

# MSHE-PWM Cascaded Inverter with Adjustable DC Voltage

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**ABSTRACT:** We have to improve the power extracting methods from renewable energy resources to minimize power demand and scarcity. Multilevel inverter is used to synthesize the desired ac output waveform from several dc sources like solar cells.

This paper presents a new multilevel selective harmonic elimination pulse-width modulation (MSHE-PWM) technique employing cascaded H-bridge inverter (CHI) configuration with adjustable dc sources, thereby the efficiency and quality of output voltage waveform is improved. Both the dc-voltage levels and the switching angles are optimized in this method, enabling elimination of more harmonics without affecting the structure of the inverter circuit. The method provides linear pattern of dc-voltage levels for constant switching angles over the modulation index range. Thereby the tedious steps required for manipulation of offline calculated switching angles can be eliminated. This eases the implementation of the MSHE-PWM for dynamic systems.

**KEYWORDS:** MSHE-PWM, Total harmonic distortion (THD)

## I. INTRODUCTION

In multilevel inverters combining several dc voltage sources to obtain the desired multi-staircase output voltage. Solar cells, fuel cells, batteries and ultra-capacitors are the most common independent sources used [1]. For medium and high-power conversion the multilevel converters are mainly focused on. There are three commercial topologies of multilevel voltage-source inverters: neutral point clamped (NPC), cascaded H-bridge (CHB), and flying capacitors (FCs) [2]. Among these due to the modular topology [3] the cascaded multilevel inverter has higher reliability, output voltage and power levels (13.8 kV, 30 MVA). Diode-clamped multilevel converters are used in conventional high-power ac motor drive applications and also been reported to be used in a back-to-back configuration for regenerative applications [4]. High-bandwidth high-switching frequency applications used flying capacitor multilevel converters. The cascaded H-bridge multilevel converters are used for the applications like static synchronous compensators active filter and reactive power compensation applications, and photovoltaic power conversion, where high power and power quality are essential.

As voltage levels increase the voltage stresses and switching losses will increase due to increase in number of switches and the circuit will become complex. The number of switches can be reduced significantly by explained topology and hence the efficiency will improve [5]. To avoid distortion in the grid and to reach the maximum energy efficiency, we have to eliminate the harmonics in output waveforms [6]. The challenge associated with techniques is to obtain the analytical solutions of the non-linear transcendental equations that contain trigonometric terms which naturally exhibit multiple sets of solutions [7]. Generally the lower order harmonics are causing more effects when compared to the higher order harmonics. The third order harmonics are eliminated itself in line voltages. It is a big challenge for any researcher to eliminate the fifth and seventh order harmonics using simple techniques in line voltages, for a motor load its effects are high. In this paper Selective Harmonics Elimination technique [8] is used. The transcendental non-linear equations are solved using the numerical technique called Particle swarm optimization method.

## II. CASCADED H-BRIDGE MULTILEVEL INVERTER

To eliminate the the unwanted harmonics multilevel inverters are used as an alternative to traditional PWM. In this topology the number of phase voltage levels at the converter terminals is  $2N+1$ , where  $N$  is the number of cells or dc link voltages. Each power circuit needs just one dc voltage source. Each H-bridge cells have positive, negative or zero voltage. Final output voltage is the sum of all H-bridge cell voltages and is symmetric with respect to neutral point, so the number of voltage levels is odd [8]. The cascaded H-bridge multilevel inverter provide the use of Separate DC Sources (SDCSs) to produce an AC voltage waveform [9]. Each H-bridge has a DC source  $V_{dc}$ . The output AC voltage waveform is produced by cascading the AC outputs of each H-bridge inverter. Each H-bridge inverter can produces the voltages:  $+V_{dc}$ , 0 and  $-V_{dc}$  by closing of appropriate switches. It is also possible to modularize circuit layout and packaging because each level has the same structure, and there are no extra clamping diodes or voltage balancing capacitors [10]. By using this new topology the number of switches can reduce. This circuit is simulated using the MATLAB software.

