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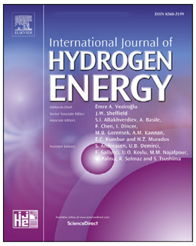

Review Article

# Energy sources and multi-input DC-DC converters used in hybrid electric vehicle applications – A review

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ABSTRACT

With the drastic inclination towards reduction of atmospheric issues, hybrid electric vehicles are becoming the major alternative for internal combustion engine vehicles. Compared to internal combustion engine vehicles, hybrid electric vehicles are remarkable in terms of efficiency, durability and acceleration capability. However, the major drawback of hybrid electric vehicle is energy storage capability. An electric vehicle requires the energy sources with high specific power (W/kg) and high specific energy (Wh/kg) to reduce the charging time. Generally, fuel cells, batteries, ultracapacitors, flywheels and regenerative braking systems are used in hybrid electric vehicles as energy sources and energy storage devices. All these energy storage devices are connected to the different DC-DC converter topologies to increase the input source voltage. From the recent past, most of the hybrid electric vehicles are using multi-input converters to connect more than one energy source in order to improve the efficiency and reliability of the vehicle. This survey presents an assessment of present and future trend of energy storage devices and different multi-input DC-DC converter topologies that are being used in hybrid electric vehicles. In addition, different electric vehicle architectures are also discussed.

## Contents

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## Introduction

From the past few decades the road transport vehicles have been mostly using internal combustion engine (ICE) because of its high reliability. Due to rising prices of diesel and petrol, environmental pollution and depletion of fossil fuels most of the vehicle manufacturers are looking for the alternative fuels such as natural gas, hydrogen and biofuels for the propulsion of vehicle [1,2]. But all these alternative fuels are not feasible for long-term transportation plan.

The Electrical vehicle (EV) is the best solution to reduce the global warming emission gases in transportation sector [3]. EV technology is becoming more trendy in transportation sector, because they consume very less amount of crude oils and environmentally friendly. Transportation sector is the major contributor in global warming emission gases. According to union of concerned scientists, in U.S nearly 30% of global warming emission gases are due to transportation vehicles [4]. The greenhouse gas emissions of different sectors in U.S are shown in Fig. 1. By using EV the operating cost of the vehicle decreases along with carbon gases emission. The average efficiency of internal combustion engine vehicle (ICEV) is 25%, which means that only 25% of total fuel is using for the vehicle and remaining 75% fuel is wasted through heat and friction whereas EV has an average efficiency of 80% [5].

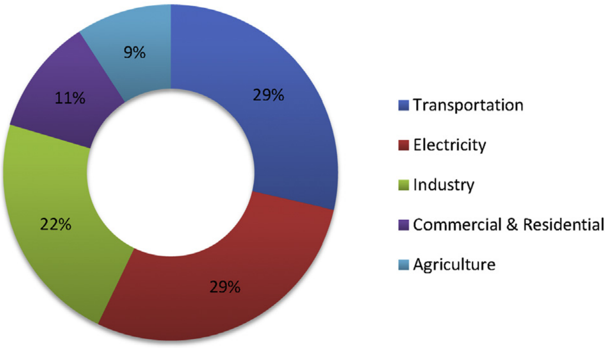

**Fig. 1 – Total U.S Greenhouse gas emissions by economic sector.**

The electric vehicles include battery electric vehicles, hybrid electric vehicles, plug-in hybrid vehicles and fuel cell electric vehicles. The main challenge in the electric vehicle is the cost of energy source. The cost of the energy source is almost one-third of the total vehicle cost [6]. The automobile companies like BMW, Volkswagen, Ford, Toyota, Mitsubishi, Honda, etc. are concentrating mostly on hybrid and plug-in hybrid vehicles.

In Refs. [7–9], the authors reviewed the different multi-input converter topologies and energy storage devices used in hybrid vehicle applications. But the developments in the converter designs made significant impact on the hybrid vehicles in recent years. In this work we made an attempt on the recent converter topologies and its control strategies applicable for the hybrid electric vehicles are presented. This work will useful for the upcoming researchers to understand the operation of the multi-input converters during vehicle designing.

This paper is organized in seven parts. After this introduction section, different types of electric vehicles and their powertrain architectures are discussed in section Types of eletric vehicles. The state-of-the-art of different energy sources used in EVs are presented in section Electric vehicles energy sources. The different multi-input DC-DC converter topologies used in EVs and their control strategies are discussed in sections Multi-input DC-DC converter topologies and Control techniques of DC-DC converter. The future scope and conclusion of the work are given in sections Future scope and Conclusion.

## Types of electric vehicles

Electric vehicles are classified into mainly four types based on the amount of electricity used for the propulsion of vehicle; they are Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV) and Fuel Cell Electric Vehicle (FCEV).

### *Battery electric vehicle (BEV)*

In BEVs, the vehicle is totally powered by electricity and it does not have any fuel tank to store the fuel, so the BEVs are also

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called as “pure electric vehicles”. BEVs consists of large rechargeable batteries to power the vehicles and they do not release any harmful gasses to the environment [10]. The battery can be recharged from the grid or from any other external power source by using a socket [11]. The drivetrain architecture of BEVs is very simple as shown in Fig. 2. In BEVs electrical to mechanical energy conversion losses are low and also the weight of the vehicle is also low. The main requirement in BEVs is high torque traction motor, which reduces the efficiency of the vehicle. BEVs are suitable for short distance and stop-and-run- conditions. The major drawbacks with BEVs are recharging time and battery management. Nissan LEAF, Ford Focus electric, Tesla Model S, BMW i3 are the examples for the battery electric vehicles.

## *Hybrid electric vehicle (HEV)*

Hybrid electric vehicle generally consists of two or more energy sources and/or two or more power sources for propulsion. The energy sources can be a flywheel, a battery, regenerative braking, etc. The power sources can be a fuel cell, an ultracapacitor, an engine, a battery, etc. [12,13]. Depending upon the power supplied to the drivetrain, HEV can be categorized into different types such as series hybrid, parallel hybrid and dual mode HEVs.

### *Series hybrid electrical vehicles*

In series HEV, the traction power is directly provided from the electric motor and the ICE is used just to charge or recharge the batteries as shown in Fig. 3. The generator converts the chemical energy from the ICE to electrical energy to power the battery and electric motor [14]. The power electronic devices used in series HEV are a rectifier to convert the alternator output to charge the batteries, a DC-DC converter to charge the battery and an inverter to convert the DC power to ac power for the motor propulsion. Series HEV have less maintenance and longer life but they require a large battery and motor to accommodate its power demand [15]. It is suitable for the stop-and-go conditions and city driving conditions. Chevrolet Volt is the example for the series HEV.

