



# SW - PWM for High Power DC-DC Boost Converter in Automotive Fuel Cell Application

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## Abstract

The dc-dc converter plays vital role in high current and high power application. Recently, dual-input DC-DC converter with Pulse Width Modulation (PWM) and Zero Current Switching (ZCS) interleaved boost dc-dc converter made switching more complicated due to the complexity in auxiliary circuit and variable phase shift angle. In this work, a Sliding Window-based Pulse Width Modulation (SW-PWM) technique is introduced to develop an efficient high power dc-dc converter for higher end power required in automotive fuel cell application like portable power generation, stationary power generation and power for transportation. The Sliding Window modulates the pulse with varied threshold constants for zero voltage switching and zero current switching modes of operandi. The on-off behaviour changes the average power of the signal due to slider window control. By switching voltage to the load with appropriate duty cycle, the output approximates a voltage at the desired threshold level. The switching noise during modulation is filtered with an inductor and a capacitor in the auxiliary circuit. The simulation of SW-PWM converter used in various high output power application is conducted. The performance study of proposed technique is done with metrics such as switching time, switching noise, power outputs and converter switching time gain ratio.

**Keywords:** DC-DC converter, Duty cycle, Pulse Width Modulation, Sliding Window, Zero-current-switching

## 1. INTRODUCTION

Fuel cell is a device used for converting the chemical energy into electricity through chemical reaction of hydrogen ions with oxygen. Fuel cells are not similar to the batteries because they require continuous source of fuel and oxygen or air to maintain the chemical reaction. In battery, the chemicals in the battery react with other to create electromotive force (emf). Fuel cells generate electricity for the given inputs. Fuel cells are used as standalone system or mixture with additional power/energy sources like battery or super-capacitor bank. Hybridization increases the system results on many features like less fuel cell cost, separating the fuel cell from load variations and improving the dynamic reaction. Hybrid fuel cell power conversion systems are suitable for applications where the average power demand is low at the same time the load dynamic are high. Proton exchange membrane fuel cells (PEMFCs) are called as polymer electrolyte membrane (PEM) fuel cells. Proton exchange membrane fuel cells (PEMFCs) are used for sliding window Pulse Width Modulation for high power DC-DC Boost Converter. PEMFC are a kind of fuel cell designed also for transport applications, stationary fuel cell applications and portable fuel cell applications. Proton exchange membrane (PEM) fuel cells are good candidate for many applications like automotive propulsion because of zero emission, low temperature and high power density.

In zero-voltage-switching pulse-width modulation (ZVS-PWM), interleaved boost dc/dc converter combines the conventional pulse-width-modulation technique and soft commutation technique to increase the circuit

performance. The two boost dc/dc converters with interleaved operation are aimed for improving the output power and reduce the input ripple current and output ripple voltage. But, the switching time is remained unaddressed. A zero-current-switching (ZCS) pulse-width modulation (PWM) interleaved boost dc/dc converter by ZCS-PWM auxiliary circuit is designed. All semiconductor devices in interleaved boost converter function at ZCS turn on and turn off. The converter functions at constant frequency and minimizes the commutation losses. The converter fails to have the current and voltage stress and conduction loss in main switch compared with hard switching converter counterpart. The interleaved boost dc/dc converter is used for the high-power application by insulated gate bipolar transistor (IGBT's).

An efficient dc-dc converter is indispensable to manage high end power by switching action to provide zero voltage switching and zero current switching to provide high performance. Zero-Voltage-Switching Pulse Width Modulation (ZVS-PWM) [1] combined pulse width modulation technique and soft commutation aiming at solving the problem of switching losses and electromagnetic interference (EMI). Zero-Current-Switching Pulse Width Modulation (ZCS-PWM) [2] used insulated gate bipolar transistor (IGBT) to reduce commutation losses at constant frequency. An isolated dual input dc-dc converter [3] was used to improve the performance of the proposed PWM converter. Pulse Width Modulation in Body Coupled Communication [5] resulted in the efficiency of more distinct duty cycles.

