widely introduce in power electronics fields. Thyristor is introduced in 1957s by General Electric [41] which give a lot of contribution in the early development of power electronic system. The literature shown that thyristor type inverter had been replaced by other devices that is MOSFET, GTO and IGBT afterward which is the current basic component of power electronics devices.

Inverter had been classify into current source and voltage source inverter. VSI is more popular in the market due to aspect of cost, size and efficacy. A general power electronic system for electrical generation purpose consist of distributed generation (DG) resources, storages system, distribution system and communication and control system. DG resources are technologies of combination of microsources and other conventional sources. Microsource include renewable energy such as wind, solar, fuel cell, biomass, geothermal and others. Conventional sources such as micro-hydro power and diesel also can be implemented into MG generation resources [42, 43]. However, each source has different power generation method and criterias which affect the power harvesting method [44].

Due to the uncertainty of the power production for certain source such as wind and solar, power storage system become an important aspect to be considered. Wind and solar energy are produced depending on the ecological situation which cause the output to be unstable. To secure consistent output generated and provide high power quality, energy storage system (ESS) is put in place to overcome the problem. Besides that, ESS also functions as extra storage for situations when the solar is unable to generate power such as at night. Energy storage is important where the excessive energy is stored to avoid energy from being wasted [45]. Most of microsources power output and storage system are in DC form. In order to utilize the power, conversion of DC to AC is required [46].
2.2 Power converter

Power converter is defined as an electrical or electro-mechanical device which is able to convert electrical energy in terms of voltage source type, frequency or voltage level [47]. Voltage source type converter refers to AD/DC conversion. The application example is rectifier for AC to DC and inverter for DC to AC. Frequency type converter refers to frequency changer and variable-frequency drive. Voltage level converter refers to the DC-to-DC converter, transformer and voltage regulator.

In power transmission system, converter is widely used due to loss reduction purpose. During the long range distance power transmission, AC line experiences more loss than the DC line. Hence, transmission loss is reduced by adopting converter system in the transmission system [48]. Employment of converter in power sector is due to capability of source type conversion. Source is referring to the alternating current (AC) and direct current (DC). Converter enables AC to convert to DC and inverter enables conversion from DC to AC.

Inverter was proposed in year 1925 by David Prince which mean inverse convertor [49]. The word ‘inverter’ is widely used in electrical terminology which refers to the DC to AC conversion device. Inverters are generally categorised into three types of AC output which are square wave, modified square wave and pure sine wave [50]. Square wave are the most inexpensive conversion method as shown in Figure 2.1. The output can be achieve with a half-wave bridge where switching regulates the DC source form positive to negative. Hence, square wave output is a very low quality AC power source.
Figure 2.1: Illustrated square wave signal

Figure 2.2 shows a modified sine wave which is also known as staircase waveform where the output is a cascade of multiple voltage levels. The step waveform has capability of harmonics reduction which improves the voltage quality. The advantage over the square wave is the higher efficiency.

Figure 2.2: Illustrated modified square wave signal

Figure 2.3 shows pure sine wave which is the most expensive inverter type among them. However, it is the optima source for all devices. The term ‘expensive’ refers to components use in the filter system applied. In this research, inverter is the main focus with the modified square wave type AC output.
2.3 Voltage source inverter

Inverters are classified into two main group that are voltage source inverter (VSI) and current source inverter (CSI). VSI operate independently generate voltage waveform output. CSI on the other hand, operate independently to generate current waveform output. Both of the inverters are widely used in power conversion application. The development of VSI is better as compared to CSI due to the early foundation. The capability of power electronics switches enable VSI to be more feasible for high power application. A comparative research study [3] was done and summarised pros and cons of inverter by the author. VSI overpowers CSI in terms of the DC component size and cost. Besides that, VSI also show advantages in shorter time to reach steady-state as compared to CSI. For the low switching frequency aspect, CSI is in the lead. However, in terms of low switching frequency, VSI leads with lower loss. The overall comparison shows the advantages of VSI in the power conversion area.

Figure 2.4 shows VSI families where there are two categories which are multilevel inverter and high power two-level inverter. High power two-level inverter is the conventional inverter operating with high complexity and bulky filter system. Multilevel inverter is classified into a single source and multiple sources. Single source type multilevel inverter are diode clamped and capacitor clamped type. Both types of inverter are capable to operate with a single DC source in single or three phase system. Multiple source is refers to cascaded H-bridge multilevel inverter. Each H-bridge
requires an individual DC source where number of DC source determines the number of voltage levels generated. However, the multiple source inverter encounters problem which is equal DC sources or an unequal DC source condition [4, 5].

