Sliding Mode Control of a CLL Resonant dc to dc Converter for Fuel Cell Applications

N.Dhivya Aishwaryaa, Dr.K.Krishnamoorthi, Dr.R.Shivakumar

Abstract— In this paper, an isolated dc/dc converter is proposed for fuel cell applications. The output voltage from the fuel cell is very low typically about 30 volts. Hence the fuel cell output has to be conditioned so that it can be used for interfacing to the load. The proposed converter is composed of two parts, a boost converter and a CLL resonant converter. The CLL converter can be designed to have an optimal switching, regardless of the load conditions. A sliding mode control strategy for the proposed converter is also presented. Sliding-mode control has been widely used in both nonlinear and linear systems. It is well-known for its strong robustness against parameter uncertainties and load variation. The proposed controller operates at two fixed switching frequencies with sliding-mode control implementation. Simulink circuit models are developed for the proposed design and the results are used to validate the performance of the proposed sliding mode control strategy.

Index Terms — CLL resonant converter, dc/dc converter, Fuel cell, Sliding mode, voltage doubler.

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1 INTRODUCTION

Fuel cells are considered to be one of the most promising sources of distributed energy because of their high efficiency, low environmental impact and scalability. Unfortunately, multiple complications exist in fuel cell operation. Fuel cells cannot accept current in the reverse direction, do not perform well with ripple current, have a low output voltage that varies with age and current, respond sluggishly to step changes in load and are limited in overload capabilities. For these reasons, power converters are often necessary to boost and regulate the voltage as a means to provide a stiff applicable DC power source [5].

The operation of a fuel cell is similar to that of a battery in that a fuel cell employs two electrodes (anode and cathode) and produces DC voltage. One key advantage that fuel cells have over battery technology is the seemingly unlimited amount of power that can be produced as long as fuel is supplied. Unfortunately, as the amount of current is increased, the voltage drop is increased. For this reason, fuel cells are often modeled as ideal DC voltage sources with a series resistor. Most of the present fuel cell stack modules produce an output voltage in the range 24–150 volts DC. However, the large number of applications in which fuel cells can be implemented necessitates that a power electronics interface be present. This interface should:

1. control the fuel cell voltage
2. convert the fuel cell output to the appropriate type and magnitude

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3. deliver a high power factor (grid applications)
4. provide little to no harmonics
5. operate efficiently under all conditions.

Fig. 1.shows a general fuel-cell power generation system. Generally, the output voltage of the fuel cell stacks V_{FC} is varied from 24 to 40 V depending on the output power. In order to obtain a utility ac source (220-V rms at 50/60 Hz) from a fuel cell, a high dc bus voltage (380–400 V) is required at the input of the dc–ac inverter. Therefore, a high step-up dc–dc converter is needed to boost the low voltage at the fuel cell stacks into the high voltage at the dc bus [6].

Fig. 1. General fuel cell power generation system
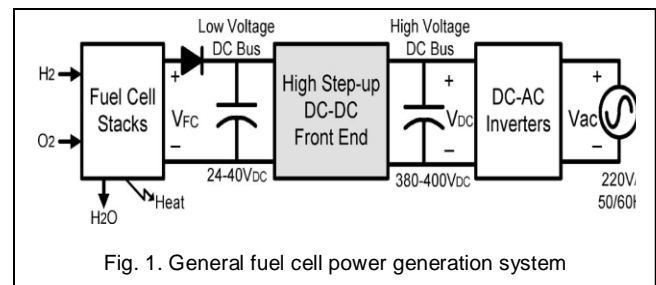
In general, a conventional boost converter can be adopted to provide a high step-up voltage gain with a large duty ratio. However, the conversion efficiency and the step-up voltage gain are limited due to the constraints of the losses of power switches and diodes [2]. Therefore, a step-up converter with a reasonable duty ratio to achieve high efficiency and high voltage gain is very important for a fuel-cell power generation system.