With increase in the number of mobile users, the radio capacity of dc-dc converter is fully occupied. In [6], Double Inverse Pulse Position Modulation (DIPPM) was applied to transmit data that resulted in the normalized power requirement. A novel PWM control scheme was designed in [7] with the objective of providing high power permanent magnet synchronous motor (PMSM). In [8], harmonic of power system was combined with space vector pulse width modulation aiming at reducing the total harmonic distortion. In [9], a comprehensive modelling of PWM converter for three-phase Voltage Source Converter (VSC) was designed. In [10], the study of operation mode and control strategies was designed using Extended Direct Duty Pulse Width Modulation (EDDPWM) with the objective of reducing the ripple effect.

In modern high-voltage power transmission systems, flexible alternating current transmission systems (FACTS) are highly required and applied for power quality smoothing using parameters impedance, current, or voltage. With the objective of reducing the harmonic balance in output voltage signals, PWM [11] was applied. A novel digital sinusoidal PWM [12] was designed based on duty cycle count (DCC) aiming at reducing the overhead time. Another method using

Optical pulse dynamics [13] resulted in the improvement of input power. Linearity of RF pulse width modulation was studied in [14] to enhance the linearity of the transmitter. In [15], Pulse Width Modulation and Pulse Density Modulation (PDM) were applied to reduce the signal to noise ratio using Noise Transfer Function (NTF). Voltage Controlled Oscillators (VCOs) are extensively used for On-Chip Power Management (OCPM) for efficient generation of switching signal where certain characteristics of this signal can be controlled. In [16], Digitally Controlled Pulse Width Modulation was designed aiming at improving the accuracy under Process, Voltage and Temperature (PVT) variations. In [17], performance analysis of unipolar PWM current was analyzed. In [18], Subtraction Complementary technique was applied aiming at improving the correlation using PWM. With the objective of reducing the power loss, in [19], Hysteresis Band was applied which not only resulted in reducing the power loss but also improved the switching efficiency. In [20], novel control strategy using Lyapunov method was designed aiming at improving the effectiveness. In [21] The ZVS and ZCS techniques are used to reduce the stress in input and output voltages/currents, reducing the switching losses, reducing the size of filter capacitor and overall cost. When compared to conventional switching methods the proposed method is improving the overall performance as well as increasing the efficiency of the converter. Nowadays the PWM based interleaved boost converter is used in power electronics applications like Photovoltaic converters, fuel cell applications, hybrid systems and power factor correction circuits.

This paper proposes a novel kind of modulation method based on the Pulse Width Modulation for the higher end power required in automotive fuel cell application using sliding window control. The sliding window control modulates the pulse with varied threshold constants for zero voltage switching and zero current switching. The modulation theory and computation of this technique is simple, which is based on the sliding window-based pulse width modulation algorithm and appropriate duty cycle strategy. It also proved to be efficient in improving the output voltage and current.

## 2. DESIGN OF DC-DC BOOST CONVERTER TOPOLOGY

In boost converter, the output voltage is comparatively higher than that of the input voltage. A boost converter using a switch M is shown in Fig 1.

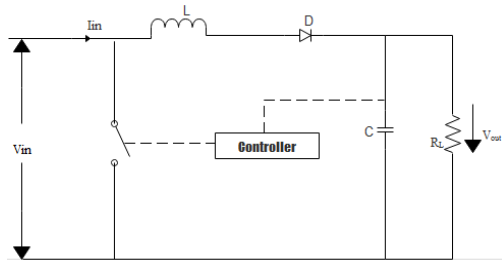


Fig 1 Design of DC-DC Boost Converter

The function of boost converter divided into two controls is direct control and indirect control. The direct control begins when switch M gets switched on at time  $t=0$ . The input current increases and runs through inductor L and switch M. Indirect control starts when switch S is switched off at time  $t=t_1$ . The input current now flows through L, C,  $R_L$ , and diode  $D_d$ . The inductor current flows till the next cycle starts. The energy stored in inductor L flows through the load.

The voltage-current relation for the inductor L is given by (i) and (1),

$$i = \frac{1}{L} \int_0^t V_{in} dt \quad (i)$$

$$V_{in} = L \frac{di}{dt} \quad (1)$$

### 3. DESIGN OF SLIDING WINDOW IN AUTOMOTIVE FUEL CELL APPLICATION

In this section, varied threshold constants for zero voltage switching and zero current switching modes of operation are presented using Sliding Window. The Sliding window is the process of modulating the pulse with varied threshold constants for zero voltage switching and zero current switching modes of operation.