![Voltage source inverter family](image)

Figure 2.4: Voltage source inverter family

In recent years, multilevel inverter is widely developed and researched due to its advantages over the conventional inverter. Conventional inverter such as high power 2-level inverter has a square waveform quality output. Bulky capacitor and complex filter system are required in order to support high harmonic voltage output. Besides that, high power rating switches are is required to handle high $\frac{dv}{dt}$ stress from the high voltage level. Hence, multilevel inverter is proposed to overcome the problem.

Multilevel inverter is applies the concept of the voltage sum of different voltage source to generate multiple times higher voltage level output. It has the advantage of generating inclusion of the high quality staircase waveform thus reducing electromagnetic compatibility problems, lower harmonic distortion and reduced $\frac{dv}{dt}$ stress on the switch. Multilevel inverter functions in both fundamental and high frequency switching conditions. The possibility of operating low frequency switches leads to low switching loss and improves the efficiency [6].
Several multilevel inverter topologies had been introduced since the year 1975. Amongst them, the most common topologies that used are the H-bridge cascade inverter, capacitor clamping inverter and diode clamping inverter [7]. There are various topologies for multilevel inverter using similar concepts and propose modified multilevel inverter such as example reversing voltage, modular and generalized multilevel current source inverter.

The power electronics switches configuration is determined by the modulation technique. There are a number of modulation techniques introduced in the literature [19]. Sinusoidal pulse width modulation (SPWM) method appear to be the most popular method. This method gain benefits where the switching frequency is several kilohertz (Hz) above which unwanted harmonic when switching will only appear at high harmonics order. Thus, filter system can be much simple and cheap.

Modulation methods are widely discussed in the current research trend. It is part of the possible improvement method in reducing the total harmonics distortion for an output. However, the research objective include to reduce both switching frequency and THD by applying other modulation methods as compared to conventional PWM method.

In the term of market values, specification high efficiency, low cost and reliability are highly sensitive issue of manufacture compares. Each level of multilevel inverter shows the increasing quality of output where the number of voltage level increases.

2.4 Multilevel inverter

The basic concept behind a multilevel inverter is achieving high voltage level power with the several low voltage level power by aid of power electronics switches to synthesize a staircase output voltage waveform. Multilevel inverter has been introduced since the year 1975s. The first patented multilevel inverter concept is the cascaded H-bridge multilevel inverter (CHB-MLI) [9]. After years of development,
new topology is proposed in year 1981 [10]. The new topology applies the characteristics of diode in current flow to synthesize a staircase AC output waveform which is known as diode clamped multilevel inverter (DC-MLI) or Neutral-Point Clamp inverter. In year 1992, capacitor clamped multilevel inverter (CC-MLI) was proposed by Meynard and Forch by applying capacitor to synthesize different voltage level [11]. After that, numerous new topologies of multilevel inverter have been proposed from the modification of the previous three main multilevel inverter concept or hybrid mode. The topologies include generalized multilevel inverter [12], hybrid multilevel inverter [13-15], soft–switched multilevel inverter [16]. DC-MLI, CC-MLI and CHB-MLI are discussed in more detail in terms of concept, topology, switching configuration, advantage and disadvantages in this section.

2.4.1 Diode Clamped Multilevel Inverter

The concept of DC-MLI function is using diode to limit the voltage current flow pathway and give different voltage level output based on the switch condition [30]. Capacitors in series with a neutral point in the middle of capacitor line as the separation of source function.

Figure 2.5 shows 3-level diode clamped multilevel inverter topology for single phase. The inverter is connected with clamping diode in series in order to provide all diodes with the same voltage rating. C1 and C2 acts as the DC link bus to separate the DC source into 2 which is $V_{dc}/2$ for each capacitor. S1 to S4 are the power electronic switches which control the switching to alter $V_{ao}$. Table 2.1 show the switching configurations for a single phase 3-level DC-MIL. When S1 and S2 are on and S3 and S4 are off, the voltage output is $V_{dc}/2$. When S2 and S3 are on and S1 and S4 are off, the voltage output is 0. When S1 and S2 are off and S3 and S4 are on, the voltage output is $-V_{dc}/2$. The line voltage are generates only 2-levels but when in three phase configuration, the delta or wye connection enables line-to-line voltage achieve 3-level voltage with same topology and switching configuration.
The main concept of DC-MLI is using diodes to limit the voltage stress of the power device. The topology of DC-MLI has a general component formula where assuming $m$ is the number of voltage level desired, then the number of switches needed is $2(m - 1)$, number of capacitors needed is $m - 1$ and number of clamping diodes needed is $m - 1$. The line functions as DC-bus which divides a single DC supply into even number. The capacitor line is connected with the clamping diodes pairs of $m - 1$ where $m$ is the number of voltage level that is desired. Photovoltaic arrays were connected as DC supply for the inverter [17,51].