Converters, such as forward, flyback, half-bridge, full-bridge, and push–pull types, can be used to convert a low voltage into a higher output voltage by adjusting the turn ratio of the transformer. However, the active switch of these converters will suffer very high voltage stress and high power dissipation due to the leakage inductance of the transformer [6].

2 CONVENTIONAL CONVERTER

Voltage fed full-bridge converter shown in Fig. 2. is used for fuel cell power conditioning when electrical isolation is required.[5]. For electrical isolation and high boost ratio, forward, pushpull, half-bridge and full-bridge are other options. Nevertheless, the full-bridge converter is the best for fuel cell power conditioning, based on the following reasons:

1. The full-bridge converter is suitable for high-power transmission because transistor voltage and current stresses are not high. Generally, push-pull and forward converters are not suitable for high-power applications.

2. Compared to the half-bridge, both the device current rating and transformer turns ratio can be reduced by one-half.

3. The full-bridge converter has small input and output current and voltage ripples.

4. The full-bridge topology is mostly used for zero voltage switching (ZVS) pulse width modulation (PWM) techniques

Fig. 2. Voltage fed full bridge converter
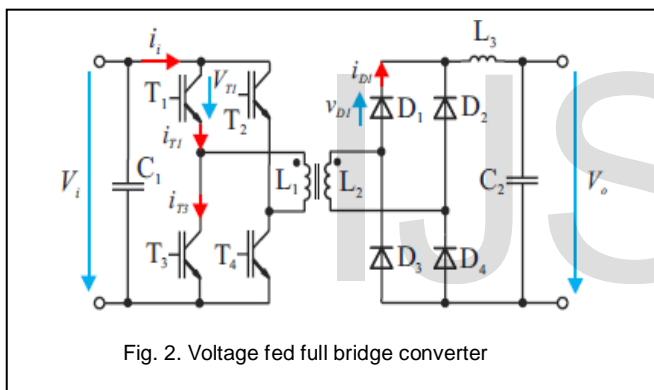
The voltage spikes of the secondary side of the transformer due to the resonance between the transformer leakage inductance and the diode junction capacitances are so severe that a high-voltage rating diode and an auxiliary snubber circuit are required.

It is one of the reasons of the efficiency degradation and electromagnetic interference. Moreover, the heavy turnoff switching loss of the primary switches may be an obstacle to increase their switching frequencies in high-current applications. Thus, they are not suitable for the use of a high-frequency converter [1].

3 PROPOSED SYSTEM

The proposed system for fuel cell power conditioning consisting of a dc to dc converter along with a CLL resonant converter is shown in the fig. 3. below. The function of each and every block is explained below.

Fig. 3. Block diagram of the proposed system
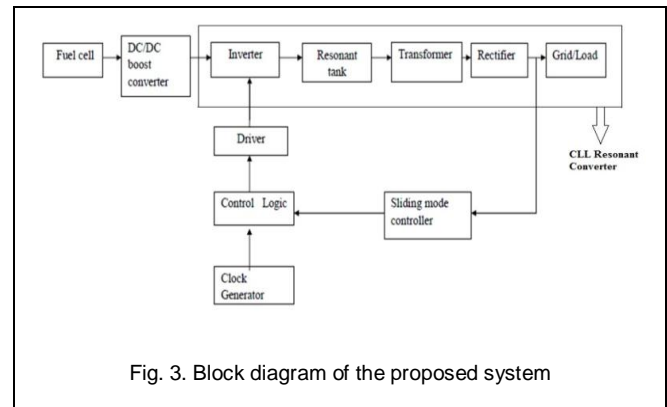
3.1 DC to DC Converter

DC to DC converters can be used as switched mode regulators to convert an unregulated dc voltage to a regulated dc output. The regulation is normally attained by PWM at a fixed frequency and the switching device is normally a BJT , MOSFET or IGBT [2] . Fig. 4. shows the DC to DC (Boost) converter circuit.