These two varied threshold constants are direct and indirect sliding window control aiming at improving the output voltage and current respectively. Fig 2 and 3 shows the block diagram of Direct Sliding Window control and Indirect Sliding Window control of the proposed Sliding Window-based Pulse Width Modulation respectively.

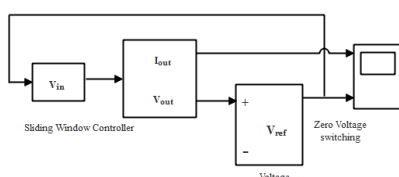


Fig 2 Block diagram of Direct Sliding Window control

Direct Sliding Window control is based on the output zero voltage switching, where the output voltage ' $V_{out}$ '

is compared with the reference voltage ' $V_{ref}$ '. Therefore, the Sliding Window surface is formulated as given below.

$$DSW_s = V_{out} - V_{ref} \quad (2)$$

From (2), the direct sliding window surface ' $DSW_s$ ' is formulated based on the output voltage ' $V_{out}$ ' and reference voltage ' $V_{ref}$ ' respectively, aiming at improving the output voltage in a significant manner.

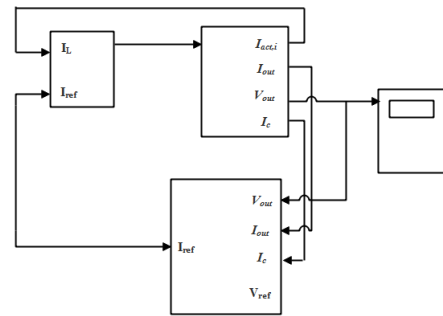


Fig 3 Block diagram of Indirect Sliding Window control

Indirect Sliding Window control is based on the zero current switching satisfying desired output voltage ' $V_{out}$ '. In this Indirect Sliding Window control method, due to the variation in load, initially, the output impedance ' $Z_{out}$ ' is obtained by the ratio of output voltage ' $V_{out}$ ' to the output current ' $I_{out}$ ' and is mathematically formulated as given below.

$$Z_{out} = \frac{V_{out}}{I_{out}} \quad (3)$$

From (3), the output impedance ' $Z_{out}$ ' is measured and then the desired load current ' $I_L$ ' is evaluated by the ratio of reference voltage ' $V_{ref}$ ' to the output impedance ' $Z_{out}$ '. It is mathematically formulated as given below.

$$I_L = \frac{V_{ref}}{Z_{out}} \quad (4)$$

So the Indirect Sliding Window surface ' $ISW_s$ ' is defined by comparison between actual indirect current ' $I_{act,i}$ ' and desired load current ' $I_L$ ' as the following:

$$ISW_s = I_{act,i} - I_L \quad (5)$$

From (5), the Indirect Sliding Window surface ' $ISW_s$ ' for zero current switching mode is obtained that in turn improves the output current in automotive fuel cell application. Fig 4 shows the Sliding Window algorithm.

|                                                                                                                                                                                                                                                     |                                                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| Input: output voltage ' $V_{out}$ ', reference voltage ' $V_{ref}$ ',<br>output voltage ' $V_{out}$ ', output current ' $I_{out}$ ', reference<br>voltage ' $V_{ref}$ ', actual indirect current ' $I_{act,i}$ ', desired<br>load current ' $I_L$ ' |                                                                   |
| Output: Improved output voltage and output current                                                                                                                                                                                                  |                                                                   |
| Step 1: Begin                                                                                                                                                                                                                                       |                                                                   |
| Step 2:                                                                                                                                                                                                                                             | Measure output voltage ' $V_{out}$ '                              |
| Step 3:                                                                                                                                                                                                                                             | Measure reference voltage ' $V_{ref}$ '                           |
| Step 4:                                                                                                                                                                                                                                             | Evaluate Sliding Window surface using<br>(2)                      |
| Step 5:                                                                                                                                                                                                                                             | Measure output current ' $I_{out}$ '                              |
| Step 6:                                                                                                                                                                                                                                             | Evaluate output impedance ' $Z_{out}$ '<br>using (3)              |
| Step 7:                                                                                                                                                                                                                                             | Evaluate desired load current ' $I_L$ ' using<br>(4)              |
| Step 8:                                                                                                                                                                                                                                             | Evaluate Indirect Sliding Window<br>surface ' $ISW_s$ ' using (5) |
| Step 9:                                                                                                                                                                                                                                             | End                                                               |

Fig 4 Sliding Window Algorithm

The sliding window algorithm is designed with the objective of improving the output voltage and output current and to develop an efficient high power dc-dc converter for higher end power required in automotive fuel cell application. To achieve this, both direct and indirect sliding window surface is measured using reference voltage and desired load current with respect to output voltage and desired load current respectively.

