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A Comprehensive Review of the Quadratic High Gain DC-DC Converter for Fuel Cell Application

Divya Navamani Jayachandran, Jagabar Sathik, Tanmay Padhi, and Aditi Kumari

Abstract*—In the recent times, lot of research work carried out in the field of fuel cells explicitly divulges that it has the potential to be an ultimate power source in upcoming years. The fuel cell has more storing capacity, which enables to use in heavy power applications. In these applications, power conditioning is more vital to regulate the output voltage. Hence, we need a dc-dc converter to provide a constant regulated output voltage for such high-power system. Currently, many new converters were designed and implemented as per the requirement. This paper has made comparative study on several topologies of the quadratic high gain dc-dc converter and the applications where these topologies can be used when the fuel cell is given as a source. Also, we have compared various parameters of all the converters considered and generated the results with steady-state and dynamic study. In this article, we briefed the types of analysis carried on the dc-dc converter to study its performance. Moreover, various application of fuel cell is presented and discussed. This paper will be a handbook to the researchers who start to work on high gain dc-dc converter topologies with quadratic boost converter as a base. This article will also guide the engineers to concentrate on the fuel cell components where it needs to be explored for optimizing its operation.

***Keywords*—Fuel cell; electric vehicle; quadratic; high gain; SSA; dynamic**

I. INTRODUCTION

AS the modern world is approaching, renewable energy sources and its uses can be found in every part of the world. It is crucial to make a technology that reduces the size and cost of the renewable source and also improves the system's efficiency. The fuel cell is widely accepted in the modern world as it is pollution-free, and its efficiency is also quite good (around 35% - 45%) compared the various renewable power sources. Also, the fuel cell has more storage capacity, enabling heavy power applications [1]. In the engineering field, it is keenly tracked how much the fuel cell is dependable and how engineers are focusing more on its research to make it more and more valuable and affordable. It is also viewed a severe decline in the availability of resources like fossil fuels as the extraction is done at a hefty rate, and there will be a complete depletion in a few years [2]. If the fuel cell and battery are compared, many similarities between the two are detected. Both of them are a type of electrochemical cell, and to convert chemical energy to electricity, they use internal oxidation. While the main entity which differentiates between the two is the structure of their electrode. In a battery, electrodes are metals immersed in a mild acid, whereas in fuel cells, they are electron-conforming fibers [2]. Apart from efficiency, fuel cells also have a high current density, low noise, and high trivial. There are many definitions of fuel cells, which are defined based on their use. Fuel cells are more efficient at low output current [3]. Also, at high power output, they are operated at rated values, so fuel cells are used in extensive power ranges, making them more reliable than other renewable resources.

However, apart from this, a dc-dc converter to provide a constant regulated output voltage is needed. A dc-dc converter is first used in the mid-20th century. After, many changes were made, and many new converters were designed and implemented as per the requirement. With this topology, the converter can maintain soft-switching when used in a wide range of operations. It also reduces the passive component size, transformer turn ratio, and output ripple current.[4]. These converters are categorized into two sub-divisions, namely isolated and non-isolated. The difference between these two can be seen by an electric barrier that is present in isolated type dc-dc converter but not in non-isolated type. The barrier is nothing but just a transformer. The use of a non-isolated type dc-dc converter is more than the isolated type due to its simple structure and cheap cost. Due to the variation in the output voltage of fuel cell, there is a need to use different dc-dc boost converter topologies to step up the output voltage. As stated in [5], semiconductors in step up converter have switching losses, which will further reduce the efficiency, so there is a need to derive topologies with single switch to minimize these effects. Currently, in automobile industry, the land vehicles and underwater vehicles have started testing fuel cells. The day is not far enough to witness the role of fuel cells in underwater applications. This article has established different high gain dc-dc converters for fuel cells and tested its characteristics for various fuel cell applications. As discussed in [6], when high power is consumed using the fuel cell, it loses its efficiency. In [7], it has been mentioned that there is an improvement factor of around 2-3 for a fuel cell vehicle compared to a battery vehicle, which is a great advantage. In [8], during the

Divya Navamani Jayachandran, Tanmay Padhi and Aditi Kumari are with Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Kattankulathur, 603203, Chennai, India (e-mail corresponding author: J Divya Navamani divyanaj@srmist.edu.in)

Jagabar Sathik is with Renewable Energy Lab, Prince Sultan University, 11586, Riyadh, Saudi Arabia.

acceleration, extra power is needed to propel the vehicle. When at low speed, to avoid the operation of fuel cells at low power, battery is used. It can also store energy at regenerative braking, which will provide extra power during acceleration. Two parameters are mainly seen while using fuel cells, i.e., driving power and the range of demand [9]. When a fuel cell is used as a source, its current ripple must be minimized [10-11]. Uneniably, harmonic and ripple content also influence the lifespan of a fuel cell. As given in [12], the input ripple current is multiple of the number of parallel switches, and hence it is a multiple of switching frequency. Here, it is quite essential to reduce the size of passive components used in the dc-dc converter.