Figure 2.5: 3-level diode clamped multilevel inverter topology
Table 2.1: 3-level diode clamped multilevel inverter switching configuration

<table>
<thead>
<tr>
<th>Stage</th>
<th>Switching states</th>
<th>$V_{an}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_1$</td>
<td>$S_2$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The advantages and disadvantages for DC-MLI are discussed below.

Advantages:

- All phase sharing same DC bus.
- Capacitor can be charged in a group for DC bus.
- High efficiency for fundamental frequency switching.

Disadvantages:

- Not suitable for high number of voltage level due to the possible growth of components needed.

2.4.2 Capacitor Clamped Multilevel Inverter

The structure of CC-MLI is similar to DC-MLI where the difference is that capacitor is used to replace the diode clamp to hold the desire voltage.

Figure 2.6 shows a 3-level capacitor clamped multilevel inverter topology. CC-MLI generally uses capacitors and power electronic switches. Consider $m$ as the number of inverter voltage levels, $m-1$ is the number of capacitor required on the DC-bus and $2(m-1)$ power electronic switches are needed. Clamping capacitor number is depending on the position and number of levels of inverter desired. Both $C_1$ and $C_2$ illustrated in Figure 2.5 is the DC-bus capacitor which are similar to that in the DC-MLI. $C_3$ is the clamping capacitor and $S_1$, $S_2$, $S_3$, $S_4$ are the power electronics switches. The clamping capacitors advantage over no block voltage as DC-MIL which increases the number of switching combination. Table 2.3 shows the 3-level capacitor clamped multilevel inverter switching configuration. When $S_1$ and $S_2$ are on and $S_3$ and $S_4$ are off, $V_{an}$ is equal to $V_{dc}/2$ due to the current flow sequence. When $S_2$ and $S_3$ are on and $S_1$ and $S_4$ are off, the voltage output is 0. When $S_1$ and $S_2$ are off and $S_3$ and
S₄ are on, the voltage output is \(-V_{dc}/2\). The sequence are the same as in DC-MLI but there are more configurations that can be plotted and the Table 2.2 is one of the possible solution.

Since the same current through all the active capacitors, energy can be transferred from more charged capacitors to less charged capacitors to balance the capacitors voltages. However the as the capacitor number increase for achieve higher voltage level, the issue of voltage imbalance in DC link occur [6, 7, 52-55].

![Figure 2.6: 3-level capacitor clamped multilevel inverter topology](image-url)
Table 2.3: 3-level capacitor clamped multilevel inverter switching configuration

<table>
<thead>
<tr>
<th>Stage</th>
<th>Switching states</th>
<th>( V_{an} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( S_1 )</td>
<td>( S_2 )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The advantages and disadvantages of CC-MLI are discussed below.

Advantages:
- Controllable active and reactive power flow.
- Reduce duration of sags and outages.

Disadvantages:
- All capacitors need to be charged up to same voltage level before start-up.
- Capacitors are more expensive and bulky compared to diodes.
- Voltage control on all capacitors for voltage levels is complicated.

### 2.4.3 Cascaded H-Bridge Multilevel Inverter

Two or more separate DC sources in a full bridge are placed in series to generate a staircase AC output waveform voltage. Figure 2.7 shows a 2-level CHB-MLI topology.

CHB-MLI requires fewer components where each voltage level requires the same amount of components. However, the number of sources is higher since \( m \) voltage level inverter, \( s = \frac{m-1}{2} \) sources are required. The number of sources \( s \) is also equal to the number of full bridge modules.

The CHB-MLI switching configuration is similar to the other topology. When \( S_1 \) and \( S_4 \) are on and \( S_2 \) and \( S_3 \) are off, voltage \( V_{an} \) is equal to \( V_{dc} \) due to the current flow sequence. When \( S_1 \) and \( S_2 \) are on and \( S_3 \) and \( S_4 \) are off, the voltage output is 0. When \( S_1 \) and \( S_2 \) are off and \( S_3 \) and \( S_4 \) are on, the voltage output is 0. When \( S_1 \) and \( S_4 \) are off and \( S_2 \) and \( S_3 \) are on, the voltage output is \( -V_{dc} \).
Every full-bridge module has four diodes and four switches in turn giving the CHB-MLI $2(m - 1) = 4s$ diodes and switches. When making a three-phase inverter with the topology, the number of needed components are multiplied by three for all components since there is no common DC-bus to share.