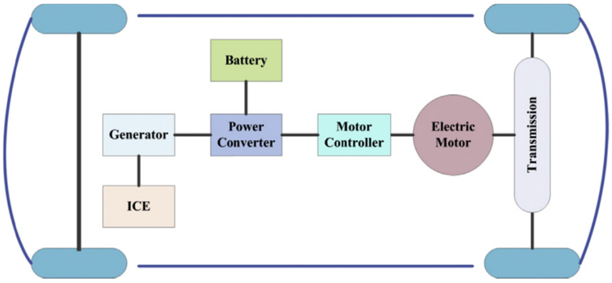

**Fig. 3 – Powertrain architecture of Series HEV.**

### *Parallel hybrid electric vehicles*

In parallel HEV, both ICE and Electric motor are connected to the mechanical transmission system for the propulsion of the vehicle [16]. Parallel HEV can power the transmission system by using only ICE or by using battery or by using both battery and ICE. A controller is designed to decide that, when to operate ICE and when to switch to electric motor or both ICE and electric motor. For small distances, the motor will provide power to the vehicle and for the long distances and during hill climbing ICE or both motor and ICE will power the vehicle transmission system. The battery will get recharged from ICE or from regenerative braking through motor/generator. The efficiency of the parallel HEVs is around 43.4%. The powertrain configuration of Parallel HEV is given in the Fig. 4 [17]. Chevrolet Malibu and Honda Civic are the examples for Parallel HEVs.

### *Dual mode hybrid electric vehicles*

Dual mode HEV is the combination of both parallel and series hybrids, so it also called as series-parallel HEV or combined HEV or power-split HEV. The powertrain architecture is as shown in Fig. 5. Dual mode HEV combines the complexities and efficiencies of both series and parallel electric vehicle [18]. This type of HEV contains power-split devices to transfer the mechanical or electrical power from the ICE to the vehicle wheels for propulsion. Dual mode HEV consists of an extra generator, compared to parallel HEV configuration, and an extra mechanical link compared to series HEV [19]. The main advantage of this system is either it can run on parallel mode or on series mode. For stop and go or slow speed conditions the vehicle will run in series mode and for long distances and high speeds the vehicle will run in parallel mode. The main drawback of these vehicles is cost and complexity.

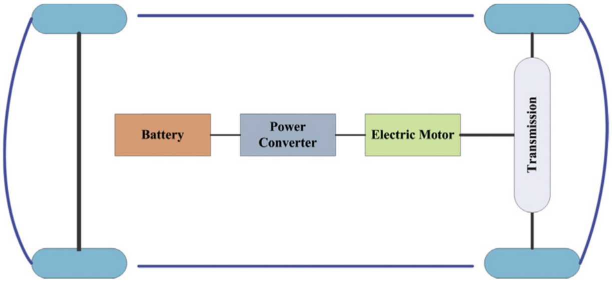

**Fig. 2 – Powertrain architecture of BEV.**

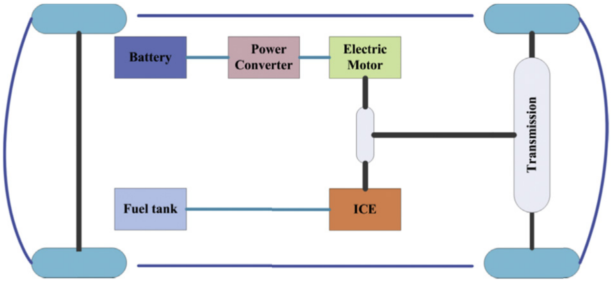

**Fig. 4 – Powertrain architecture of Parallel HEV.**

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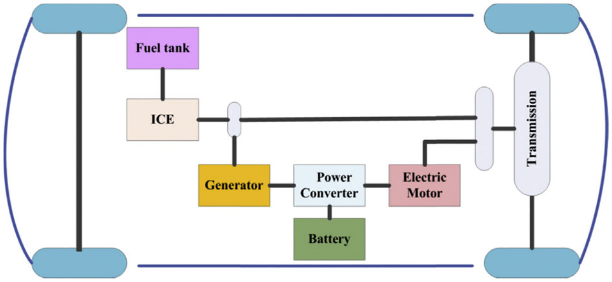

**Fig. 5 – Powertrain architecture of power-split HEV.**

### *Plug-in hybrid electric vehicles*

Plug-in HEVs are new and upcoming technology in the power and transportation sector [20]. Plug-in HEV is also known as extended-range electric vehicle and it consists of both ICE and rechargeable battery packs. These vehicles recharge the battery either by regenerative braking or by plugging to an external power source [21–23]. Plug-in HEVs runs mostly on electric power until the battery gets discharged after that they drive by ICE. Plug-in HEV uses less fuel and releases less emissions compared hybrid vehicles. The main drawback of plug-in HEV is battery cost is very high. The examples for plug-in HEV are Chevy Volt, Ford C-MAX Energi and Toyota Prius.

### *Fuel cell electric vehicles*

In fuel cell electric vehicles (FCEV) hydrogen is used as fuel. The powertrain architecture of FCEV is same as battery electric vehicles. Fuel cell acts as battery and generates electric power to the motor for the propulsion of vehicle. Fuel cell stack converts the hydrogen energy into electricity by using the oxygen from the air [24–26]. Proton exchange membrane fuel cell (PEMFC) technology is mostly used in FCEVs. FCEVs doesn't produce any harmful emissions and environmentally friendly [27]. The main drawback of FCEV is the cost of hydrogen is very high. Toyota Mirai, Honda FCX Clarity and Hyundai Tuscan are the examples for the fuel electric vehicles. The characteristics of different electric vehicles are given in the Table 1.

## Electric vehicle energy sources

The energy sources used in HEVs are fuel cells, batteries, flywheels and ultracapacitor. The energy sources are selected based on the power flow configuration of the HEV. Most of the HEVs uses two energy sources viz., "Main Energy System" (MES) and "Rechargeable Energy Storage System" (RESS). MES has high energy storage capability and is used for steady state power supply, whereas the RESS has high power capability and reversibility and is used for transient power supply and regenerative braking [28]. To choose the MES and RESS correctly, the energy density and power density of the sources are taken into consideration. The operating range of the different energy sources is given in the Fig. 6 and it shows that battery and fuel cell have high energy density with lower power density. Thus, batteries and fuel cells are suitable for MES. Ultracapacitor and flywheels can be used as RESS because of their high power density, high discharge rate and low energy density.