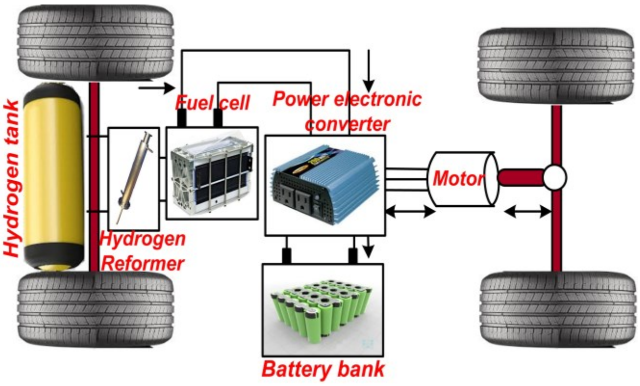


Fig. 1. Power architecture of fuel cell powered vehicle

Fig 1 explains the basic working of an electric vehicle using a fuel cell mechanism. Notably, the fuel cell is connected to the hydrogen tank. The vehicle proposed here can be fueled with hydrogen gas(pure) through the cylinder. As discussed earlier, different cars can have additional capabilities that depend on the performance, emission rate, and other specifications of the vehicle like weight and comfort. In this kind of vehicle, the power flow is unidirectional, and it is done purposely to bring regenerative braking into the act. Generally, a 40-kW fuel cell is used for small to medium-sized vehicles and is found to be enough for those vehicles [13]. In [14], the main challenge in fuel cell vehicles is improving the vehicle's efficiency.

As mentioned earlier, the dc-dc converter act as a regulator for output voltage, and different topologies for the same are used for comparative study. The motor plays a vital role as it is used for regenerative function and used to drive the wheels. In [15], it has been explained that the battery cell used in the above figure can be used as storage when the fuel cell generates electricity, which can either be used to power the machines.

In this paper, the analyses on different quadratic dc-dc converter with different topologies are made with comparison. This paper has compared several topologies of the quadratic based high gain dc-dc converter and the applications where these topologies can be used when the fuel cell is given as input. Sections 2 and 3 are wholly devoted to the dc-dc Quadratic boost converter topologies where its design and space state modeling of few converters has been discussed. A comparative analysis and summary have been shown in section 4 and 5 respectively. Conclusion is made at the end.

II. DESIGN OF QUADRATIC BOOST CONVERTER

In this section, the power converters used for renewable power sources are discussed. Quadratic boost converter is taken as the base converter for analysis and the structure of the converter is presented in Fig. 2. The advantages of quadratic boost converter are enhanced gain compared to the traditional boost converter and non-pulsating input current which in turn draws ripple free current from the source. This will increase the reliability of the sources.

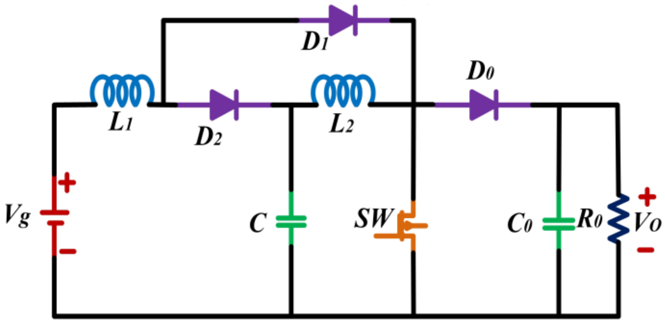


Fig. 2. Quadratic boost converter

A. Quadratic boost converter with passive switched inductor cell (QBPSL)

A combination of an inductor and passive or active switches is made to form a high gain cell to enhance the converter's voltage gain. In this combination, the switches are switched to make the inductors charged in parallel. During the discharging state, the inductors are arranged in series to discharge the energy to the nearby storage element and finally to the load. Several structures for step-up/step-down are presented in [16]. Active switched inductor based high gain converters is derived for various applications. Series/parallel connection of the inductors during the discharging and charging (OFF/ON) mode of the converter is explained in [17][18]. Fig 3 (a) illustrates the integration of switched inductor cell to the quadratic boost converter.