## DESIGN OF SLIDING WINDOW-BASED PULSE WIDTH MODULATION

The Sliding Window-based Pulse Width Modulation (SW-PWM) technique determines the changing instances of the square wave and measures how long the square wave stays "on". By switching voltage to the load with the appropriate duty cycle, the output approximates a voltage at the desired threshold level. The duty cycle and time period are then mathematically formulated as given (ii & iii) below.

$$\text{Duty Cycle (D)} = \frac{T_{ON}}{T_{ON} + T_{OFF}} \quad (\text{ii})$$

$$D = \frac{T_{ON}}{T} \quad (\text{6})$$

$$T_{ON} = D * T \quad (\text{7})$$

$$T_{OFF} = T - T_{ON} \quad (\text{iii})$$

$$T_{OFF} = T - D * T \quad (\text{iv})$$

$$T_{OFF} = (1 - D)T \quad (\text{8})$$

From (6), the 'duty cycle' due to sliding window control is the ratio of percentage on time ' $T_{ON}$ ' and total time period (i.e., on time and off time) ' $T$ ' which is also referred to as the percentage measure of how long the square wave stays on. Fig 5 shows the Pulse Width Modulation Duty Cycle.

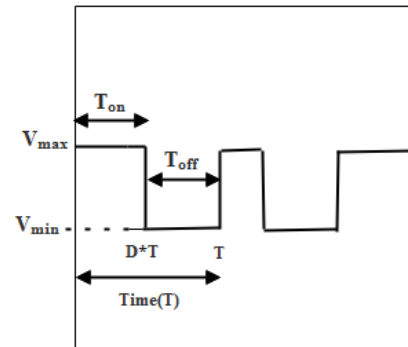


Fig 5 Pulse Width Modulation Duty Cycle

The Pulse Width Modulation in SW-PWM technique approximates the voltage at the desired threshold level and therefore controls the power delivery. The on-off behaviour of PWM changes the average power of the signal due to slider window control. The on-off behaviour alternates within a specified time interval (i.e. ' $T$ ') and is mathematically formulated as given below.

$$Alt = \frac{1}{T} \int_0^T f(t) dt \quad (\text{9})$$

From (9), the on-off alternate behaviour ' $Alt$ ' is then a measure of alternate values of specified time interval of time ' $T$ '. The average power of the signal due to slider window control is then mathematically formulated as given below.

$$Alt = \frac{1}{T} \left( \int_0^{D*T} V_{max} dt + \int_{D*T}^T V_{min} dt \right) \quad (\text{10})$$

$$= \frac{D * T * V_{max} + T * (1 - D) * V_{min}}{T} \quad (\text{11})$$

$$V_{avg} = (D * V_{max}) + (1 - D) * V_{min} \quad (\text{12})$$

From (12), the average power of the signal is measured where ' $V_{min}$ ' is taken as zero volts whereas ' $D$ ' refers to the duty cycle. If signal toggles between on and off is quicker than the load, then the load is not affected by the toggling. By switching the voltage to the load with the appropriate duty cycle and average power of the signal, the output efficiently approximates the voltage to the desired level.

When the slider window control switch M gets turned on, the difference in the current value is given by,

$$\Delta_i = \frac{(V_{in} - V_m)T_{ON}}{L} \quad (13)$$

From (13), the input voltage and the voltage across the switch is represented as ' $V_{in}$ ' and ' $V_m$ ' respectively. When the slider window control switch gets turned off, the difference in the current value is given by,

$$\Delta_i = \frac{(V_{out} - V_{in} + V_D)T_{OFF}}{L} \quad (14)$$

From (14), the voltage drop across the diode ( $D_a$ ) is denoted as ' $V_D$ '. The output voltages are represented by ' $V_{out}$ '. By equating (14) and (15) through the delta  $i$ , ' $V_{out}$ ' is calculated.

$$\frac{(V_{in} - V_m)T_{ON}}{L} = \frac{(V_{out} - V_{in} + V_D)T_{OFF}}{L} \quad (15)$$