### *Battery*

Battery is most commonly available energy storage device in the market [29]. It consists of one or more electrochemical cells, in which chemical energy is converted into electrical energy. The batteries used in HEVs are totally different from the batteries using in consumer electronics such as cell phones and laptops. The batteries using in HEVs require high energy capacity and it must handle the high power within defined space at an affordable cost. The batteries are classified into two types: primary batteries and secondary batteries. Primary batteries are not rechargeable, whereas secondary batteries are rechargeable. In HEV applications secondary batteries are used. There are different types of batteries available for HEV applications. Mainly lead acid battery, nickel-metal hydride battery, nickel-zinc battery, nickel cadmium and lithium ion batteries are used in electric vehicles.

A lead acid battery is the cheapest and, most commonly used battery in EVs. In these batteries positive plate is made with lead peroxide and the negative plate with soft sponge lead. These plates are dipped in dilute Sulphuric acid (electrolyte) to produce electricity [30]. Life cycle of this battery is 300–500 cycles. The energy density lead-acid battery is around

**Table 1 – Characteristics of different electric vehicles.**

| | BEV | HEV | Plug-in HEV | FCEV |
|---|---|---|---|---|
| Propulsion | Electric motor drive | Electric motor drive<br>ICE | Electric motor drive<br>ICE | Electric motor drive |
| Energy system | Battery<br>Ultracapacitor | Battery<br>Ultracapacitor<br>ICE | Battery<br>Ultracapacitor<br>ICE | Fuel cell<br>Battery |
| Energy sources &infrastructure | Electric grid charging | Gasoline stations | Electric grid charging<br>Gasoline stations | Hydrogen fuel |
| Advantages | Zero emission<br>Independence on crude oils | Less emission<br>Long driving range | Less emission<br>Long driving range | High efficiency<br>Zero emissions |
| Disadvantages | High initial cost<br>Battery management | Depend on crude oils<br>Higher cost | Depend on crude oils<br>Higher cost | Hydrogen cost is high |

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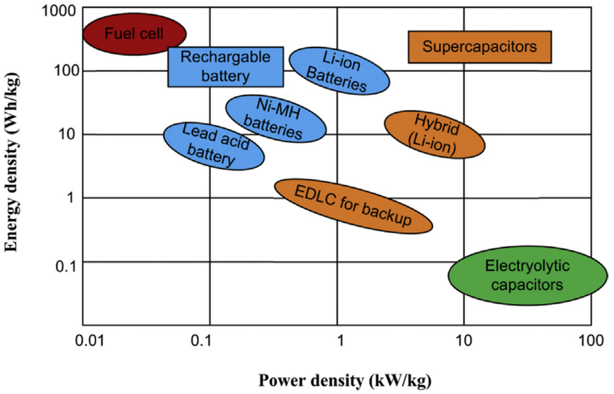

**Fig. 6 – Power density vs Energy density of different energy sources.**

30 Wh/kg and the rated voltage of a cell is 2 V. The chemical reaction at cathode and are shown in Eqs. (1) and (2).

At anode:

$$Pb + SO_4^{2-} \leftrightarrow PbSO_4 + 2e^- \tag{1}$$

At cathode:

$$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \leftrightarrow PbSO_4 + 2H_2O \tag{2}$$

Lead-acid batteries have the advantages of low maintenance, easy to install, high energy efficiency and discharge rate is low. The main disadvantage of the lead-acid batteries is bulky in size and gets overheated during charging [31]. These batteries are used in small electric vehicles for starting, lighting and other electrical functions.

In Nickel-metal hydride (NiMH) battery alkaline solution is used as the electrolyte. In these batteries positive plate is composed of nickel hydroxide and the negative plate consists of an alloy nickel, vanadium and titanium metals. Compared to the lead-acid battery the energy density of NiMH battery is almost double [32,33]. NiMH battery has much longer life and environmentally friendly. The main drawbacks of these batteries are taking more time to charge or recharge compared lead acid battery and heat is generated during high temperatures.

Nickel-Zinc (NiZn) battery is an alternative to NiMH battery introduced by Power Genix. NiZn battery is rechargeable and environmentally friendly battery. NiZn battery has high power density and the operating range is from −10 °C to 50 °C [34,35]. The life cycle of these batteries are very less so that these batteries are not much used in vehicle applications.

Metallic cadmium and nickel oxide hydroxide are used as electrodes in Nickel-cadmium (NiCa) batteries. These batteries can be discharged fully without damage and are rechargeable. The energy density and life cycle of these batteries are high. During the recycling process it may affect the environment and the major drawback is the high cost.

Lithium-ion batteries are mostly used in laptops, cell phones and other electronics and medical devices. Energy and power densities are high for lithium-ion batteries. The positive electrode of lithium-ion battery is made with oxidized cobalt, the negative electrode with carbon material and lithium salt is used as an electrolyte. At present most of the all-electric vehicle uses lithium-ion batteries because of high energy efficiency, long battery life, and low self-discharge and satisfactory high temperature performance. The major drawback is production cost is very high [36]. Tesla Roadster, Hybrid Chevrolet Volt and Nissan Leaf are using lithium-ion batteries as energy storage device [37–39].

## *Fuel cell*

A fuel cell is an electrochemical device which converts fuel into electricity. The inputs of the fuel cell are air and fuel and it converts into water and electricity through a chemical reaction [40,41]. Hydrogen is most commonly used fuel in the fuel cells. The main advantage of the fuel cell is it will work continuously like internal combustion engine vehicle until the fuel is available. The characteristics of a fuel cell are very much similar to a battery under the load conditions. In 1839 Sir William Robert Grove developed a first fuel cell. In 1950 Sir Francis Bacon developed the first usable fuel cell of 5 kW. In the late 1950's, a 12 kW alkaline fuel cell was developed by International fuel Cells for NASA's spacecraft. Since then, fuel cells have become more popular and they are used as primary and backup power source for residential, commercial and industrial buildings in remote areas. In the recent years, fuel cells grabbed much more attention in automobile industries in developing environmental friendly vehicles.

The schematic diagram of the fuel cell is as shown in the Fig. 7 [42]. It works on the principle of electrochemical conversion, in which chemical energy is converted into electrical energy. A single fuel cell consists of two electrodes (anode and cathode) and an electrolyte. When the hydrogen fuel is fed to the anode the catalyst separates the positive and negative charged ions. When the hydrogen and oxygen are fed into the cell, electricity is generated at the output of the cell in the presence of an electrolyte. No gasses are emitted from the fuel cell because it produces only heat and water as the wastage of the reaction [43].