B. Quadratic boost converter with passive switched inductor-capacitor cell (QBPSLC)

The switched inductor/capacitor is integrated into the conventional boost converter to make the extendable topology [22]. An effective combination of the passive switched inductor-capacitor cell is made by replacing a diode from Fig 8 (a) with a capacitor [23]. Due to the addition of the capacitor, the gain of the converter gets enhanced. The circuit configuration with an effective passive switched inductor-capacitor cell is presented in Fig. 3 (b). Furthermore, ultra-high

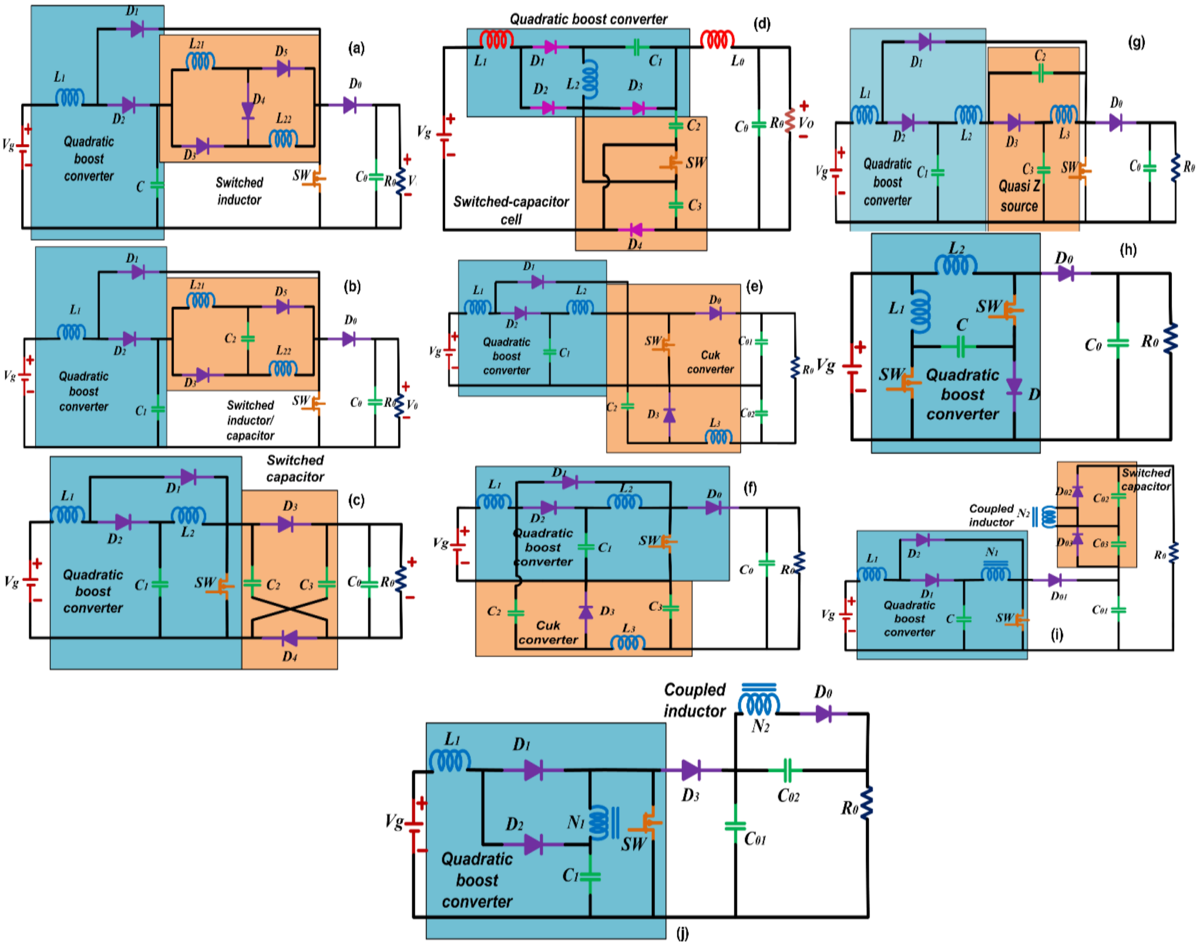


Fig. 3. (a) Quadratic boost converter with passive switched inductor cell (QBPSL) in [18] (b) Quadratic boost converter with passive switched inductor-capacitor cell (QBPSLC) in [20] (c) Quadratic boost converter with passive switched capacitor cell-I (QBPSC-I) in [23] (d) Quadratic boost converter with passive switched capacitor cell-II (QBPSC-II) (e) Quadratic boost converter with cuk integrated -I(QBCI-I) (f) Quadratic boost converter with cuk integrated -II (QBCI-II) (g) Quadratic boost converter with Quasi Z (QBQZ) (h) Quadratic boost converter with restructured arrangement (QBRA) (i) Quadratic boost converter with coupled inductor and switched-inductor (QBRCISC) (j) Quadratic boost converter with coupled inductor (QBCI)

step-up can be achieved with the passive switched inductor-capacitor cell and various diode-capacitor cells [21].