From (7) and (8), the equation (15) is written as,

$$(V_{in} - V_m)D = (V_{out} - V_{in} + V_D)(1 - D) \quad (16)$$

By neglecting the voltage drop across the diode ' $V_D$ ' and the switch ' $V_m$ ',

$$V_{out} = \left( \frac{V_{in}}{1 - D} \right) \quad (17)$$

For ' $N$ ' number of capacitor and diode used in the dc-dc boost converter circuit, equation (19) is written as,

$$V_{out} = \left( \frac{N}{1 - D} \right) * V_{in} \quad (18)$$

From (18), the output and input voltages are represented by ' $V_{out}$ ' and ' $V_{in}$ ' with switch-on duty ratio denoted by ' $D$ ' for the switch ' $S$ '. ' $N$ ' is the number of capacitor and diodes used in the capacitor circuit of the converter. One of the most essential metrics in the proposed technique is the switching time. This in turn minimizes the converter switching time. It also helps in measuring the switching losses in automotive fuel cell application in an extensive manner.

The noise occurring during switching from 'on-off' to 'off-on' noise is filtered with an inductor and a capacitor in the auxiliary circuit. When output voltage is lower than the input voltage, slider window control turns on the switch. When the output voltage is above the input voltage ( $V_{in}$ ), slider window control turns off the switch.

$$\text{if}(V_{out} < V_{in}) \text{ then } SWC = 'ON' \quad (19)$$

$$\text{if}(V_{out} > V_{in}) \text{ then } SWC = 'OFF' \quad (20)$$

From (19) and (20), the slider window control efficiently switches between 'ON' and 'OFF' according to the measure between the noise 'Noise' and the desired output voltage ' $V_{out}$ ' respectively. Fig 6 shows the Sliding Window-based Pulse Width Modulation algorithm.

|                                                                                                    |                                                 |
|----------------------------------------------------------------------------------------------------|-------------------------------------------------|
| Input: On time, Time period ' $T$ ', Minimum voltage ' $V_{min}$ ', Maximum voltage ' $V_{max}$ ', |                                                 |
| Output:                                                                                            |                                                 |
| Step 1:                                                                                            | Begin                                           |
| Step 2:                                                                                            | For each time period ' $T$ '                    |
| Step 3:                                                                                            | Measure duty cycle using (6)                    |
| Step 4:                                                                                            | Measure on-off behaviour alternates using (9)   |
| Step 5:                                                                                            | Measure average power of the signal using (12)  |
| Step 6:                                                                                            | End for                                         |
| Step 7:                                                                                            | If ( $V_{out} < V_{in}$ )                       |
| Step 8:                                                                                            | Then slider window control turns on the switch  |
| Step 9:                                                                                            | End if                                          |
| Step 10:                                                                                           | If ( $V_{out} > V_{in}$ )                       |
| Step 11:                                                                                           | Then slider window control turns off the switch |
| Step 12:                                                                                           | End if                                          |
| Step 13:                                                                                           | End                                             |

**Fig 6 Sliding Window-based Pulse Width Modulation Algorithm**

As shown in the Fig above, the Sliding Window-based Pulse Width Modulation algorithm initially measures the duty cycle for each period with the aid of the low voltage and high voltage value. Based on the value of the duty cycle obtained, the on-off behaviour alternates are measured to reduce the switching noise on the basis of period. Followed by the alternate on-off behaviour value, the average power of the signal is measured due to slider window control. As a result, the slider window control turns on and off the switch by comparing the output and input voltage.

#### 4. EXPERIMENTAL SETTINGS

Simulation experiments are conducted with Matlab Simulink to achieve high output power with reduced ripple effects on the current and voltage gains using, the proposed SW-PWM technique in MATLAB platform. There are three modes converter implemented in MATLAB. The model consists of output voltage and inductor current which is in the system. Interleaved boost converter consists of parameter namely inductance, capacitance and internal resistance.

The performance of proposed SW-PWM technique is compared with the existing Zero-Voltage-

Switching Pulse Width Modulation (ZVS-PWM) [1] and Zero-Current-Switching Pulse Width Modulation (ZCS-PWM) [2]. The feasible study of the system is done by experimenting through the factors such as o/p power, switching noise, switching time and converter switching time gain ratio with voltage and current settings.