Fig. 4. DC to DC Converter
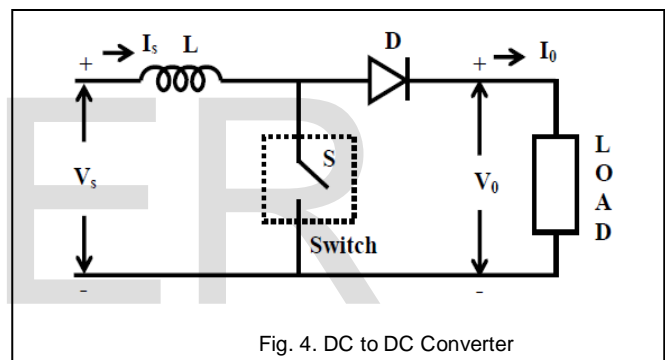
The boost converter produces an output voltage which is greater than the input voltage. The switch S is closed for a period $T_{ON} \leq t \leq 0$, where T_{ON} is the on period of the switch ,the output voltage is zero. The current from the source(i_s) flows in the inductance L. The value of current increases linearly with time in this interval, with di/dt being positive. As the current through L increases, the polarity of the induced emf is taken as, positive [9].

The switch, S is put OFF during the period, $T \leq t \leq T_{ON}$, the OFF period being ,$T_{OFF} = T - T_{ON}$, is the time period. As the current through L decreases, the induced emf reverses. So, the induced emf (taken as –ve) is added with the supply voltage, being of the same polarity, thus, keeping the current ($i_s = i_o$) in the same direction. The average value of output voltage for a DC to DC (Boost converter) is V_o which is given by

$$V_0 = V_s (1/ 1\text{-}k) \qquad (1)$$

where k is the duty ratio of the switch given by k= T_{ON}/T. Since the output voltage is greater than the input voltage, the converter is called a boost converter.

3.2 CLL Resonant converter

The basic diagram of a CLL type resonant converter is shown in Fig. 5. This type of converter promises soft switching for different load conditions [1]. A CLL converter is expected the speed of response, voltage regulation and better load independent operation. The resonant techniques process power in sinusoidal form.
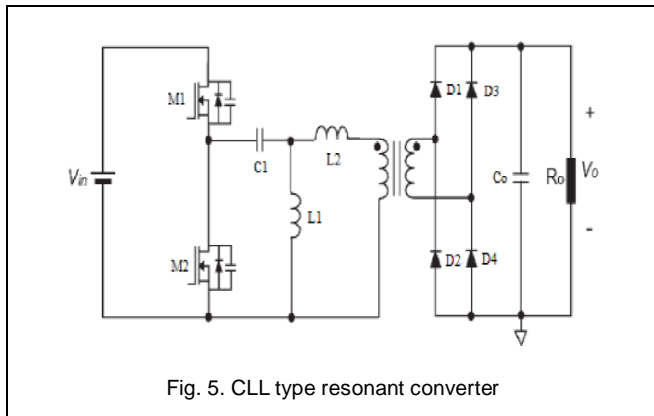

Fig. 5. CLL type resonant converter

The resonant tank consisting of three reactive energy storage elements (CLL-T) has overcome the conventional resonant converter that has only two reactive energy storage elements. The first stage converts a DC voltage to a high frequency ac voltage. The second stage of the converter is to convert the AC power to DC power by suitable high frequency rectifier and filter circuit. Power from the resonant circuit is taken either through a transformer in series with the resonant circuit or series in the capacitor comprising the resonant circuit. In both cases the high frequency feature of the link allows the use of a high frequency transformer to provide voltage transformation and ohmic isolation between the DC source and the load.