The operating principle of the fuel cell is shown in Eq. (3).

$$2H_2(g) + O_2(g) \rightarrow 2H_2O + \text{energy} \tag{3}$$

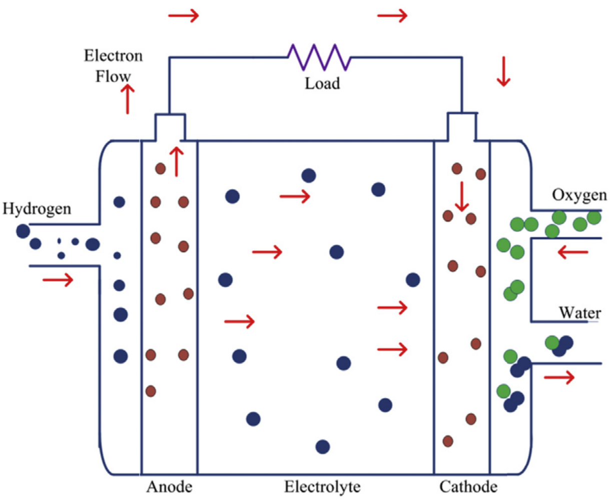

**Fig. 7 – Fuel cell.**

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The chemical reaction at cathode and are shown in Eqs. (4) and (5).

At cathode:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{4}$$

At anode:

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{5}$$

Theoretically 1.23 V is produced by the chemical reaction of $0_2$ and $H_2$, but due to ohmic loss and activation loss practically the voltage produced by the reaction is less than 1.23 V [44].

Fuel cells are classified into different types based upon the type of electrolyte substance used namely Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Proton Exchange Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), and Molten Carbonate Fuel Cell (MCFC) [45,46]. Among these fuel cells AFC, PAFC, PEMFC and DMFC are low temperature fuel cells having the operating temperature below 250 °C. SOFC and MCFC are high temperature fuel cells with an operating temperature of more than 500 °C. At present, the PEMFC is dominating in the automobile industry due to its high power density, low operating temperature, small size and quick start-up [47,48]. The detailed mathematical modeling of the PEMFC system is as follows:

The output voltage of the single PEMFC system is given as [49]

$$V_{FC} = E_{nernst} - V_{ohm} - V_{act} - V_{con} \tag{6}$$

where $E_{nernst}$ is open circuit thermodynamic voltage; $V_{ohm}$ is ohmic overvoltage; $V_{act}$ is activation overvoltage; $V_{con}$ is concentration overvoltage.

$E_{nernst}$ can be determined by using the following formula [50,51].

$$\begin{aligned} E_{Nernst} = {} & 1.22 - 8.5e^{-4}(T_{FC} - 298.15) + 4.308e^{-5}[\ln(P_{H2}) \\ & + 0.5\ln(P_{O2})] \end{aligned} \tag{7}$$

Where $T_{FC}$ is PEMFC cell temperature, $P_{H2}$ and $P_{O2}$ are oxygen and hydrogen partial pressures respectively.

The ohmic overvoltage is given by the expression [52,53].

$$V_{ohm} = I_{cell}(R_M + R_C) \tag{8}$$

where $R_M$ equivalent resistance of electron flow and $R_C$ is proton resistance. $R_M$ is expressed as

$$R_M = \frac{\rho_m L}{A} \tag{9}$$

$$\rho_m = \frac{181.6\left[1 + 0.03J + 0.062\left(T_{FC}/303\right)^2 J^{2.5}\right]}{[G - 0.634 - 3J]e^{\frac{4.18(T_{FC}-303)}{T_{FC}}}} \tag{10}$$

where $\rho_m$ is specific resistivity of membrane, $A$ is area of membrane, $L$ is thickness of membrane, $G$ is membrane water content and $J$ is current density. $J$ is defined as

$$J = \frac{I_{cell}}{A} \tag{11}$$

The activation overvoltage can be expressed in a parametric form as follows

$$V_{act} = -\left(\xi_1 + \xi_2 T_{FC} + \xi_3 T_{FC}\ln(C_{O_2}) + \xi_4 T_{FC}\ln(I_{cell})\right) \tag{12}$$

where $\xi_1$, $\xi_2$, $\xi_3$ and $\xi_4$ are empirical coefficients of each cell and $C_{O2}$ is the oxygen concentration and is expressed as

$$C_{O_2} = \frac{P_{O_2}}{(5.08e^6)exp(-498/T_{FC})} \tag{13}$$

The concentration overvoltage is given by

$$V_{con} = -\frac{RT_{FC}}{nF}\ln\left(1 - \frac{J}{J_{max}}\right) \tag{14}$$

where $R$ is universal gas constant, $J_{max}$ is maximum current density and $F$ is Faraday's constant.

### *Ultracapacitor*

Ultracapacitor is also known as electrochemical capacitor or supercapacitor. Ultracapacitor has high energy density and it is modernization in the field of capacitors [54,55]. The range of conventional fuel is in the range of milli-farads (mF) to pico-farads (pF), whereas the range of ultracapacitor is in Farads (F). The energy density and power density of ultracapacitor are $10^4$ Wh/m$^3$ and $10^6$ W/m$^3$ range respectively, whereas for the conventional capacitor has energy density 50 Wh/m$^3$ and power density of $10^{12}$ W/m$^3$ range. The surface area of ultracapacitor electrodes is very much higher than the surface area of conventional capacitor or battery. Ultracapacitor charges and discharges quickly and efficiently and also it has a long life cycle. In conventional capacitor ceramic, polymer films or aluminum oxide is used as dielectric material and in supercapacitor activated carbon is used as the dielectric material.

Based on the type of material used for electrodes, ultracapacitors are mainly classified into three types viz., Electrostatic Double Layer Capacitors (EDLC), Pseudocapacitors and hybrid capacitors as shown in Fig. 8 [56,57]. Double layer capacitor uses carbon electrodes and pseudocapacitors uses conducting polymer or metal oxide polymers. Hybrid capacitor use electrodes of different characteristics. Among these EDLC is most commonly used and cheapest ultracapacitor.

### *Flywheel energy storage*

Flywheel is a type of energy storage device which stores energy in the form of mechanical energy. The operating mechanism of flywheel has energy storage and energy release states. When the torque is applied to the flywheel it stores the energy. Conversely, the energy is released to the connected mechanical shaft in the form of torque [58]. The main parts in the FES are rotating flywheel, rotor bearings and power interface. Flywheels are categorized into two types: a low speed flywheel having the operating speed of 6000 rpm and a high speed flywheel with operating speed of 50,000 rpm [59]. Low speed flywheels are made up of with conventional bearings and steel rotors. High speed flywheels are made up of with ultra-low friction bearings and the rotor is made with advanced composite materials.