C. Quadratic boost converter with passive switched capacitor cell-I (QBPSC-I)

Different combinations of diode-capacitor (DC) cells are added to increase the converter's voltage conversion ratio. To achieve extendable voltage gain, a voltage multiplier (VM) cell is added [22]. With these switched capacitor cells, ultra-gain dc-dc converters are derived [23]. Around 15 diode-capacitor cells are listed, and the performance of these cells with quadratic boost converter is discussed in [24]. Both positive and negative output cells are presented with the comparison. Inverting and non-inverting SC cell is reported and analyzed detail in [25]. The active switched inductor is combined with the switched capacitor to increase further the voltage gain [26][27]. One of those switched-capacitor cells is depicted in Fig. 8 (c) with a quadratic boost converter.

D. Quadratic boost converter with passive switched capacitor cell-II (QBPSC-II)

All the conventional topologies are categorized as a three-terminal PWM switch model, whereas to boost the voltage four-terminal PWM high gain switch cell is proposed in [28].

The four-terminal cell is integrated with a quadratic boost converter to reduce the voltage stress across the switch and increase the output voltage. This circuit configuration is presented in Fig. 3 (d). Compared to the topologies in Fig. 3 (a) and (b), the stress across the MOSFET is reduced which in turn reduces the $R_{ds(on)}$ and conduction loss of the switch. This leads to a cost reduction with enhancement in the efficiency of the converter.

E. Quadratic boost converter with Cuk integrated -I(QBCI-I)

This DC-DC converter is characterized by a single active switch, which can be seen in Fig. 3 (e) and is termed as Quadratic Boost Converter with Cuk Integrated Type 1. The hold-off voltage of the switch is equal to the output voltage. However, this topology reduces the voltage stress across the switch compared to other dc-dc converters [29]. This design is obtained by merging a Quadratic Boost with a Cuk converter. While performing this study, it is noted that the topology configuration is simple to perform the analysis.

F. Quadratic boost converter with Cuk integrated -II (QBCI-II)

This design presents quite similar characteristics of the Type 1 converter as seen in Fig. 3 (f), and is termed identical to it as Quadratic boost converter with Cuk integrated Type 2. As per the design and the simulation, it is seen that the voltage across the single switch in the Type 2 converter is quite less than the Type 1 [29]. A significant difference can also be seen in the diode voltage compared to the diodes in Type 1 configuration.

G. Quadratic boost converter with Quasi Z (QBQZ)

In Fig. 3 (g), a Quasi-Z source is proposed with boost characteristics. This proposed topology uses a Quasi-Z source to get a higher voltage gain. A high DC link voltage can be generated by the number of passive elements placed in the circuit. The Quasi-Z technique is used to obtain a higher voltage gain. The gain is obtained with a small duty cycle, which further avoids the inductors' instability [30]. One of the significant reasons to use this topology is that the capacitors' voltage stress is immensely reduced. Using less passive components, a substantial amount of boost value can be obtained in this topology.

H. Quadratic boost converter with restructured arrangement (QBRA)

In this topology, there are two switches in the design and illustrated in Fig. 3 (h). The design also consists of two capacitors, two diodes, and a load. Same Pulse Width Modulation (PWM) signal is given to control both the switches with time T and duty cycle being D. The voltage stress on the power switch and the inductor current of this design is low, which further decreases the power losses. This leads to an increase in the efficiency of this dc-dc converter [31]. Also, it requires a very low duty ratio for the same boost characteristics, which reduces the risk of inductive saturation.

i. Quadratic boost converter with coupled inductor and switched-inductor (QBCISC)

The QBCISC structure can be seen in Fig. 3 (i). In this topology, a coupled inductor is integrated with the voltage doubler (switched-capacitor) to boost the voltage gain. Here, the coupled inductor taken is assumed to be an ideal transformer with a turn ratio of n and the magnetizing inductor Lm for analysis. In this design, increasing the turn ratio of the ideal transformer can step up the voltage gain. The clamp circuits are used in this design as the energy stored in the leakage inductance of the primary side cannot be transferred to the secondary side, causing voltage spikes [32]. One of the main advantages of this proposed design is that the leakage energy can be recycled on the output side using clamping circuits.

j. Quadratic boost converter with coupled inductor (QBCI)

The circuit configuration of QBCI is shown in Fig. 8 (j). Like the previous circuit demonstrated in Fig. 3 (i), we can witness an ideal transformer with magnetizing inductor Lm. As stated in [33], this converter's maximum efficiency can rise to 93%, and full load efficiency at full load can be around 89%. To reduce the voltage of the switch, the leakage inductor energy can be used. Further, it minimizes the voltage stress of the switch that maintains the efficiency quite significantly. The converter attains a high voltage gain with a suitable duty cycle, and also the stress on the power switch is relatively less.