In CLL converter the load voltage can be controlled by varying the switching frequency or by varying the phase difference between the two inverts where the switching frequency of each is fixed to the resonant frequency. The phase domain control scheme is suitable for wide variation of load condition because the output voltage is independent of load. The DC current is absent in the primary side of the transformer, there is no possibility of current balancing. Another advantage of this circuit is that the device currents are proportional to load current. This increases the efficiency of the converter at light loads to some extent because the device losses also decrease with the load current. If the load gets short at this condition, very large current would flow through the circuit [3]. This may damage the switching devices. To make the circuit short circuit proof, the operating frequency should be changed. Fig. 6. shows the Gain characteristics of a CLL resonant converter. This converter works with variable frequency control. In this converter, two resonant frequencies exist. One is the resonant frequency of resonant inductor L1 and resonant capacitor C1 called the series resonant frequency (f1), another one is the resonant frequency of L1 plus L2 with C2 called the parallel resonant frequency (f2)
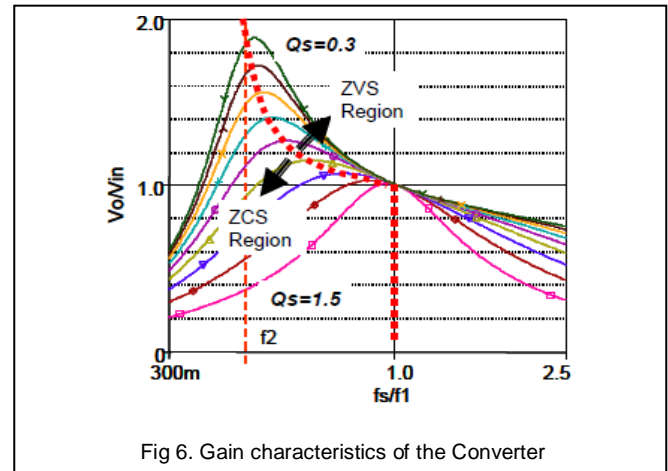

Fig 6. Gain characteristics of the Converter

From the DC characteristic of the converter, it can be seen that the peak of the gain is moving with load change. As load becomes light, this peak moves close to the resonant frequency of L1 +L2 and C1. When load becomes heavier, the peak moves to the resonant frequency of L1 and C1, and gain at resonant frequency f1 is always unity [3].

The operation region can be divided into two area: ZCS area and ZVS area. When switching is higher than f1, the converter is always running at ZVS condition. When the switching frequency is higher than f2, the converter always run at ZCS condition. When operating is between f1 and f2, the load condition will determine if the converter is running at ZVS or ZCS condition. For this application, MOSFET is used as primary switches, so ZVS is preferred. To ensure ZVS operation, the operating range of this converter is above resonant frequency f2 [2].

3.3 Control Strategy

Sliding-mode control (SMC) is a particular type of variable structure control. It is one of the most powerful solutions for many practical control designs. It is a robust control scheme based on the concept of changing the structure of the controller in response to changing the state of the system in order to obtain desired output. Therefore SMC is a successful control method for nonlinear systems [7].

A first-order sliding-mode controller consists of two distinct control laws: switching control and equivalent control. The most important task is to design the switching control law which enforces the system to the sliding surface s(t), defined by the user, and to maintain the system state trajectory on this surface as shown in Fig. 7. in which e and ė denote the tracking error and first-time derivative of the tracking error, respectively. 't' in s(t) is the independent variable time [7].

