Harmonic analysis in modified cascaded multilevel inverter with nature-inspired switching-angle optimization algorithm

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Abstract. Selective harmonic elimination pulse width modulation (SHEPWM) is a fundamental frequency switching angles calculation technique that eliminates the undesired low order harmonics while maintaining the desired fundamental component. A natured-inspired optimization algorithm, grasshopper optimization algorithm (GOA), is applied in SHEPWM to obtain the optimized switching angles. Compared to Newton Raphson (NR), GOA is able to provide wider range of solutions. Optimize switching angles obtained from MATLAB analysis are applied to a 5-phase 7-level modified cascaded multilevel inverter (MCMLI). This paper presents the performance of GOA applied to the MCMLI. The 3rd and 7th harmonics are chosen to be eliminated while the desired fundamental component is maintained.

1. Introduction
Conventional energy sources such as coal and natural gas are widely used to generate electricity. Some of the drawbacks of conventional energy sources are they will release carbon dioxide gas and causes greenhouse effect [1]. Therefore, renewable energy is introduced to reduce the usage of conventional energy. Among the renewable energy, solar energy has gained high popularity because it is clean and widely available. Solar energy can be harvested through a photovoltaic (PV) module and converted into DC electrical energy. However, the household appliances require AC power to operate. Therefore, an inverter is needed to convert the DC electricity to AC electricity [2]. 2-level pulse width modulation (PWM) inverter and cascaded H-bridge multilevel inverter (CHBMLI) are the conventional topologies that are used to convert DC to AC electricity [2,3]. However, there are some disadvantages for both topologies. Conventional 2-level PWM inverter has drawbacks of high switching losses, higher voltage harmonic content while conventional CHBMLI has drawback of high number of switch count compared to a modified cascaded multilevel inverter (MCMLI). The number of power switches used in CHBMLI will become significant as the number of phases and number of voltage level are higher. Thus, this will reduce the reliability of the inverter [2, 4]. To generate a 7-level voltage waveform, conventional CHBMLI required 12 switches per phase while the MCMLI required 6 switches per phase.

Switching angles applied to MLI must be computed carefully to minimize the total harmonic distortion (THD). In [4], the author used level shifted in-phase disposition (LS-IPD) to generate a sine wave with better quality. However, LS-IPD is the conventional high frequency modulation technique which results in high switching losses. Therefore, a fundamental frequency modulation technique, selective harmonic elimination pulse width modulation (SHEPWM) is implemented to reduce the
switching loss. SHEPWM can be used to eliminate the low order harmonics and maintain the fundamental component and a set of non-linear transcendental equations of selected harmonics are needed to be solved [8]. Conventionally, Newton-Raphson (NR) is used to solve the transcendental equation in SHEPWM [9]. However, NR requires good initial switching-angles guesses and unable to provide solutions for wide range of modulation index. Therefore, a soft-computing method is introduced to overcome the drawbacks of NR [10]. The advantage of soft-computing method is that it does not require good initial switching-angles guesses. In this paper, a nature inspired soft-computing optimization algorithm known as grasshopper optimization algorithm (GOA) is recommended to solve the equations in SHEPWM. The application of GOA in eliminating the THD in the MCMLI has rarely been reported. Therefore, in this paper, GOA based SHEPWM will be employed to obtain the optimal switching angles for 5-phase 7-level MCMLI, which is adapted from [4], is explored.

2. Five-phase seven-level modified cascaded multilevel inverter

A 5-phase 7-level MCMLI can be constructed with two DC voltage sources with an increment of binary ratio. The number of power switches required to construct the MCMLI is 6 power switches per phase. The total number of voltage level, \( m \), and the total number of power switches, \( n_{sw} \), of a 5-phase MCMLI are given by (1) and (2), respectively, where \( s \) is the number of DC sources per phase and \( r \) is the total number of power switches per phase. For example, for a 5-phase 7-level modified MCMLI shown in figure 1 requires 6 power switches per phase which needs a total of 30 power switches for 5-phase.

Similar to CHBMLI, MCMLI is capable to generate \(+V_{DC},0,-V_{DC}\). MCMLI requires lower number of power switches compared to conventional CHBMLI which differ with a number of 6 switches per phase. Therefore, MCMLI is more reliable compared to CHBMLI.

\[
m = 2^{(s+1)} - 1
\]
\[
n_{sw} = 5r
\]

![Figure 1. Modified Cascaded Multilevel Inverter (MCMLI)](image-url)
3. Switching angles calculation techniques

3.1. Selective Harmonic Elimination Pulse Width Modulation

SHEPWM is a fundamental frequency switching angles calculation technique which is used to eliminate the undesired low order harmonics while maintaining the desired fundamental component of the output voltage waveform. For a 5-phase 7-level MCMLI connected with balanced load, the 3rd and 7th harmonics are chosen to be eliminated. The quintuple odd harmonics are eliminated naturally in 5-phase system. Harmonic content for fundamental harmonic, 3rd harmonic and 7th harmonic can be expressed as (3):

\[
\begin{align*}
V_1 &= \frac{4V_{DC}}{\pi} \left[ \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) \right] \\
V_3 &= \frac{4V_{DC}}{3\pi} \left[ \cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) \right] \\
V_7 &= \frac{4V_{DC}}{7\pi} \left[ \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) \right]
\end{align*}
\]