The power interface consists of motor/generator, a variable speed power converter and a controller to control the power. The motor/generator is generally a high speed permanent magnet motor/generator. A PWM power converter either a

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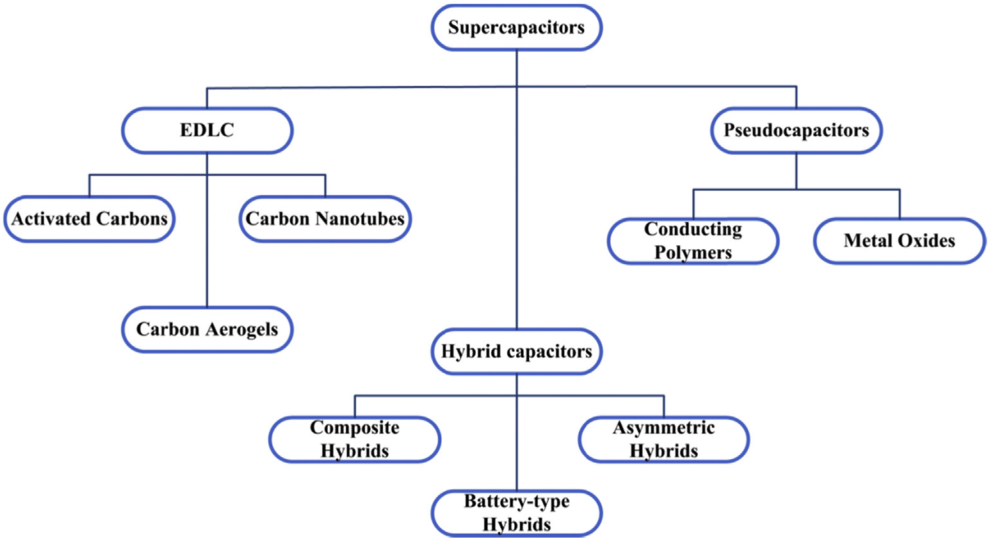

**Fig. 8 – Classification of supercapacitor.**

single stage (AC to DC) or a double stage (AC to DC to AC) converter is used depending on the application. Finally, to control the power system variables a power controller is required. Flywheel energy storage system has the advantages of low recharge time, long lifecycle, quick response and required less maintenance. The major issues of a flywheel in electric vehicle applications are safety issues and the gyroscopic force management. The FES systems are used in the applications wind turbines, spacecraft energy storage systems, electric vehicles, grid energy storage, soft toys and UPS [60].

### Regenerative braking

During braking or coasting, the kinetic energy from a propelling vehicle generates electric power back to the battery or other energy storage device is known as regenerative braking [61]. Regenerative braking is also known as kinetic energy recovery system. Regenerative braking energy is captured by using four different methods. First, the electric energy generated is stored directly in energy storage system. Second, hydraulic motors are used to store the energy in a small canister. Third, energy is stored in flywheel energy storage system as rotating energy and in the last method energy is stored in a spring as gravitational energy [62]. The regenerative braking system does not generate sufficient energy to stop the vehicle, so it operates together with the friction brake to stop or slow down the vehicle. The efficiency of regenerative braking depends on the capacity of electric generator, drive topology and state-of-charge of ultracapacitor and battery [63]. Regenerative braking increases the overall efficiency of the vehicle and reduces the fuel emissions.

However, the major drawback of the hybrid electric vehicles is the cost of the energy storage devices. As presented by Ref. [64], a decrease of energy storage devices cost is anticipated by 2025, which will cause a notable decrease in the acquisition price of the electric vehicles. Fig. 9 shows the annual cost analysis of different energy storage devices.

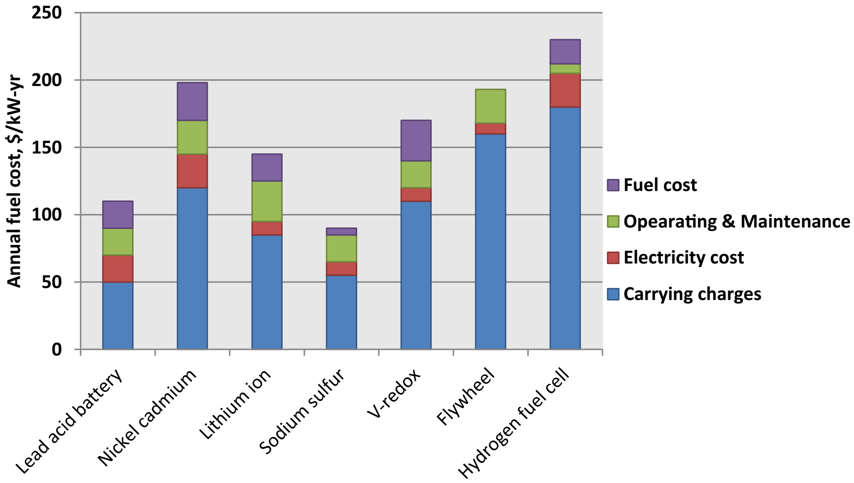

**Fig. 9 – Annual cost analysis of different energy sources.**

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## Multi-input DC-DC converter topologies

Power converters are mainly used in EVs, PV power generation, aircrafts and microgrid application to meet the required power demands. There are four types of converters such as rectifier, inverter, DC-DC converter and AC-AC converters [65,66]. In electric vehicles mostly DC-DC converters and inverters are used. DC-DC converters are used in electric vehicles to interface the battery, supercapacitor or fuel cell to the DC link. The inverters are used to convert this DC power into AC to power the electric motor. This paper focuses only on multi-input DC-DC converters.

Batteries, fuel cells, solar PV arrays and ultracapacitors are widely used in EV/HEV applications as energy storage devices or as electric power sources [67]. To improve the efficiency and performance of HEVs two or more these sources are employed in the vehicle architecture. When more than two sources are connected then multi-input converter is used to regulate the DC bus voltage. The topology of multi-input converter is as shown in Fig. 10. These converters are obtained by synthesizing more than two single input converters. Multi-input converter topology is the unique for integrating more than two power sources of different power and voltage ratings. The multi-input converters are classified into three groups as listed below [68,69]:

i) Electrical coupled multi-input converters
ii) Magnetic coupled multi-input converters
iii) Electro-Magnetic coupled multi-input converters

### *Electrical coupled multi-input converters*

Y.M Chen et al. proposed a novel multi-input PWM DC-DC converter for low/high voltage sources as shown in Fig. 11 [70]. The proposed converter has drawn power from two different sources individually or simultaneously. The different modes of operation of this converter are illustrated in the Table 2. The relation between input and voltages of the converter is given as follows:

$$V_0 = \frac{D_1}{1-D_2}V_1 + \frac{D_2}{1-D_2}V \tag{15}$$

This converter has the advantages as follows: multi-winding transformer is not required, without need of any additional equipment soft switching occurs and the main drawback is recharging of battery is not possible.