Ideal sliding-mode can be found by equivalent control approach. First time derivative of s(t) along the system trajectory is set equal to zero and the resulting algebraic system is solved for the control law. If the equivalent control exists, it is substituted into s(t) and the resulting equations are the ideal sliding-mode [7].
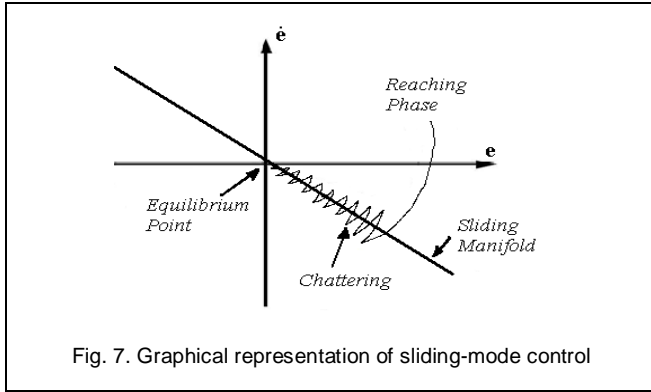
Fig. 7. Graphical representation of sliding-mode control

The sliding function s(t) is a function of the tracking error e(t), where e(t) is the difference between set point and output measurement, as given in Eq. 2, :

$$s(t) = \left(\lambda + \frac{d}{dt}\right)^{n-1} e(t) \qquad (2)$$

where n denotes the order of uncontrolled system, λ is a positive constant. λ is the tuning parameter which determines the slope of sliding manifold When the system is in the sliding-mode, both s(t) and are equal to zero, s(t)=ṡ(t)=0.

The control law u(t),is determined so that the tracking error and its derivative should converge to zero from any initial state to the equilibrium point in a finite time. u(t) consists of two additive signals switching signal, $u_{sw}(t)$, and equivalent signal $u_{eq}(t)$, determined separately

$$u(t) = u_{eq}(t) + u_{sw}(t) \qquad (3)$$

If the initial trajectory is not on the sliding surface, the switching control, $u_{sw}(t)$, enforces the error toward the origin of the sliding surface and this is called the reaching phase. The equivalent control may not be able to move the system state toward sliding surface [7]. Therefore, the switching control is designed on the basis of relay-like function because it allows changes between the structures infinitely fast.

$$u_{sw}(t) = -k\,\text{sign}(s(t)) \qquad (4)$$

where k is a positive constant that should be large enough to suppress all matching uncertainties and unpredictable system dynamics and sign (s(t)) is a signum function.

4 PROPOSED CONTROL SCHEME IMPLEMENTATION

The operational region is generally used for the resonant converter operation because both the ZVS and zero current switching can be achieved. The proposed converter includes a boost converter and a CLL resonant converter.

The circuit diagram of full-bridge CLL resonant converter and proposed sliding-mode control scheme are shown in Fig. 8. In order to improve the dynamic response and the system robustness, the sliding surface is established by sampling the

output voltage and the output filter capacitor current. The hysteresis comparator is employed to generate the sliding-mode control signal u, which determines the switching frequency of CLL resonant converter. It can be defined as follows:

$$f = (f_{max} + f_{min}) \cdot u \qquad (5)$$
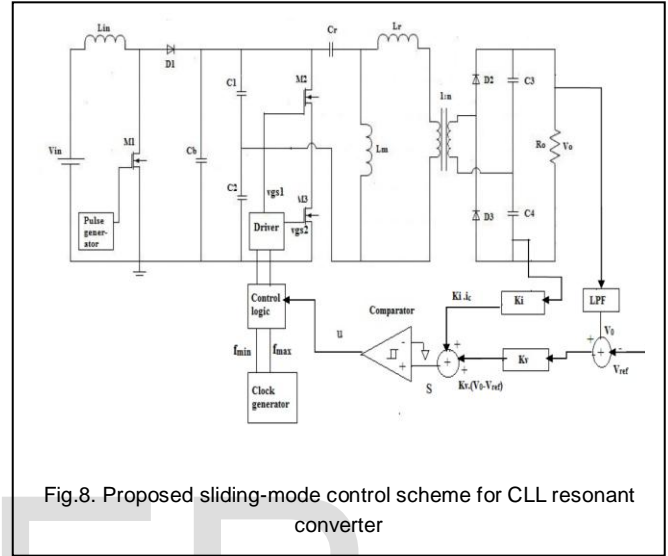
$$u = \begin{cases} 0 \\ 1 \end{cases} \qquad (6)$$