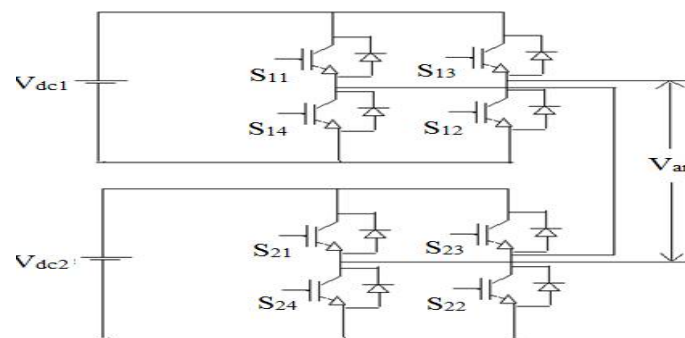


Fig. 1. Cascaded five-level inverter

### Cascaded five-level inverter

The power circuit of a five-level cascaded inverter is shown in Fig.1. Cascaded multilevel inverter is based on series connection of single phase H-bridge inverters with separate DC sources. The cascaded multilevel inverter have less space occupancy than other topologies due to its modular structure [11]. Compared to the flying capacitor and diode clamped multilevel inverter topologies the CHI-bridge topology requires less number of components. In addition to this cascaded multilevel inverter does not require a specially designed transformer as like in the multiphase inverters [12]-[14]. Each H-bridge shown in Fig.1 could produce three different levels:  $+V_{dc}$ , 0 and  $-V_{dc}$  by connecting the DC supply to AC output side by different combinations of the four switches  $S_{X1}, S_{X2}, S_{X3}$  and  $S_{X4}$ , where  $X$  represents the H-bridge number.  $S_{X1}$  and  $S_{X2}$  switches are turned on for  $+V_{dc}$  voltage. While or  $-V_{dc}$  level  $S_{X3}$  and  $S_{X4}$  are turned on  $-V_{dc}$  voltage. For zero output voltage switching on either the switch pairs  $S_{X1}$  and  $S_{X3}$  or  $S_{X2}$  and  $S_{X4}$ . At fundamental switching scheme the output voltage representation of a five-level cascaded inverter is shown in Fig. 2. The number of levels ( $m$ ) in the output phase voltage is  $2s+1$  where  $s$  is the number of H-bridges used. The outputs of three single phase inverters could be connected in star or delta shape to obtain three phase connection.

## III. SELECTIVE HARMONICS ELIMINATION(SHE)

The Selective Harmonic Elimination Stepped-Waveform (SHESW) technique is very suitable for a multilevel inverter circuit. The low Total Harmonic Distortion THD output waveform without any filter circuit is possible, while employing this technique along with the multilevel topology.

The equation(1) represents the fourier expression of the multilevel output voltage for equal DC voltages in multilevel inverters

$$V(t) = \sum_{n=1,3,5}^{\infty} 4V_{dc}/n\pi(\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \dots + \cos(n\theta_s)) \sin(n\omega t) \quad (1)$$

Because of odd quarter-wave symmetry the output voltage has no even harmonics in output waveform. The switching angles  $\theta_1, \theta_2, \dots$  and  $\theta_s$  determines the peak values of these odd harmonics. Furthermore, the harmonic equations produced from (2) are transcendental equations. Based on the harmonic elimination theory to eliminate the  $n^{\text{th}}$  harmonic, equate

$$\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \dots + \cos(n\theta_s) = 0 \quad (2)$$

That means choose a series of switching angles to make  $n^{\text{th}}$  harmonic be zero. Therefore, to control the  $s$  different harmonic values use an equation with  $s$  switching angles. Generally, For a single level inverter an equation with  $s$  switching angles is used to determine the fundamental frequency value, and to eliminate  $s-1$  low order harmonics. For an equation with three switching angles, (2) becomes

$$V(t) = \sum_{n=1,3,5}^{\infty} 4V_{dc}/n\pi(\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \dots + \cos(n\theta_s)) \sin(n\omega t) \quad (3)$$

In comparison to other PWM techniques multilevel SHE-PWM technique provides highest output power quality at low switching. This technique also called as programmed PWM technique [13]. Each phase in three-phase structure of a five-level cascade inverter consists of two series connected H-bridge inverters H1 and H2, and each H bridge cell is fed by an isolated dc source. From the sum of the output voltage of these cells, the output phase voltage is obtained. By the SHE-PWM technique, the switching angles for each cell of the five-level cascade inverter are calculated for a quarter of a period.