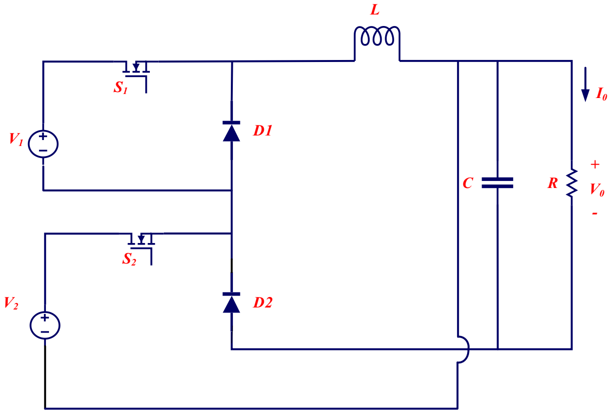

**Fig. 11 – Multi-input buck/buck-boost topology [70].**

Di Napoli et al. proposed a multi-input DC-DC converter for fuel cell hybrid vehicles as shown in Fig. 12 [71]. This converter has battery, UC tank and Fc generator. Among all these sources FC is the main energy source. According to Fig. diode $D_1$ and switch $S_1$ for a boost converter and diode $D_2$ and switch $S_1$ make up a buck converter. During the buck mode the battery and UC supplies the power to the load and during boost mode FC supplies the power. The main advantages of this topology are; multi-winding transformer is not required and different voltage sources can be used and the main drawbacks is number of switching devices are high. The voltage conversion ratio of converter is given as

$$V_0 = \frac{V_1}{1-D_2} = \frac{V_2}{1-D_4} = \frac{V_3}{1-D_6} \tag{16}$$

Gavris et al. proposed a novel multi-input hybrid buck for DC-DC converter for automobile applications [72]. As shown in Fig. 13, the circuit has two converters; hybrid buck C on the top and hybrid buck L on the bottom. The operating principle of the converter is given in the Table 3. The input-output voltage relation of the converter is given as follows

$$V_0 = \frac{D_1}{2-D_2}V_1 + \frac{D_2}{(2-D_1)(2-D_2)}V_2, \text{for } D_1 > D_2 \tag{17}$$

$$V_0 = \frac{D_1}{2-D_2}V_1 + \frac{2D_2-D_1}{(2-D_1)(2-D_2)}V_2, \text{for } D_1 \le D_2 \tag{18}$$

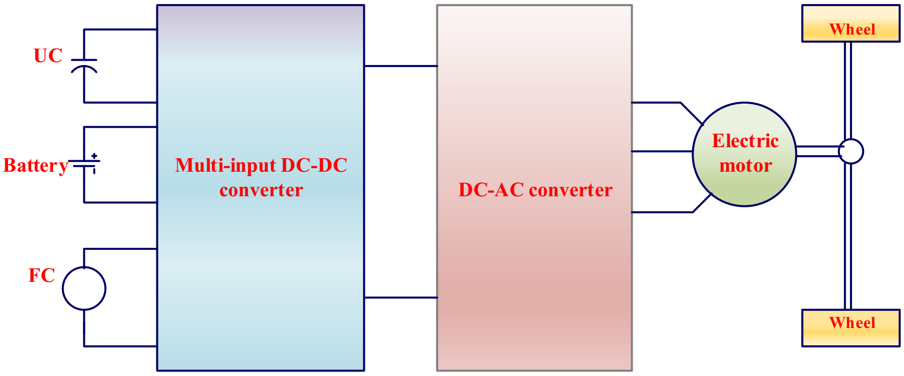

**Fig. 10 – Multi-input converter topology.**

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**Table 2 – Modes of operation of multi-input buck/buck-boost converter [70].**

| Mode | $S_1$ | $S_2$ | Description |
|---|---|---|---|
| Mode-1 | ON | OFF | $D_2$ conducts and $D_1$ is reverse bias. $V_1$ charges the inductor, capacitor and also provides the electrical energy to load |
| Mode-2 | OFF | ON | $D_1$ conducts and $D_2$ is reverse biased. $V_2$ charges the inductor |
| Mode-3 | OFF | OFF | Both $D_1$ & $D_2$ conduct. Inductor and capacitor provides the electrical energy to load. |
| Mode-4 | ON | ON | Both $D_1$ & $D_2$ are reverse biased. Both $V_1$ & $V_2$ provides the energy to load. |