Fig.8. Proposed sliding-mode control scheme for CLL resonant converter

In general, the most commonly used sliding surface is a linear combination of system variables. To reduce the chattering of sliding-mode control, the discontinuous terms are transferred to the first order or higher order derivatives of the control input by differential switching function of routine sliding-mode control. The switching function is obtained by sampling the output voltage and the output capacitor current

$$S(x,t) = K_v x(t) + K_i i_c(t) \qquad (7)$$

where x(t) is the output voltage error, $x(t) = v_0(t) - V_{ref}$. K_v and K_i are the control gain parameters [8]. Thus the sliding surface can be expressed as:

$$S(x,t) = Kx(t) + \frac{dv_0}{dt} = 0 \qquad (8)$$

For the fixed switching frequencies, the control law is obtained by applying the often-used reaching condition $S \cdot S < 0$

$$u = \begin{cases} 0 \text{ when } s > 0 \\ 1 \text{ when } S < 0 \end{cases} \qquad (9)$$

In the actual system, a hysteresis comparator is employed to ensure the feasibility of sliding-mode control. Thus, the control law can be modified as:

$$u = \begin{cases} 0 \text{ for } S > \sigma \quad or \quad |S| < \sigma, S < 0 \\ 1 \text{ for } S < -\sigma \quad or \quad |S| < \sigma, S > 0 \end{cases} \qquad (10)$$

where σ is the phase delay on the phase plane. The following

fig. 9 shows the phase plane, where the x-axis is the output voltage error x(t) and the y-axis is the differential term $\frac{dv_o}{dt}$. The sliding surface is a straight line through the point (0, 0) on the phase plane, which is extended to the banded sliding region.
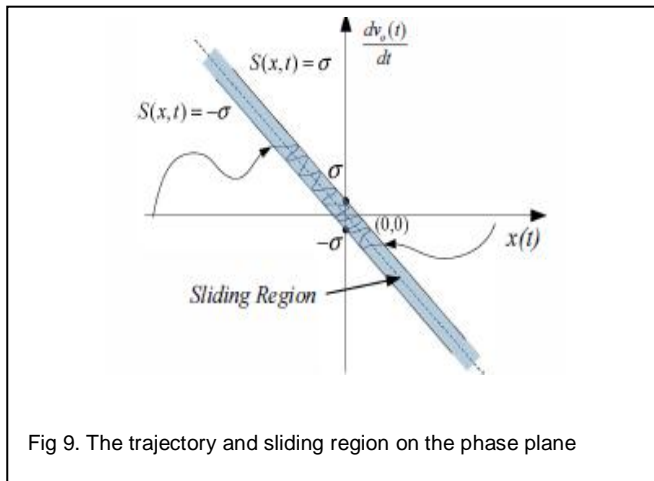

Fig 9. The trajectory and sliding region on the phase plane

On the phase plane, the x-axis represents the average steady error of output voltage while the y-axis on behalf of the output voltage ripple. Thus the steady-state performance is distinctly shown on the phase plane [8].

In the proposed controller, three circuit control parameters (K_v, K_i and the hysteresis width) are involved. They are simplified to two relations as given below

$$K = \frac{K_v}{K_i C_o} \qquad (11)$$

$$\sigma = \frac{\xi}{K_i C_o} \qquad (12)$$

where K is the sliding-mode control gain and σ is the phase delay on the phase plane.

5 SIMULATION RESULTS

The fuel cell output voltage is fed as an input to the power conditioning circuit consisting of a boost converter with a CLL resonant converter. This design helps in reducing the number of diodes by two and reduces the fringing effect. The gate pulses to the MOSFET M3 are fed through through a pulse generator. The gate pulses for M1 and M2 are generated through sliding mode control technique. The overall simulation diagram is shown in Fig 10.