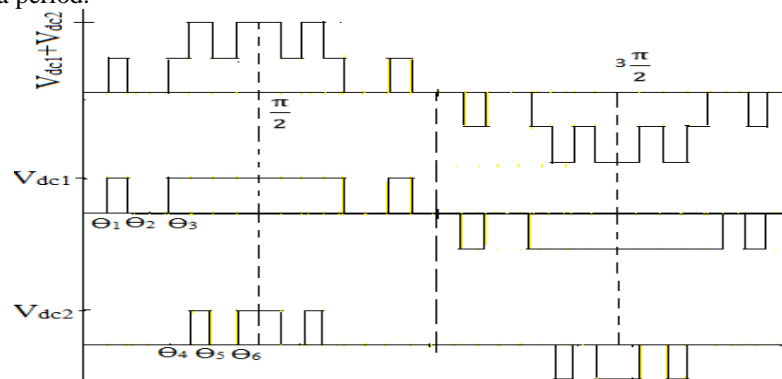


Fig. 2. Five-level phase voltage output

Each cell of such a single-phase inverter switches  $m$  times per quarter cycle. The sum of the output voltages of the cells H1 and H2 is corresponds to the amplitude of the  $n^{\text{th}}$  harmonic of the inverter phase voltage.

$$V_n = 4V_{dc1}/n\pi(\cos(n\alpha_1) \pm \cos(n\alpha_2) \pm \dots \pm \cos(n\alpha_m)) + 4V_{dc2}/n\pi(\cos(n\beta_1) \pm \cos(n\beta_2) \pm \dots \pm \cos(n\beta_m)) \quad (4)$$

where  $V_{dc1}$  and  $V_{dc2}$  are the input dc voltages of the cells H1 and H2, and  $n$  is the order of the harmonics respectively. Theoretically, by solving  $2m-1$  non-linear equation  $2m-2$  odd harmonics can eliminate. To achieve this equate the amplitudes of the selected harmonics to zero and setting the fundamental to a desired value. Considering Fig. 2, with equal DC sources amplitude, the Fourier series expansion of this waveform is:

$$V(\omega t) = \sum_{n=1,3,5}^{\infty} 4V_{dc}/n\pi(\cos(n\theta_1) \pm \cos(n\theta_2) \pm \dots \pm \cos(n\theta_s)) \sin(n\omega t) \quad (5)$$

The switching angles  $\theta_1 - \theta_p$  must satisfy the following equation:

$$0 \leq \theta_1 \leq \theta_2 \dots \leq \theta_s \leq \frac{\pi}{2} \quad (6)$$

In equation (4), The rising and falling edges of the voltage waveform are indicated by positive signs and negative signs respectively. In this paper, a five-level cascaded inverter and  $p=3$  is chosen as a case study, where  $p$  is the number of switching events per quarter cycles for each H-bridge. To improve the fundamental component and to eliminate four low-order harmonics i.e. 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup>, there need six angles as degrees of freedom. For three phase system, elimination of triplen harmonics i.e. 3<sup>rd</sup>, 9<sup>th</sup>, 15<sup>th</sup> is not necessary because they are eliminated automatically from line-line voltage [14]. In other words, for five-level inverters with  $p=3$ , the following non-linear equation should be solved:

$$\begin{aligned} \left(\frac{S\pi}{4}\right)M &= V_{dc}(\cos(\theta_1) \pm \cos(\theta_2) \pm \cos(\theta_3) \pm \dots \pm \cos(\theta_s)) \\ 0 &= \cos(5\theta_1) \pm \cos(5\theta_2) \pm \cos(5\theta_3) \pm \dots \pm \cos(5\theta_s) \\ 0 &= \cos(7\theta_1) \pm \cos(7\theta_2) \pm \cos(7\theta_3) \pm \dots \pm \cos(7\theta_s) \\ 0 &= \cos(11\theta_1) \pm \cos(11\theta_2) \pm \cos(11\theta_3) \pm \dots \pm \cos(11\theta_s) \\ 0 &= \cos(13\theta_1) \pm \cos(13\theta_2) \pm \cos(13\theta_3) \pm \dots \pm \cos(13\theta_s) \end{aligned} \quad (7)$$