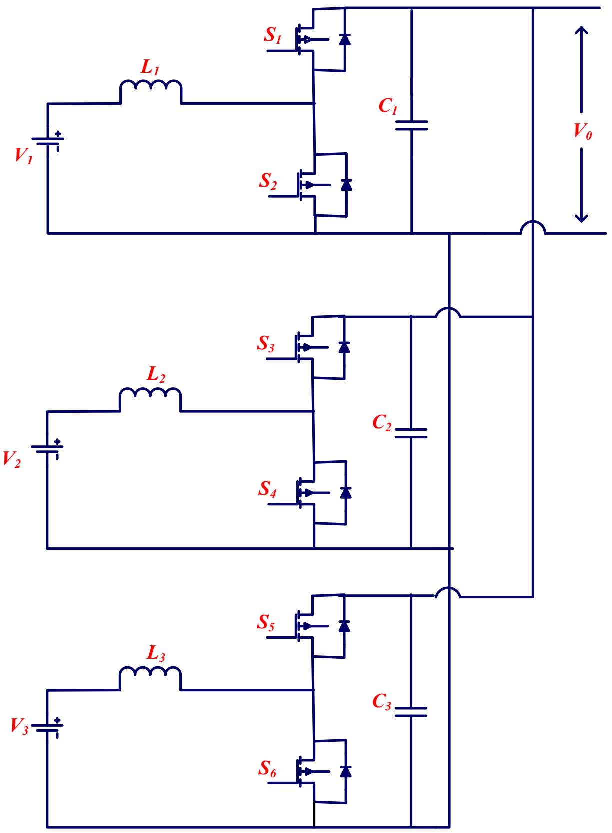

**Fig. 12 – Multi-input converter [71].**

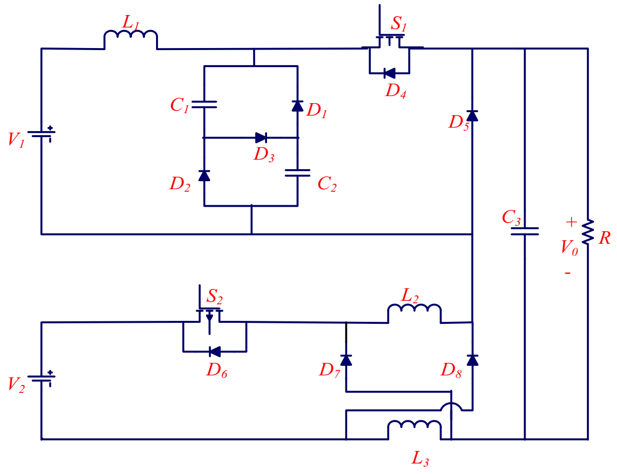

**Fig. 13 – Hybrid buck/buck DC-DC converter [72].**

In Ref. [73], MR Feyzi et al. proposed a multi-input boost converter as shown in Fig. 14. In this converter fuel cell ($V_1$), solar cell ($V_2$) and battery ($V_3$) are used as energy sources. The operation control modes (OCM) of the converter are illustrated in the Table 4. The relation between input-output voltages is given as follows.

$$V_0 = \frac{V_1 + D_4 V_3}{1 - D_1 - D_4} \tag{19}$$

$$V_0 = \frac{V_2 - D_3 V_3}{1 - D_2 - D_3} \tag{20}$$

F Nejabatkhah et al. proposed a novel three input DC-DC converter for renewable applications as shown in Fig. 15 [74–77]. The converter has three energy source; solar cell, fuel cell and a battery. In this topology the battery is used as the storage device. The modes of operation of the converter are given in the Table 5.

In Ref. [78], Ali Nahavandi et al. proposed a multiple input multiple output DC-DC converter for electric vehicle applications as shown in Fig. 16. In this converter, $V_1$ is a energy stored device such as battery and $V_2$ is fuel cell. In this topology $V_1$ is greater than $V_2$. The output of the converter has two different voltage levels which can be used to interface the two different loads electric vehicle.

The modes of operation of the converter as follow: In mode-1, switches $S_1$ and $S_2$ are ON, the inductor L charged by the battery $V_3$. In mode-2, switch $S_1$ and diode $D_1$ are ON then inductor L charged by the fuel cell $V_2$. In mode-3, $S_4$ and $D_1$ are ON and load 2 is supplied by $V_2$. In mode-4, both the diodes $D_1$ and $D_3$ are ON and load 1 is supplied by $V_2$.

Ye Yuan-mao et al. proposed a multiple input converter based on switched-capacitor is as shown in Fig. 17 [79]. The duty cycle of the switches is 50% with a phase a phase shift of 180°. The output voltage of the converter is sum of the three input voltages.

$$V_0 = V_1 + V_2 + V_3 \tag{21}$$

In Ref. [80], BG Dobbs et al. proposed a buck-boost converter for n numbered input sources as shown in Fig. 18. The main advantages of this converter are; less number of components required and the single inductor is shared by all the input sources. The main drawbacks of this topology are, it operates in unidirectional and only one input source will deliver power to the load. To overcome these drawbacks, Khaligh A et al. proposed a multi-input bidirectional DC-DC converter [81]. The topology of this converter is as shown in Fig. 19. The converter operates in buck, boost and buck-boost modes. The main drawback of the converter is number of devices are increased compared to the converter proposed in Ref. [80].

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**Table 3 – Operating principle of the converter proposed in Ref. [72].**

| Mode | $S_1$ | $S_2$ | Description |
|---|---|---|---|
| Mode-1 | ON | OFF | Diodes $D_1$, D2, $D_7$ and $D_8$ are forward biased. $V_1$ charges the inductor $L_1$ and provides electrical energy to load. |
| Mode-2 | OFF | ON | Diodes $D_3$ and $D_5$ are forward biased. $V_1$ charges $C_1$ & $C_2$ and $V_2$ charges $L_2$ & L3. |
| Mode-3 | ON | ON | Diodes $D_1$ and $D_2$ are forward biased. V1 & $V_2$ both sources supplies energy to the load. |
| Mode-4 | OFF | OFF | Diodes $D_5$, $D_7$ and $D_8$ are forward biased. $L_2$, $L_3$ and $C_3$ supply the energy to load. |

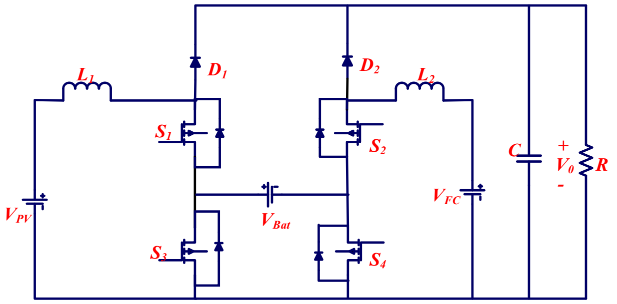

**Fig. 14 – Multi-input DC-DC converter proposed in Ref. [73].**

**Table 4 – Operating principle of the converter proposed in Ref. [73].**

| OCM | $S_1$ | $S_2$ | $S_3$ | $S_4$ | Switching period |
|---|---|---|---|---|---|
| MPPT control | ON | OFF | ON | OFF | $D_1T$ |
| FC power control | OFF | ON | OFF | ON | $D_2T$ |
| Battery charging | OFF | ON | ON | OFF | $D_3T$ |
| Battery discharging | ON | OFF | OFF | ON | $D_4T$ |
| No operation | OFF | OFF | OFF | OFF | $D_5T$ |

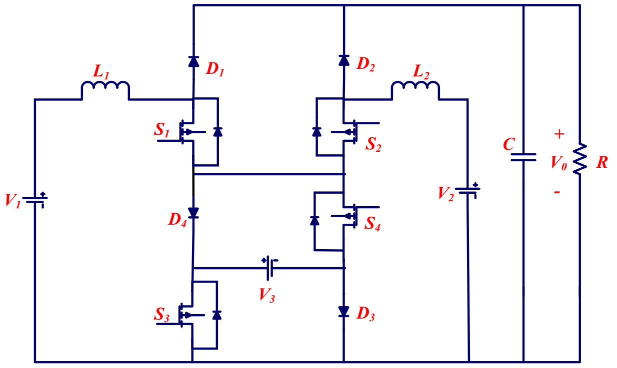

**Fig. 15 – Three input DC-DC boost converter [74].**

Ali Delhimi et al. proposed a multi-input DC-DC converter topology to interface multiple inputs at different output characteristics with a common load as shown in Fig. 20 [82]. The voltage of gain the converter is increased by increasing the input sources. Both voltage and current sources can be used for the converter. The average output voltage of the converter is given as

$$V_0 = \sum_{i=1}^{n} \frac{V_i}{1 - D_i} \tag{22}$$

The summary of the electric coupled multi-input DC-DC converter is given in Table 6.