A CLL resonant converter is designed with appropriate values to meet the output voltage requirement. The transformer output is rectified through a bridge converter circuit and then filtered and fed to the load and the load voltage is measured accordingly.

DC-DC converter using CLL resonant converter and a sliding mode control is shown in the Fig. 10. Input of 24V DC

applied to the converter is shown in Fig. 11 is boosted to 30V DC and then converted into AC using half bridge inverter.

The CLL circuit provides soft switching. The AC value is stepped up to 400V AC by using step up transformer. The output of the transformer is rectified and is increased to 810V by using voltage doubler circuit in the secondary side of transformer.
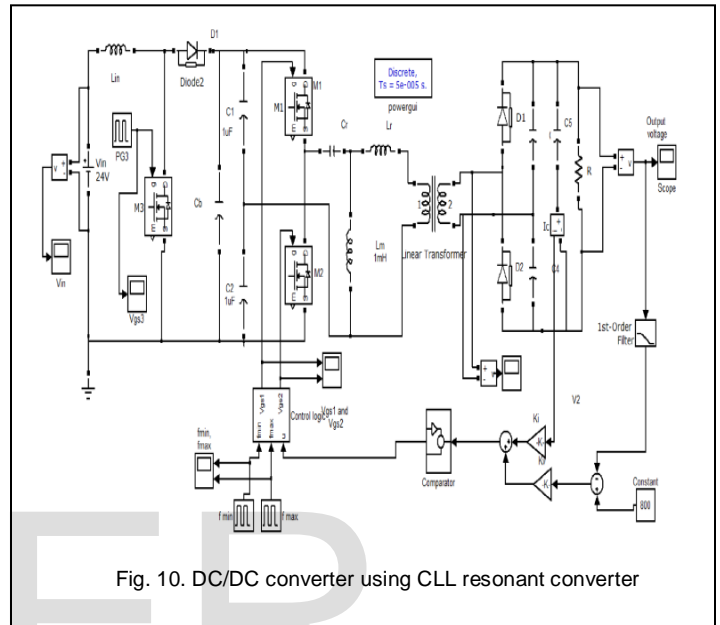

Fig. 10. DC/DC converter using CLL resonant converter

The output voltage and capacitor current are used as the sliding surfaces. They are multiplied by suitable proportionality constants to generate a signal for the hysteresis comparator. The hysteresis comparator then generates the necessary signal to be given to the control logic.
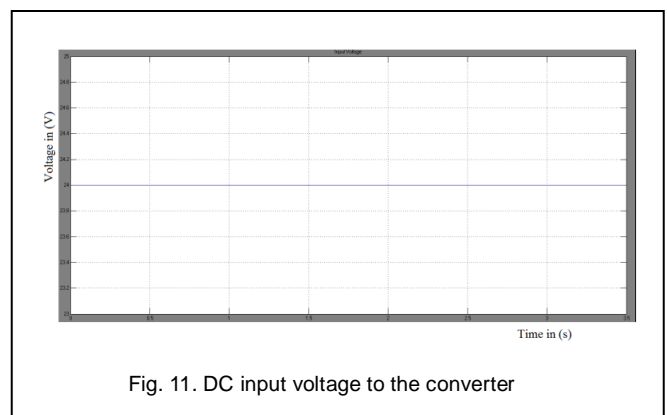

Fig. 11. DC input voltage to the converter

The control logic block accepts 3 inputs namely, fmin, fmax, u and generates the control signal for M1 and M2 .Accordingly the signals Vgs1 is fed to MOSFET M1 and Vgs2 is fed to MOSFET M2. Driving pulses for the transistor M1 and M2 are shown in Fig. 12 and those for M3 is shown in Fig. 13 respectively.