III. STATE-SPACE MODELING OF FEW QUADRATIC BOOST TOPOLOGIES

State-space averaging is applied to the non-isolated and isolated dc-dc converter for dynamic analysis [34] [35]. This technique is also applied to partial-power converters to derive the small-signal model [36]. It is also applied to the multilevel and multi-stage converter for deriving the transfer function [37]. Mostly, researchers prefer the SSA technique for the dynamic study of the power converters. In this section, state-space modeling of few topologies reported in section 4 is modeled, and the matrices are derived. Fig. 4 (a)-(d) represents the configuration of quadratic high gain topologies for explaining the state-space averaging of the dc-dc converter. These figures also deliberately show the state variables considered for state-space analysis (SSA).

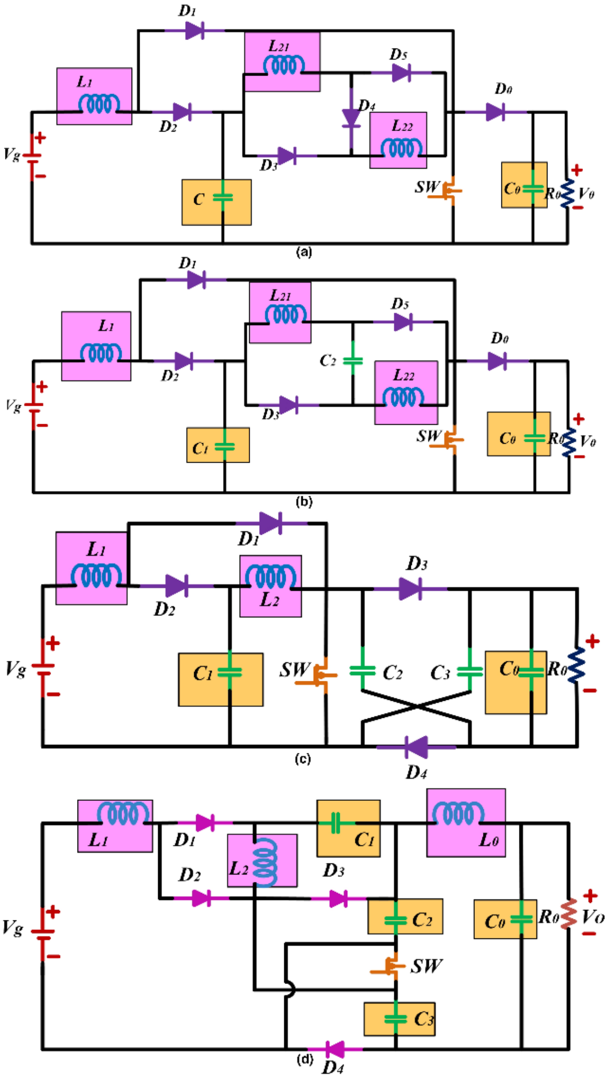


Fig. 4. State variable-components of the topology (a) QBPSL (b) QBPSLC (c) QBPSC-I (d) QBPSC-II

In SSA, the derivative of inductor currents and capacitor voltages are averaged over one switching period. State-space model is obtained separately for ON and OFF mode of the converter. To study the small signal behavior of the converter, perturbation technique is introduced and the required transfer function for dynamic study and controller design are obtained.

A. Quadratic boost converter with passive switched inductor (QBPSL):

$$\begin{bmatrix} \overline{i_{L1}} \\ \overrightarrow{i_{L2}} \\ \overline{v_C} \\ \overline{v_{CO}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -D'/L_1 & 0 \\ 0 & 0 & (1+D)/2L_2 & -D'/2L_2 \\ D'/C & -(1+D)/C & 0 & 0 \\ 0 & D'/C_O & 0 & -1/R_O C_O \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_C \\ v_{Co} \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} V_g \end{bmatrix}$$

$$\begin{bmatrix} v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_C \\ v_{Co} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix} \tag{1}$$

B. *Quadratic boost converter with passive switched inductor/ capacitor (QBPSLC):*

$$\begin{bmatrix} \overline{i_{L1}} \\ \overline{i_{L2}} \\ \overline{v_C} \\ \overline{v_{CO}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -D'/L_1 & 0 \\ 0 & 0 & (1+2D)/3L_2 & -D'/3L_2 \\ D'/C & -(1+2D)/C & 0 & 0 \\ 0 & D'/C_O & 0 & -1/R_O C_O \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_C \\ v_{Co} \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} V_g \end{bmatrix}$$

$$\begin{bmatrix} v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_C \\ v_{Co} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix} \tag{2}$$