The performance analysis of Sliding Window-based Pulse Width Modulation (SW-PWM) technique is carried out using MATLAB for various simulation settings. Maximum-likelihood training is performed with the objective of measuring a closed-form expression that takes linear time in order to achieve high output power with reduced switching noise on the zero voltage switching and zero current switching modes of operandi in the proposed high power dc-dc converter for higher end power required in automotive fuel cell application. It is compared with the existing Zero-Voltage-Switching Pulse Width Modulation (ZVS-PWM) [1] and Zero-Current-Switching Pulse Width Modulation (ZCS-PWM) [2]. The performance is evaluated according to the following metrics.

#### Impact of Power Output

The power output power for higher end power required in automotive fuel cell application using Sliding Window Based Pulse Width Modulation (SW-PWM) technique is measured by applying the input voltage ' $V_{in}$ ' and input current ' $I_{in}$ ' respectively. The dc-dc power converter for higher end power is measured by the product of input voltage and input current. The converter power output is measured in terms of watts. The mathematical evaluation for converter power output is given as below.

$$\text{Power output (Watts)} P_{out} = V_{in}(\text{Dc supply in volts}) * I_{in}(\text{Amperes}) \quad (21)$$

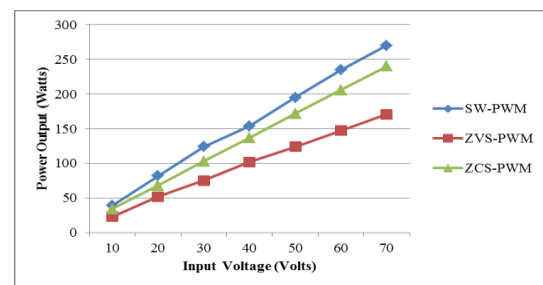
The dc-dc converter power output evaluated using the three methods are as given below.

|                                                       |
|-------------------------------------------------------|
| Power output (using SW-PWM) = 10(V) * 5(A) = 40W      |
| Power output (using ZVS-PWM) = 10 (V) * 2.5(A) = 25W  |
| Power output (using ZCS-PWM) = 10 (V) * 3.5 (A) = 35W |

The performance indices for the power output with respect to varying cycles (i.e. input voltage) are shown in Fig 7. These statistical performance indices of power output gives a clear picture of performance improvement for SW-PWM technique when compared to ZVS-PWM and ZCS-PWM and is lower than ZVS-PWM and ZCS-PWM showing that SW-PWM technique has improved performance results in a steady manner with respect to differing cycles (i.e. input voltage). The quantitative results for these performance indices are given in Table 1.

**Table 1 Tabulation for power output**

| Input voltage (V) | Power output (watts) |         |         |
|-------------------|----------------------|---------|---------|
|                   | SW-PWM               | ZVS-PWM | ZCS-PWM |
| 10                | 39                   | 23      | 34      |
| 20                | 82                   | 52      | 68      |
| 30                | 124                  | 75      | 103     |
| 40                | 154                  | 102     | 137     |
| 50                | 195                  | 124     | 172     |
| 60                | 235                  | 147     | 206     |
| 70                | 270                  | 171     | 240     |



**Fig 7 Measure of power output with respect to input voltage**

In order to check the robustness of the proposed Sliding Window Based Pulse Width Modulation (SW-PWM) technique, series of cycles (i.e. input voltage) is applied to the system. The duration of 7 input voltages ranging from 10 V to 70 V are applied. It shows that the proposed SW-PWM technique is comparatively lower than the state-of-the-art works though the maximum power output is at  $V_{in} = 70$ , comparatively, optimization of power output achieves at  $V_{in} = 70$ , with 37.34% and 13.30% improvement compared to ZVS-PWM and ZCS-PWM respectively. A comparison of the results shows that SW-PWM technique has more performance improvement using Sliding Window that measures both direct and indirect sliding window surface, therefore, more suitable for the commercial systems for higher end power required in automotive fuel cell application.

#### Impact of Switching Noise

Switching noise is defined as the ratio of the root mean square (rms) value of the output voltage to the absolute value of the reference voltage. The mathematical evaluation of switching noise (i.e. switching voltage) is given below and is measured in terms of percentage (%).

$$\text{Switching noise (\%)} = \frac{\text{RMS value of output voltage}}{\text{absolute value of reference voltage}} * 100 \quad (22)$$

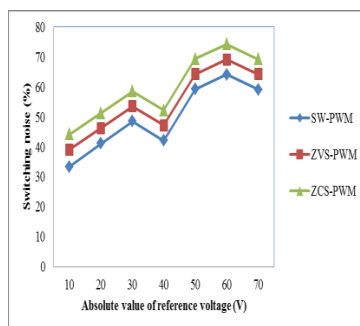
The switching noise obtained using the three methods are as given below.