Where, M is modulation index and defined as:

$$M = \frac{\pi V_1}{4S V_{dc}} \quad (0 \leq M \leq 1) \quad (8)$$

Where  $V_1$  is the fundamental of output voltage,  $V_{dc}$  is the input dc voltage and S is the number of H-bridge sections. It is necessary to determine six switching angles, namely  $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$  and  $\theta_6$  such that the equation set (6) are satisfied. The above non-linear transcendental equations are known as SHE-PWM equation. They may have multiple solutions. The solution of this SHE-PWM equation equations is obtained by applying Particle Swarm Optimization(PSO) technique.

#### IV. PARTICLE SWARM OPTIMIZATION(PSO) FOR FUNCTION OPTIMIZATION

The PSO algorithm is very simple but powerful. For artificial neural networks or to minimize/maximize high dimensional function the PSO can be used as a training method. PSO adapts this behaviour and searches for the best solution-vector in the search space. Here each particle represents a single solution. Each particle has a fitness/cost value and velocity. The fitness/cost value of each particle is evaluated by the function to be minimized, and the velocity that directs the "flying" of the particles. The optimum solution is achieved by following the optimum particles in the search space. The algorithm is initialized with particles at random positions, and then it explores the search space to find better solutions. In every iteration, each particle adjusts its velocity to follow two best solutions. The first is the cognitive part, where the particle follows its own best solution found so far. This is the solution that produces the lowest cost (has the highest fitness). This value is called pBest (particle best). The other best value is the current best solution of the swarm, i.e., the best solution by any particle in the swarm. This value is called gBest (global best). Then, each particle adjusts its velocity and position with the following equations:

- $v' = wv + c1.r1.(pBest - x) + c2.r2.(gBest - x)$
- $x' = x + v'$

$v$  is the current velocity,  $v'$  the new velocity,  $x$  the current position,  $x'$  the new position, pBest and gBest as stated above, r1 and r2 are even distributed random numbers in the interval [0, 1], c1 and c2 are acceleration coefficients and w is the inertia weight. Where c1 is the factor that influences the cognitive behaviour, i.e., how much the particle will follow its own best solution, and c2 is the factor for social behaviour, i.e., how much the particle will follow the swarm's best solution.

**V. ADJUSTABLE DC SOURCE WITH MSHE-PWM CHI**

Without affecting the structure of the inverter circuit, MSHE-PWM method optimizes both the dc-voltage levels and the switching angles, thereby eliminating more harmonics. The method provides linear patterns of dc-voltage levels for constant

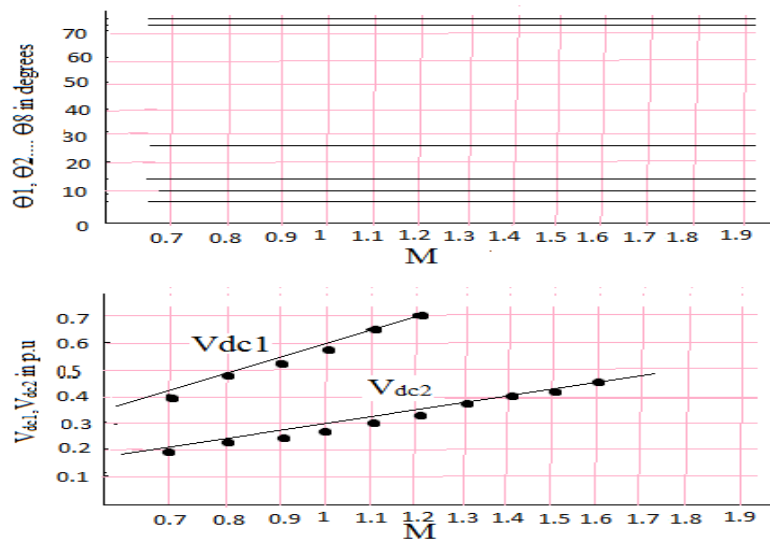


Fig.3. Switching angle and dc-voltage levels solution for five-level waveform  $0.64 < M < 1.72$ .