C. *Quadratic boost converter with passive switched capacitor-I (QBPSC-I):*

$$\begin{bmatrix} \overline{i_{L1}} \\ \overline{i_{L2}} \\ \overline{i_{LO}} \\ \overline{v_{C1}} \\ \overline{v_C} \\ \overline{v_{CO}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -D'/L_1 & 0 & 0 \\ 0 & 0 & 0 & 1/L_2 & -D'/L_2 & 0 \\ 0 & 0 & 0 & 0 & (1+D)/C_O & -1/C_O \\ D'/C_1 & -1/C_1 & 0 & 0 & 0 & 0 \\ 0 & -D'/2C & -(1+D)/2C & 0 & 0 & 0 \\ 0 & 0 & 1/C_O & 0 & 0 & -1/R_O C_O \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{LO} \\ v_{C1} \\ v_C \\ v_{CO} \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix}$$

$$\begin{bmatrix} v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{LO} \\ v_{C1} \\ v_C \\ v_{CO} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix} \tag{3}$$

D. *Quadratic boost converter with passive switched capacitor-II (QBPSC-II):*

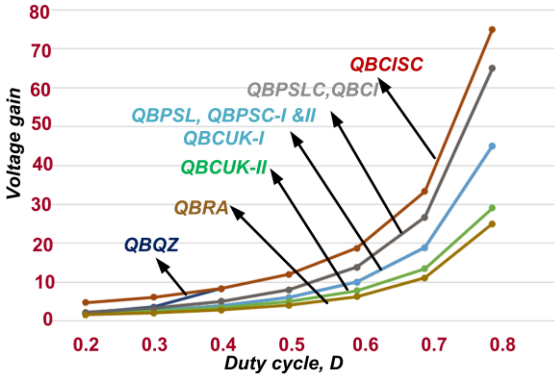
$$\begin{bmatrix} \overline{i_{L1}} \\ \overline{i_{L2}} \\ \overline{i_{LO}} \\ \overline{v_{C1}} \\ \overline{v_{C2}} \\ \overline{v_{C3}} \\ \overline{v_{CO}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & D'/L_1 & -D'/L_1 & 0 & 0 \\ 0 & 0 & 0 & -1/L_2 & D/L_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/L_O & D/L_O & -1/L_O \\ -D'/C_1 & 1/C_1 & 0 & 0 & 0 & 0 & 0 \\ D'/C_2 & -(1+D)/2C_2 & -(1+D)/2C_2 & 0 & 0 & 0 & 0 \\ 0 & D'/2C_3 & -(1+D)/2C_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/C_O & 0 & 0 & 0 & -1/R_O C_O \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{LO} \\ v_{C1} \\ v_{C2} \\ v_{C3} \\ v_{CO} \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix}$$

$$\begin{bmatrix} v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{LO} \\ v_{C1} \\ v_{C2} \\ v_{C3} \\ v_{CO} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix} \tag{4}$$

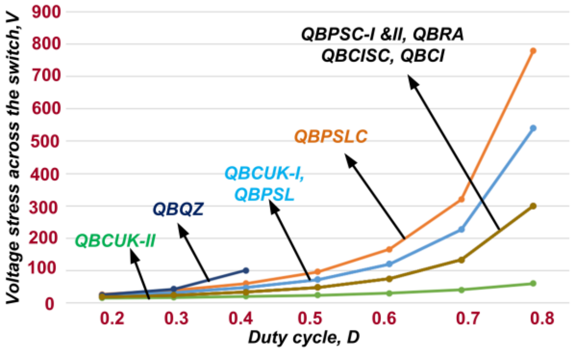
(1)-(4) represents the state and output equations of the quadratic high gain converter topologies. The above section will be a guide for the researchers to work on the dynamic model of the dc-dc converters especially with higher order system. Recently, many algorithms are proposed and applied for finding the solution of the resolvent matrix $[sI-A]^{-1}$ which simplifies the computation of SSA technique.

IV. COMPARATIVE ANALYSIS

In this section, various topologies chosen for study by considering a quadratic boost converter as a base are compared. Fig. 5 (a) and (b) present the voltage gain and switch voltage stress versus the converters' duty cycle, respectively. The voltage gain comparison shows that the quadratic boost converter integrated with the coupled inductor and switched capacitor has higher voltage gain than other topology. Furthermore, the quadratic boost converter with Quazi-Z source presents boosting capability for the duty cycle<0.4. This comparative study also noted that the voltage gain improvement could be achieved with a higher component count or a magnetic coupling technique. With the voltage stress comparison, it is perceived that the quadratic boost with Cuk-II configuration has lower switch voltage for various duty cycles compared to other chosen converters. However, the output gain of the converter is very much lower. Table 1 compares the voltage gain, component count, maximum switch voltage, and current stress.



(a)



(b)

Fig.5. (a) Voltage gain Vs duty cycle (b) Voltage stress across the switch Vs duty cycle

From Table I, all the converters chosen have the more or less same component count (twelve). Hence, the comparison made on these ten topologies is valid. Moreover, based on the same converter configuration and most advantageous, the chosen topologies are single switch topologies. In addition to that, the converters studied are suggested for fuel cell application. Battery and fuel cell sources prefer to connect with the converter that draws ripple-free input current. In the quadratic high gain dc-dc converter, an input inductor is connected in series with the source. It draws a ripple-free current, which increases the source's reliability. Hence, quadratic high gain dc-dc converters are a more suitable fuel cell-powered application.