Switching noise (using SW-PWM) =  $(3.3 \text{ (V)} / 10 \text{ (V)}) * 100 = 33\%$   
 Switching noise (using ZVS-PWM) =  $(3.8 \text{ (V)} / 10 \text{ (V)}) * 100 = 38\%$   
 Switching noise (using ZCS-PWM) =  $(4.3 \text{ (V)} / 10 \text{ (V)}) * 100 = 43\%$

The switching noise of the proposed SW-PWM technique is analysed using different reference voltage rates. Experiments are carried out with the reference voltage rate 10 V and 70 V and the response of the system is investigated in Table 2. The test bed of the proposed switching noise on varied reference voltage rate is depicted in Fig 8. The minimum switching noise of the proposed technique is observed between reference voltage 30 V and 40 V using all the methods. But comparatively, lower with the proposed technique that is measured as 48.55% to 42.16% and it varies according to the reference voltage rate and filtered with an inductor and a capacitor in the auxiliary circuit.

**Table 2 Tabulation for switching noise**

| Absolute value of reference voltage (V) | Switching noise (%) |         |         |
|-----------------------------------------|---------------------|---------|---------|
|                                         | SW-PWM              | ZVS-PWM | ZCS-PWM |
| 10                                      | 33.45               | 39.15   | 44.21   |
| 20                                      | 41.21               | 46.24   | 51.29   |
| 30                                      | 48.55               | 53.58   | 58.63   |
| 40                                      | 42.16               | 47.19   | 52.24   |
| 50                                      | 59.32               | 64.35   | 69.40   |
| 60                                      | 64.18               | 69.21   | 74.26   |
| 70                                      | 59.21               | 64.24   | 69.29   |



**Fig 8 Measure of switching noise with respect to absolute value of reference voltage**

The switching noise is given in Fig 8. The minimum switching time on multiple reference voltages with varied voltage is 42.16% which reaches to 759.21% respectively compared with the existing ZVS-PWM [1] and ZCS-PWM [2]. But the switching noise was found to be 53.58% to 47.19% using ZVS-PWM and 58.63% to 52.24% using ZCS-PWM was applied. So comparatively,

the switching noise by applying SW-PWM is observed to be less. This is because of the application of small variation of output impedance ' $Z_{out}$ ' and then the desired load current ' $I_L$ ', Sliding Window Control making an inference of 10.90% and 21.57% better comparatively to the two other existing methods [1, 2]. It is therefore significant that the proposed SW-PWM technique minimizes the switching noise in an appropriate and flexible manner.

### Impact of Switching Time

Switching time of the dc-dc converter for higher end power is defined as the summation of on time and off time. It is measured in terms of millisecond (ms).

$$\text{Switching Time (ms)} = T_{ON} + T_{OFF}$$

$$T_{sw} = T_{ON} + \left( \frac{V_{in}}{V_{out} - V_{in}} \right) T_{ON} \quad (23)$$

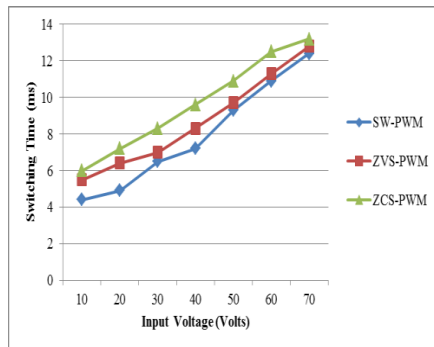
The switching time evaluated using the three methods is as given below.