switching angles over the modulation index range. Thereby it eliminates the tedious steps required for offline calculation of switching angles and therefore, MSHE-PWM implementation for dynamic systems make easy. As modulation index changes the corresponding set of switching angle also changes according to equation(7). But in case of two adjustable dc source, for different modulation index by linearly varying the the dc source the same harmonic profile obtained according to equation(4). In equation (4)  $V_n$  define the harmonic and fundamental value, and that depends on modulation index value. The above technique increases the number of freedoms for harmonic elimination, leading to better harmonic profile and wider converter's bandwidth. Compared to fixed voltage dc levels, it provides solution of the switching angles for a much wider range of the modulation index. Fig. 3. shows switching angle and dc-voltage levels solution for five-level waveform for a modulation index ranges from  $0.64 < M < 1.72$ .

**IV SIMULATION AND RESULTS**

The Simulation circuit of cascaded h-bridge inverter with SHE-PWM technique for the eliminatin of four lower order hamonics is shown in Fig 4. The PSO algorithm is used for the calculation of the values of  $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$  &  $\theta_6$ .

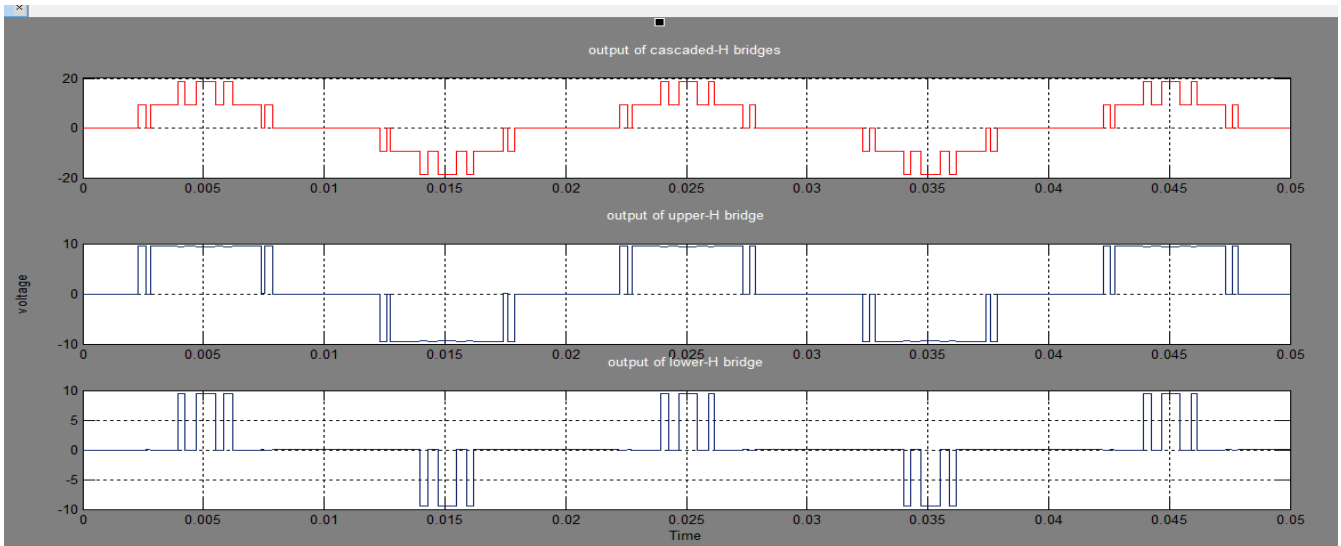


Fig.4. Simulation outputs

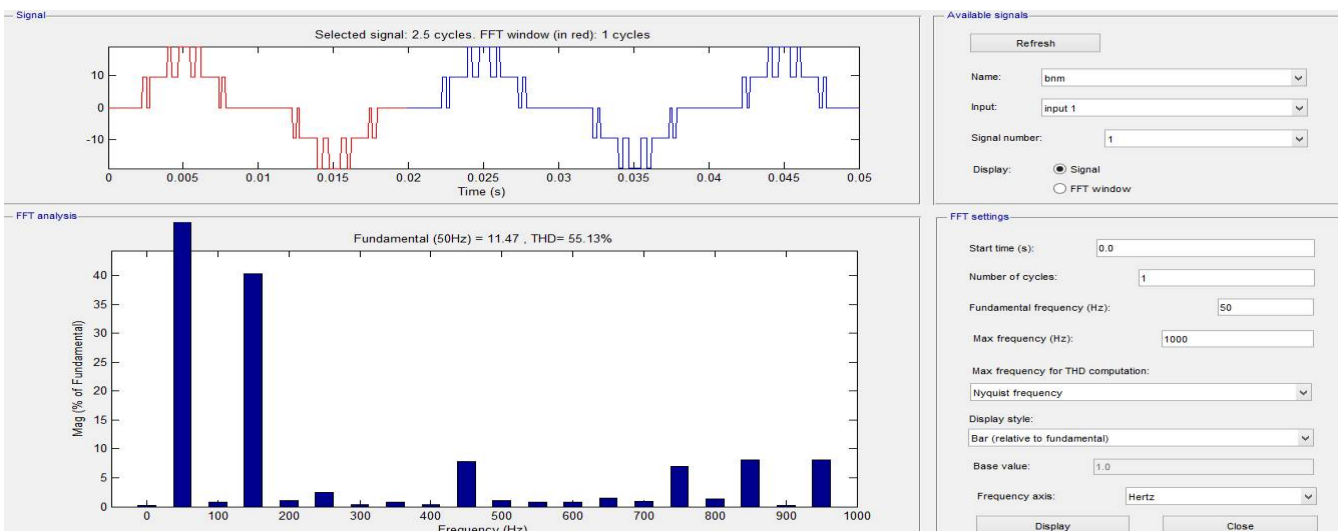


Fig.6. FFT analysis

The function corresponds to SHE-PWM equation is programmed as:

```
function [z]=fnm(x1,x2,x3,x4,x5,x6)
j=1;
while(j<8)
    F(j)=(cos(((2*j)-1)*((pi/180)*x1))-cos(((2*j)-1)*((pi/180)*x2))+cos(((2*j)-1)*((pi/180)*x3))+cos(((2*j)-1)*((pi/180)*x4))-cos(((2*j)-1)*((pi/180)*x5))+cos(((2*j)-1)*((pi/180)*x6)));
    j=j+1;
end
z=(abs(F(1))-
(pi*0.7/4))+abs(F(2))+abs(F(3))+abs(F(4))+abs(F(5))+abs(F(6))+abs(F(7)));
end
```

The simulation of basic cascaded 5-level inverter is done by using MATLAB software. The values of input DC voltage and load resistance is taken as  $V_1 = 10\text{v}$ ,  $V_2 = 10\text{v}$ ,  $R = 10\ \Omega$ ,  $F = 50\ \text{Hz}$ .