V. SUMMARY

Advancement in the modern vehicle, the power train's electric appliances has become necessary to improve the vehicle's performance and efficiency. There are no second opinion that most electronic devices need a dc power supply, so there is always a need to enhance the dc-dc power converter's performance used at the present age. Hence, the design of these converters is very much needed. Simultaneously, there is an improvement factor for a fuel cell vehicle compared to a battery vehicle, which is a great advantage.

Though there are many more improvements that can be made in the proposed designs of the fuel-powered system. The performance metrics like cost, a lesser number of passive components, and efficiency can be further improved to optimize the system's performance. Though FCVs are more expensive than IC vehicles, we have seen that their price has decreased significantly with the approached goals for 2020. Slowly, the advancement in modern technology, forces the automobile domain to intrude into the vehicles with renewable power sources. Consequently, we can shortly perceive many upcoming automobiles that use these technologies rather than the present one. Likewise, the voltage conversion ratio of power conditioning unit needs to be increased. It can be implemented in forthcoming vehicles like the Hybrid EVs, which need more power and the required power converters are more complex to design.

Nevertheless, solar vehicles have come on roads, they are too expensive to afford, and this makes a path for FCVs to enter the automobile world. Though many points are not discussed in this paper, further research is applied to study them. The key players in hydrogen fuel cell vehicles are Honda, Toyota, Audi, Daimler, BMW, Ford, Hyundai, General Motors, Volvo, Ballard, etc.

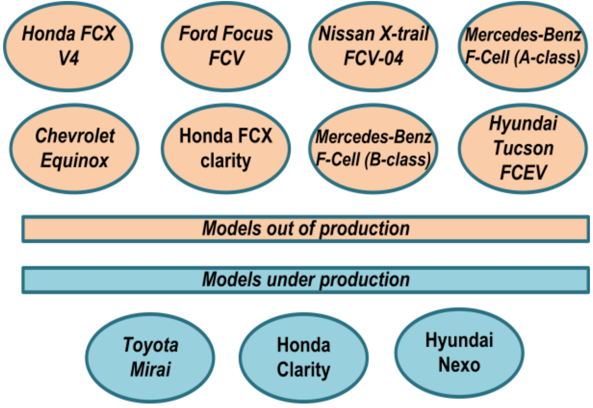


Fig. 6. Fuel cell powered electric vehicle researched

TABLE I
COMPARISON OF QUADRATIC BASED HIGH GAIN DC-DC CONVERTER

Topologies	Voltage gain	Component count				Max Switch stress	Max current stress	Max diode voltage stress
		Sw	D	L	C			
QBPSL	$\frac{1+D}{(1-D)^2}$	1	6	3	2	V_O	$\frac{(3-D)I_O}{(1-D)^2}$	$V_{D1}=\frac{2V_gD}{(1-D)^2};V_{DO}=V_O;V_{D2}=V_{D4}=\frac{V_g}{1-D};V_{D3}=V_{D5}=\frac{V_gD}{(1-D)^2}$
BPSLC	$\frac{1+2D}{(1-D)^2}$	1	5	3	3	V_O	$\frac{(4-D)I_O}{(1-D)^2}$	$V_{D1}=\frac{3V_gD}{(1-D)^2};V_{DO}=V_O;V_{D2}=\frac{V_g}{1-D};V_{D3}=V_{D4}=\frac{V_gD}{(1-D)^2}$
QBPSC-I	$\frac{1+D}{(1-D)^2}$	1	4	3	4	$\frac{V_O}{1+D}$	$\frac{(2-D)(1+D)I_O}{(1-D)^2}$	$V_{D1}=\frac{V_gD}{(1-D)^2};V_{D2}=\frac{V_g}{1-D};V_{D3}=V_{D4}=\frac{V_g}{(1-D)^2}$
QBPSC-II	$\frac{1+D}{(1-D)^2}$	1	4	3	4	$\frac{V_O}{1+D}$	$\frac{(2-D)(1+D)I_O}{(1-D)^2}$	$V_{D1}=\frac{V_g}{1-D};V_{D2}=\frac{V_gD}{(1-D)^2};V_{D3}=V_{D4}=\frac{V_g}{(1-D)^2}$
QBCUK-I	$\frac{1+D}{(1-D)^2}$	1	4	3	4	$\frac{V_g}{1-D}$	$\frac{(2D+D^2+D^3)I_O}{(1-D)^2}$	
QBCUK-II	$\frac{1+D(1-D)}{(1-D)^2}$	1	4	3	4	V_O	$\frac{(2D+D^2+D^3)I_O}{(1-D)^2}$	$V_{D1}=V_{D4}=\frac{V_g}{1-D};V_{D2}=V_{D3}=\frac{V_g}{(1-D)^2}$
QBQZ	$\frac{1}{(1-D)(1-2D)}$	1	4	3	4	V_O	$\frac{(3-D^2)I_O}{(1-D)(1-2D)}$	$V_{D1}=\frac{2V_gD}{(1-D)(1-2D)};V_{D2}=\frac{V_g}{1-D};V_{D3}=\frac{V_g}{1-2D};V_{DO}=V_O$
QBCISC	$\frac{1+n}{(1-D)^2}$	1	5	1(CI) 1	4	$\frac{V_O}{1+n}$	$\frac{(2-D)(1+n)I_O}{(1-D)^2}$	$V_{D1}=\frac{V_O(1-D)}{1+n};V_{DO2}=V_{DO3}=\frac{V_On}{1+n};V_{D2}=\frac{V_OD}{1+n};V_{DO1}=\frac{V_O}{1+n}$
QBCI	$\frac{1+nD}{(1-D)^2}$	1	4	1(CI) 1	3	$\frac{V_O}{1+nD}$	$\frac{(2-D)(1+nD)I_O}{(1-D)^2}$	$V_{D1}=\frac{V_OD}{1+nD};V_{D2}=\frac{V_O(1-D)}{1+nD};V_{D3}=\frac{V_O}{1+nD};V_{D4}=\frac{nV_O}{1+nD}$
QBRA	$\frac{1}{(1-D)^2}$	2	2	2	2	V_O	$\frac{DI_O}{(1-D)^2};\frac{DI_O}{1-D}$	$V_{D1}=\frac{V_g}{1-D};V_{DO}=V_O;V_{D2}=\frac{(2-D)V_g}{(1-D)^2}$