Switching time (using SW-PWM) = 1.5 (ms) + 2.9 (ms) = 4.4 ms  
 Switching time (using ZVS-PWM) = 2 (ms) + 3.5 (ms) = 5.5 ms  
 Switching time (using ZCS-PWM) = 2.5 (ms) + 3.5 (ms) = 6 ms

**Table 3 Tabulation for switching time**

| Input Voltage (V) | Switching time (ms) |         |         |
|-------------------|---------------------|---------|---------|
|                   | SW-PWM              | ZVS-PWM | ZCS-PWM |
| 10                | 4.4                 | 5.5     | 6       |
| 20                | 4.9                 | 6.4     | 7.2     |
| 30                | 6.5                 | 7.0     | 8.3     |
| 40                | 7.2                 | 8.3     | 9.6     |
| 50                | 9.3                 | 9.7     | 10.9    |
| 60                | 10.9                | 11.3    | 12.5    |
| 70                | 12.4                | 12.8    | 13.2    |

Table 3 summarizes the simulation results of switching time for the proposed SW-PWM technique and elaborate comparison made with the existing methods ZVS-PWM [1] and ZCS-PWM [2] respectively with respect to differing input voltage signals between 10V and 70V respectively.



**Fig 9 Measure of switching time with respect to different input voltage**

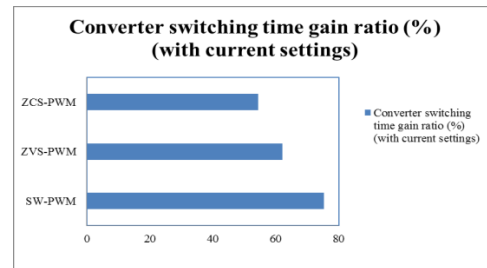
To decrease the switching time with respect to different input voltages, in this work Sliding Window-based Pulse Width Modulation algorithm is applied. The Sliding Window-based Pulse Width Modulation algorithm reduces the converter switching time as shown in Fig 9. The Sliding Window-based Pulse Width Modulation algorithm measures the duty cycle for each period with the aid of the low voltage and high voltage value. This in turn minimizes the converter switching time by 12.82% compared to ZVS-PWM. In addition, the average power of the signal is measured using slider window control by comparing the desired output voltage. This in turn minimizes the converter switching time of SW-PWM by 26.09% compared to ZCS-PWM.

#### Impact of Converter Switching Time Gain Ratio with Current Settings

Table 4 and Fig 10 show that the proposed SW-PWM technique provides higher amount of converter switching time gain ratio on varying input voltage signals in the range of 10V to 70V and different reference voltages in the range of 10V to 70V when compared to the existing ZVS-PWM [1] and ZCS-PWM [2].

**Table 4 Tabulation for converter switching time gain ratio**

| Methods | Converter switching time gain ratio (%) (with current settings) |
|---------|-----------------------------------------------------------------|
| SW-PWM  | 75.32                                                           |
| ZVS-PWM | 62.14                                                           |
| ZCS-PWM | 54.39                                                           |



**Fig 10 Measure of converter switching time gain ratio**

The converter switching time gain ratio efficiency is improved because of the application of Pulse Width Modulation in SW-PWM technique. It efficiently estimates the voltage at the desired threshold level and therefore controls the power delivery for various input signals. This in turn improves the converter switching time gain ratio on varying input signals by 17.49% and 12.47% compared to ZVS-PWM [1] and ZCS-PWM [2] respectively.

## 5. CONCLUSION

This work provides an insight into the developing of an efficient high power dc-dc converter for higher end power required in automotive fuel cell application using a technique called Sliding Window-based Pulse Width Modulation (SW-PWM). The integrated framework Sliding Window and Pulse Width Modulation is combined with varied threshold constants for zero voltage switching and zero current switching modes of operandi that efficiently helps in handling multiple current and voltage measure to minimize the converter switching time and improve the output voltage and current. A prototype of the multiple input signals with different cycles and input voltage and reference voltage was simulated and tested. A MATLAB environment with Simulink was used to calculate the converter switching time and switching noise on varying number of cycles followed by output voltage and output current. The technique also covered appropriate duty cycle and filtering the switching noises using inductor and a capacitor in the auxiliary circuit proving the efficiency of the technique. Simulation results show the power output improved by 25.32% on varied input voltages 10V to 70V. The transient response test shows that the switching noise was reduced by 16.24% on multiple speeds for varying reference voltage signals. The experimental measurements show that the converter switching time gets reduced by 12.82% to 26.09% compared to ZVS-PWM and ZCS-PWM respectively. Experiments results indicated that the proposed SW-PWM is an efficient technique that minimizes the converter switching time among various input signals in order to efficiently develop high power dc-dc converter in automotive fuel cell application.

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