Applications suitable for the CHB-MLI are for example where photovoltaic cells, battery cells or fuel cells are used [5, 18, 19]. The consideration of number of level for CHB-MLI are different from other. The calculation of CHB-MLI of number of voltage levels are including the negative side of each voltage level while other topologies do not.

![2-level cascaded H-bridge multilevel inverter topology](image)

Figure 2.7: 2-level cascaded H-bridge multilevel inverter topology

The advantages and disadvantages of CHB-MLI are discussed below.

**Advantages:**

- Achieve higher voltage level with same component as compared to other topologies.
- Can be modulated separately.
Disadvantages:

- Limited application due to separate DC source characteristic.

Overall, the comparison of components for single phase are show in Table 2.3 where \( m \) is the number of inverter level. Generally the number of switches for all three topology are the same including the diode for each switch. The difference between the topologies component are the clamping type which was diodes or capacitors and the DC-bus capacitor. CHB-MLI shows advantage of less components needed as there is no requirement for clamping and DC-bus.

Table 2.2: Components comparison of multilevel inverter topologies

<table>
<thead>
<tr>
<th>Component</th>
<th>DC-MLI</th>
<th>CC-MLI</th>
<th>CHB-MLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switches</td>
<td>( 2(m - 1) )</td>
<td>( 2(m - 1) )</td>
<td>( 2(m - 1) )</td>
</tr>
<tr>
<td>Diodes</td>
<td>( 2(m - 1) )</td>
<td>( 2(m - 1) )</td>
<td>( 2(m - 1) )</td>
</tr>
<tr>
<td>Clamping diodes</td>
<td>( (m - 1)(m - 2) )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clamping capacitor</td>
<td>0</td>
<td>( (m - 1)(m - 2)/2 )</td>
<td>0</td>
</tr>
<tr>
<td>DC bus capacitors</td>
<td>( (m - 1) )</td>
<td>( (m - 1) )</td>
<td>0</td>
</tr>
</tbody>
</table>

2.5 Total harmonic distortion

One of the principal sources of harmonic is converter or also known as inverter also. The non-sinusoidal current generated contain high harmonic characterises. Inverter implementing the power electronic switching devices such as diodes, thyristors, IGBT, GTO and others. The process of power conversion switching causes the generation of harmonics. The gap of the current draw out from source during switching cause harmonic occurs. Harmonic current cause device overheating and damage if a serious harmonics problem occurs, especially in motors and transformer.
Total harmonic distortion is signal measurement of the ratio between the harmonic components and the fundamental frequency component which can be calculated as Equation 2.1,

$$\text{THD} \% = 100 \left( \frac{\sqrt{V_2^2 + V_3^2 + \cdots + V_n^2}}{V_1} \right)$$

(2.1)

Where $V_n$ is the RMS voltage of the $n^{th}$ harmonic and $n = 1$ is the fundamental frequency. The number of the harmonics after the fundamental is considered a ruler for the quality of a power sources. The lower the number of harmonic gives a higher quality source.

### 2.6 Modulation techniques

Modulation technique have greatly influence on harmonics effect of multilevel inverter. The most popular modulation method is the carrier based PWM, space vector PWM and the harmonic based PWM. Each modulation method exist with pros and cons. The modulation method are generally separate into fundamental switching frequency type and high switching frequency type. Figure 2.8 shown the classification of multilevel inverter modulation method. For fundamental switching frequency categories included SVPWM and OHSW which mean the switches switch for on off per cycle. While for high switching frequency categories, SPWM, SVPWM and OHSW is included. SPWM method found to be only applicable in high switching frequency modulation method.
2.6.1 Carrier based pulse width modulation

Carrier based pulse width modulation method is referring to the sinusoidal pulse width modulation in cooperating with multiple type of barrier parameter. SPWM operational theory is that the desired pulse width is obtained by comparison of triangular wave which acts as a carrier and sinusoidal wave of desired fundamental frequency [56]. SPWM modulation have several branches, which are phase disposition, phase opposition disposition and phase shift modulation method. Characteristic of each method is shown as below where \( m \) is referring to be voltage levels.

Phase disposition modulation (PD)

- PD method is part of the multi carrier PWM method where the number of carries depend on the multilevel inverter. The method applied \((m - 1)\) carrier where \( m \) refers number of sources.

Phase opposition disposition modulation (POD)

- POD method is similar to the PD method. Both are applying \((m - 1)\) carrier but the difference is the 180 degree phase out of bottom carrier by referring the zero reference.