Few models in a fuel cell-powered car are out of production due to inevitable failures in the model. Three models are recently under production and commercialized in the market, which is depicted in Fig. 6. In the out-of-production models, Honda FCX clarity was launched in 2006 as a hydrogen fuel cell vehicle. Due to the shortage of hydrogen filling stations, it has been phased out, and at present, the country introduced Honda clarity. Similarly, the others are phased out due to

- Highly flammable
- Not economical
- Scarcity in hydrogen infrastructure
- Trouble in hydrogen leakage detection
- Problem in Hydrogen's efficiency

Toyota Mirai was launched in 2014, and the global sale reached 10000+ by the end of 2019. It has a 113-kW motor powered from a hydrogen fuel cell with a boost converter. We suggest a high gain dc-dc converter as an alternative to the conventional boost converter in the above-mentioned fuel cell vehicle. We need topologies on the below-mentioned features to build an efficient power conditioner for the vehicle.

- Higher voltage gain
- Less voltage and current stress across semiconductor devices
- Lesser component count
- Inductor in series with source.
- Single switch topology.

The research on the fuel cell-powered vehicle can be concluded that still, the research is open for the components such as

- Fuel cell stack
- Power conditioning unit
- Fuel processor
- Air compressor and humidifier
- Hydrogen refilling station.

CONCLUSION

Various non-isolated quadratic high gain dc-dc converters have been given in this paper. The review has been done by keeping the design aspects and applications in consideration. Many vital metrics, like voltage gain, stress across the switch, are considered and compared.

In the first section of the paper, the application where the non-isolated quadratic high gain dc-dc converters can be used is briefed. Simultaneously, how the upcoming generation needs a quick and efficient design for these converters, and how they can be applied in the future are highlighted. In the subsequent section, we have shown how the fuel cell as a source can be used in those applications. The usage of the power converters as a regulator and its significant role in pollution-free tools like EVs and heavy machinery are also presented. Further, we have discussed how it can be integrated in a fuel cell electric vehicle with more efficiency and vehicle compactness.

Next, we compared ten different topologies of quadratic boost converters and discussed their limitations. We have also stated their advantage over others in terms of stress on the switch and other vital parameters. The comparison is valid as each of the ten configurations has an equal number of passive elements though the individual component may differ in each configuration. On comparing the voltage gain among these quadratic high gain converters, we conclude that a Quadratic boost converter with coupled inductor and switched-inductor (QBCISC) has the highest voltage gain for various duty cycle graph. This is due to the integration of two high gain techniques in the converter, as mentioned above. Also, the stress across the switch for all the converters has been compared. It is concluded that the quadratic boost with Cuk-II configuration has a lower switch voltage for various duty cycles than other chosen quadratic converters. However, the output gain is relatively low.

This study observes that there is still scope for deriving a high gain converter with several configurations and various high gain techniques. For future scope, this review can be extended by doing dynamic analysis in detail. Moreover, it can also be stretched for reliability and fault-tolerant study of high gain dc-dc converters, which are integrated with the critical loads.

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