The simulation output of MSHE-PWM cascaded H-bridge inverter after eliminating 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> harmonic is shown in Fig.4. The switches are operated by repeating pulses. The FFT analysis of corresponding output waveform is shown in Fig.5. The output waveform of contains high triplen and higher order harmonics. At the same time all lower order harmonics are eliminated by SHE-PWM. The THD value of the output waveform is 55.13 % . almost 85% of THD is due to triplen harmonics. The increased triplen harmonics are eliminated while change over to line voltage and the higher order harmonics are easily eliminated by a low pass filter. Hence obtain a THD value that's less than 10 %.

## VI. CONCLUSION

A novel MSHE-PWM control technique implementable with the cascaded H-bridge topology was proposed and investigated in this paper. The proposed formulation of the MSHE-PWM provides an output with a wider range of modulation index by making the dc-voltage levels variant without affecting the number of harmonics being eliminated. It further provides constant switching angles and linear pattern of dc-voltage levels over the full range of the modulation index, which in turn eliminates the tedious steps of the offline calculations of switching angles and eases the implementation of the MSHE-PWM for dynamic systems such as STATCOM. Different loading conditions were considered in both simulation and experimental studies and it was found that the proposed method outperforms the latter in many aspects such as output voltage harmonic profile (THD), response time, and steady-state performances. Variable dc-voltage sources were obtained through a simple dc-dc converter, where the advancement and the rapid development in power semiconductor devices and advanced materials promised high efficiency dc-dc conversion systems. Although only buck converter was considered in this paper, however, other topologies can be equally applied and this will be investigated in future works for potential maximization of the system efficiency and performance.

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