3.2. Grasshopper Optimization Algorithms

GOA is a population-based nature-inspired algorithm which is based on the swarm behaviour of grasshopper. The algorithm mimics the movements of the grasshoppers in migration and food foraging process. The mathematical model for implementing the movement of grasshoppers is given by (4):

\[
x_i^d = c \sum_{j=1}^{N} \frac{c_{ub_d} - lb_d}{2} s \left( \left| x_j^d - x_i^d \right| \right) \frac{x_j^d - x_i^d}{d_{ij}} + T_d
\]

where \(ub_d\) is the upper bound in the \(d\)-th dimension, \(lb_d\) is the lower bound in the \(d\)-th dimension, \(T_d\) is the value of the \(d\)-th dimension in the target (best solution found so far) and \(d_{ij}\) is the distance between \(i\)-th grasshopper and \(j\)-th grasshopper. \(c\) is a decreasing coefficient which is expressed as (5):

\[
c = c_{max} - i \frac{c_{max} - c_{min}}{i_{max}}
\]

where \(c_{max}\) is the maximum value of the coefficient, \(c_{min}\) is the minimum value of coefficient, \(i\) is the current number of iteration and \(i_{max}\) is the maximum number of iterations. The function \(s\) is the social force used to decide the movement of grasshopper and it is presented as (6):

\[
s(r) = \frac{r}{l} - e^{-r}
\]

where \(r\) is the normalized distance between \(i\)-th grasshopper and \(j\)-th grasshopper, \(l\) is the attractive length scale and \(f\) is the intensity of attraction. The objective function (OF) is used in GOA-SHEPWM for minimizing the 3rd and 7th harmonics while maintaining the desired fundamental harmonics as shown in (7):

\[
OF = \left( 100 \times \frac{V_D - V_1}{V_D} \right)^4 + \frac{1}{3} \left( \frac{50 \times V_3}{V_1} \right)^2 + \frac{1}{7} \left( \frac{50 \times V_7}{V_1} \right)^2
\]

where \(V_d\) is the desired fundamental harmonic, \(V_1\) is the fundamental harmonic, \(V_3\) is the 3rd harmonic, \(V_7\) is the 7th harmonic of the phase voltage waveform. The first term of (7) is used to regulate the desired fundamental harmonics while the second and third terms are used to reduce the 3rd and 7th harmonics,
respectively. The objective of the first term is limiting the relative error of 1% between the $V_D$ and $V_I$. For the second and third terms, the 3rd and 7th harmonics are kept under 2% of the fundamental harmonic. Therefore, all desired conditions could be controlled with the proposed OF while the optimum solutions for all modulation index could be determined by using GOA.

GOA is applied in SHEPWM to optimize the switching angles using MATLAB. Pseudo code are used to illustrate the implementation of GOA-SHEPWM in figure 3.

```
Initialize population $X_i (i = 1, 2, \ldots, n)$, $i_{\text{max}}$, $c_{\text{max}}$ and $c_{\text{min}}$, $l$, $f$

Calculate the OF value for each search agent $T_d = \text{best search agent}$

while ($i < i_{\text{max}}$)
    Update $c$
    for each search agent
        Normalize the distance between grasshopper
        Update the position of each grasshopper
        Bring the search agent back if it goes outside the boundaries
    endfor
    update $T_d$
    $i = i + 1$
endwhile

Return $T_d$
```

**Figure 2.** Pseudo code for GOA

4. Results
GOA based SHEPWM is implemented in MATLAB to obtain the optimum switching angles. MATLAB had been used to evaluate the optimum switching angles from the modulation index of 0.01 to 1.00 with an interval of 0.01 by implementing the parameter for GOA in Table 1. NR has been used as a benchmark to validate the performance of GOA.

| Parameter   | Value |
|-------------|-------|
| Grasshopper | 100   |
| $l$         | 1.5   |
| $f$         | 1.5   |
| $c_{\text{min}}$ | 0.00001 |
| $c_{\text{max}}$ | 0.5   |
| $i_{\text{max}}$ | 100  |
Figure 3. NR switching angles.

Figure 4. GOA switching angles.

Figure 5. OF values obtained from GOA
NR and GOA have been implemented to solve the non-linear transcendental equations in SHEPWM and the switching angles solutions over a wide range of modulation index are shown in figures 3 and 4. It is obvious that GOA provides wider range of solutions compared to NR. Figures 5 and 6 show the results of OF and cumulative distribution function that achieved by GOA, respectively. OF at the modulation index range of 0.57 to 0.67 and 0.76 to 0.85 are minimized where the value of the OF is lower than $10^{-7}$ as evidently shown in figure 5. 20% of the modulation index range achieve OF value of $10^{-7}$ and lower as clearly shown in figure 6. Figure 7 shows the harmonic response that achieved by the GOA. The desired fundamental component is maintained nearly at 100% over the wide range of modulation index, whilst the undesired 3rd and 7th harmonics are eliminated at the modulation index of 0.57 to 0.67 and 0.76 and 0.85 as validated in figure 5.
Figures 8 and 9 show the phase voltage waveform and the Fast Fourier Transform (FFT) analysis of the phase voltage at the modulation index of 0.76, respectively. The fundamental component of the phase voltage is 34.84V and the 3rd and 7th harmonics components are eliminated as presented in figure 9. Figure 10 and figure 11 show the line-to-line voltage waveform and the FFT analysis, respectively. For 5-phase system, the line-to-line fundamental voltage is 40.95V and the 3rd, 5th and 7th harmonics are eliminated. The quintuple odd harmonics such as V₅ and V₁₅ are eliminated naturally in the line-to-line voltage of a 5-phase configuration.
5. Conclusion
The optimum switching angles are computed using MATLAB and applied to the MCMLI in PSIM. The analysis shows that GOA is better than NR because GOA is able to provide wider range of solution compared to NR. Based on the simulation results, GOA based SHEPWM is able to maintain the desired fundamental harmonic, whilst eliminate the undesired low order harmonics. In addition, the quintuple harmonics in the line-to-line voltage are eliminated naturally in the 5-phase system.

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