Phase shift modulation (PS)
• PS method is each \((m - 1)\) carrier is phase shifted by 90 degree.

The carrier based pulse had advantages over high order harmonics can be done due to operate in high switching frequency. The high order harmonics are more ease to be filter and removed as compared to low order harmonics. The advantages also lead to disadvantages where switching frequency need to be very high where life-span of the switches is no preserved.

2.6.3 Third harmonics injection pulse width modulation method

Third harmonic injection is an upgrade method to be apply onto SPWM to utilize the available DC bus supply voltage. A 3rd harmonics with peak magnitude of \(\frac{1}{6}\) to modulation waves is added into the general SPWM system which resultant reduction of peak voltage output but increase the fundamental component voltage [58]. Third harmonic injection pulse width modulation technique capable to overcome the existing problem of SPWM that is lower output voltage than the supplied input voltage. However, this method still facing high switching loss problem as SPWM.

2.6.3 Space vector pulse width modulation

Space vector pulse width modulation method is an algorithm to control the switching pulse in order to create AC waveform. Each combination of switching stage is converted into a space vector diagram. This method assigns each possible switching configuration into a space vector diagram. Then applying a mathematical calculation on the vector to get the switching timing. The proses start from sector identification. Once the sector has been identified, switching time for each switch is calculated. Lastly, identifying the switching state of the switch, whether is on or off [55, 57]. This modulation method is very systematic and operate both fundamental and high switching frequency. However, it is limited to three voltage level if facing unbalance DC sources.
2.6.4 Harmonics Based Optimized harmonics stepped waveform modulation

Optimized harmonics stepped waveform (OHSW) modulation is a modulation technique to operate an inverter in low switching frequency [20]. The modulation method operates with fundamental frequency which generally increases the life span of switching devices and reduces power losses through reduced harmonics. The possibility to generate filterless output is possible by adapting this technique.

2.7 Selective harmonics elimination

The characteristics of this modulation method are capable of removing low order harmonics and apply on equal or unequal DC source multilevel inverter [20]. Several methods were found in the study of literature to solve the non-linear SHE equation.

The Newton-Raphson method is one of the methods found in [21]. Newton-Raphson is an iterative method which begins with an initial value and converges to a zero for the nonlinear equation calculation. Hence, it was applied into the switching angles determination. The results obtained are in multiple sets which require testing and simulation to obtain the best. The method gives clear switching angles and highly accurate results with very small increment steps. However, the method is time consuming since it computes all possible angles sets, then refines to find the best one.

Bee algorithm is an optimization algorithm which mimics the bees natural behavior in searching for food. The optimization algorithm is capable of solving the nonlinear equation of switching angles as shown in the result in [22]. Bee algorithm is a high approaching global solution method where it has a good convergence rate. The high approaching global solution shows a high viable solution set also. Hence, bee algorithm also takes a longer time to optimize the best result.

Bat algorithm is lately introduced by several researchers [18, 19]. It utilizes the bat echolocation sense to develop the algorithm. Bat algorithm showed a fair result for
selective harmonics elimination as compared to bee algorithm and a genetic algorithm is shown. Hence the method is still currently under developing stage to optimize and enhance the performance.

Particle swarm algorithm is also one of the method to be applied in the multilevel switching angle. The algorithm also show capability in resolving switching angle function where the low harmonics are clearly optimized [23].

2.8 Previous Research Work on multilevel inverter

Chiasson et. al.[59-61], optimize switching angle had been shown to be helpful in reducing harmonics. The result show for certain amount order of harmonics has been successfully reduced or eliminated by Resultant Theory method. The resultant show highly complex where the expression polynomials reaching 22\textsuperscript{th} degree. Hence, obvious increasing of complexity shown in the result as the number of voltage level increase.

Engin Ozdemir et al.[62], standalone photovoltaic system applying diode clamped multilevel inverter with fundamental frequency modulation. The switching angle is calculated by applying transcendental equations calculation method. The result show success of harmonics elimination. According to other literature [76, 77], it was found that the transcendental equation is useful in single source application. When apply this method in unbalance DC sources, the equation became complex and hardly capable to be solve by contemporary computer algebra software tools if the number of voltage level exceeding three.

Several studies on different multilevel inverter using various method of optimization to reduce harmonics distortion have ensued. N. Farokhnia et al. (2010) [35], shown a calculation method by using calculation of the line to line THD with equal DC sources for five level cascaded H-bridge multilevel inverter. The calculation claimed to be success in resolve the problem however it also mention
REFERENCES