Fig. 12. Driving pulses for the MOSFET M1 and M2

Fig. 13. Driving pulses for the MOSFET M3
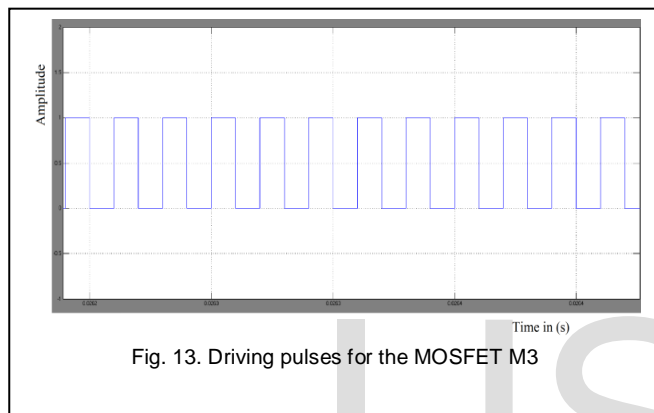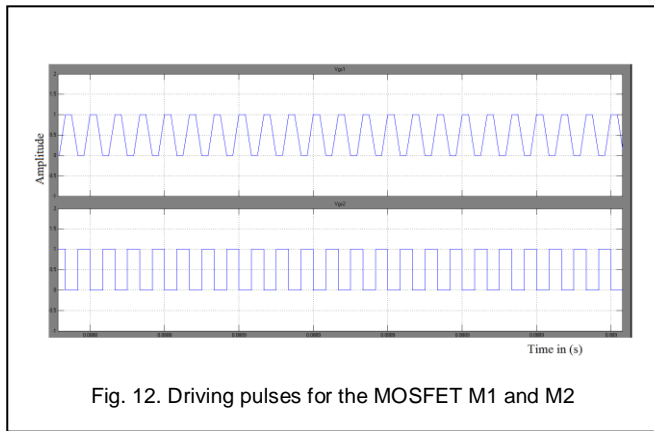
The resultant output is shown in Fig. 14. Hence a CLL resonant DC/ DC converter has been designed and the input voltage has been suitably raised and maintained to about 810 Volts by sliding mode control technique .

Fig. 14. Output of CLL resonant type dc/dc converter
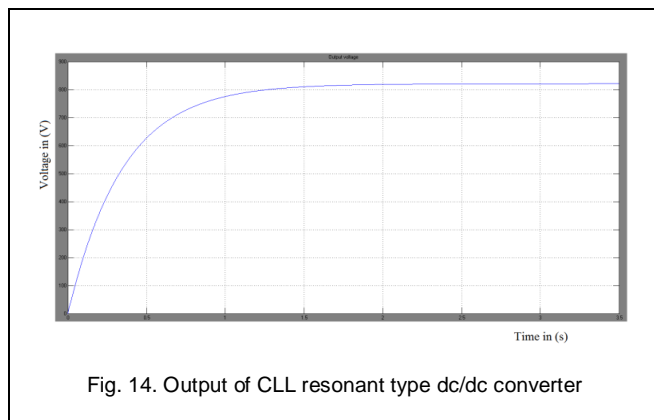
It can therefore be concluded that the proposed SM controller may be a good alternative over conventional controllers for fast-response boost-converter applications.

6 CONCLUSION

A method for converting low magnitude voltage from fuel cell to high step up voltage by resonant DC-DC converter has been designed for fuel cell application. A CLL resonant converter topology which includes voltage doubler in the secondary side of the transformer for rectification and to increase the voltage. It reduces the size, reduces the fringing effect, increases the output voltage, and increases efficiency of the converter. A sliding-mode control scheme of CLL resonant converter is also presented here. The gate pulses to the resonant inverter are generated by sliding mode control technique which provides a closed loop control. Any change in the output voltage is sensed by the controller and accordingly gate pulses are generated so as to maintain the output voltage at the desired value. Thus simulation for DC-DC converter using CLL converter along with sliding mode control was performed in MATLAB simulink.

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