### *Magnetically coupled multi-input DC-DC converters*

The first magnetically coupled multi-input DC-DC converter was proposed by H Matsuo et al. as shown in Fig. 21 [89–91]. It is a buck-boost type multi-input converter. This converter operates in three modes as illustrated in Table 7. The main drawbacks of this topology are only any one source will supply the load at any time, soft switching is not possible and battery recharging is also not possible. The relation between input and output voltages of the converter is given as

$$V_0 = \frac{D_1}{N_1(1 - D_1 - D_2)} V_1 + \frac{D_2}{N_2(1 - D_1 - D_2)} V_2 \tag{23}$$

In Refs. [92,93], Y. M Chen et al. proposed a multi-winding multi-input DC-DC converter as shown in Fig. 22. In this converter, the different input sources can deliver power to the load individually or simultaneously. Phase-shifted PWM control technique is used to control the power flow and output voltage regulation of the converter. The advantages of the converter are as follows: different dc input voltage source can be used, electric isolation occurred naturally and the dc input sources can power the load simultaneously or individually. The output voltage of the converter is given as

$$V_0 = \frac{N_3}{N_1} V_1 + \frac{N_2}{N_1} V_2 \tag{24}$$

Yan Li et al. proposed a soft-switching multi-input full bridge DC-DC converter for hybrid renewable energy applications as shown in the Fig. 23 [94,95]. In this topology, the energy sources supplies the power to the load simultaneously or individually. The modes of operation of the converter are as follows. In first mode, switches $S_1$, $S_4$ and $S_5$ are ON then the sum of input voltages appears at the transformer primary winding. In second mode, $S_1$ and $S_4$ are ON and $V_1$ alone supplies the power to transformer primary. In third mode, $S_2$, $S_3$ and $S_6$ are ON then the sum of input voltages appears at the transformer primary in reverse polarity.

In Ref. [96], Danwei Liu et al. proposed a ZVS bidirectional multi-input DC-DC converter for hybrid energy storage devices. The converter has a high frequency multi-winding transformer and three half bridges as shown in Fig. 24. In this topology, soft switching is naturally implemented by transformer leakage inductors and snubber capacitors. This converter has high efficiency compared to the multi-input full bridge converter and also it is a bidirectional converter.

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**Table 5 – Modes of operation three input DC-DC converter.**

| $S_1$ | $S_2$ | $S_3$ | $S_4$ | Modes of operation |
|---|---|---|---|---|
| ON | ON | OFF | ON | $V_1$ and $V_2$ power control |
| OFF | ON | OFF | ON | $V_1$ supplies output and $V_2$ power control |
| OFF | OFF | OFF | OFF | No operation |
| ON | ON | ON | ON | $V_3$ discharges |
| ON | ON | ON | OFF | $V_1$ and $V_2$ power control |
| OFF | ON | ON | OFF | $V_1$ supplies output and $V_2$ power control |
| ON | ON | OFF | OFF | $V_3$ charges by $V_1$ and $V_2$ |
| OFF | ON | OFF | OFF | $V_3$ charges by $V_2$ |

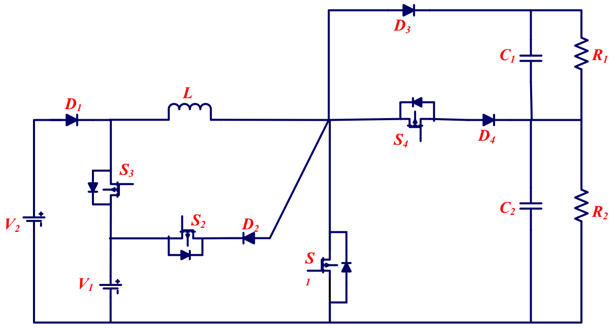

Fig. 16 – Multi-input multi-output DC-DC converter [78].

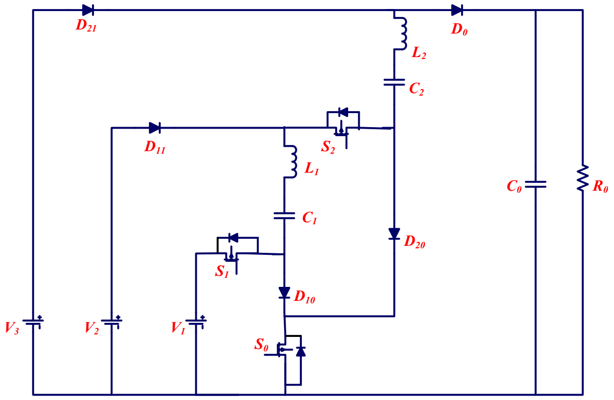

Fig. 17 – Multi-input converter based on switched capacitor [79].

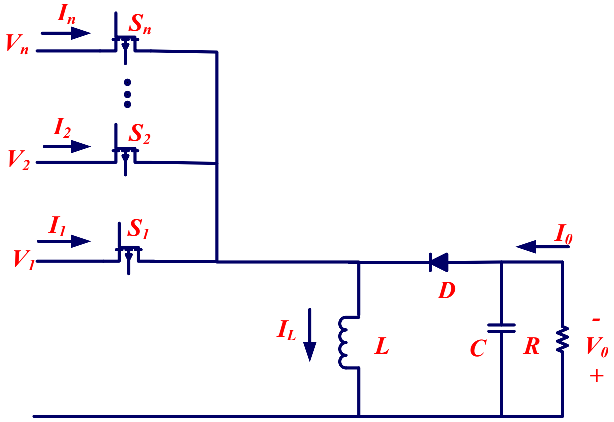

Fig. 18 – Unidirectional multi-input DC-DC converter [80].

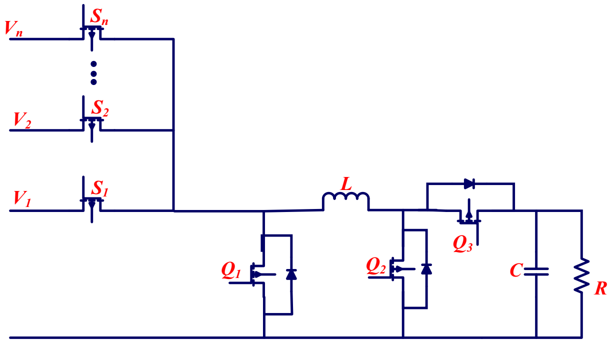

Fig. 19 – Bidirectional multi-input DC-DC converter [81].

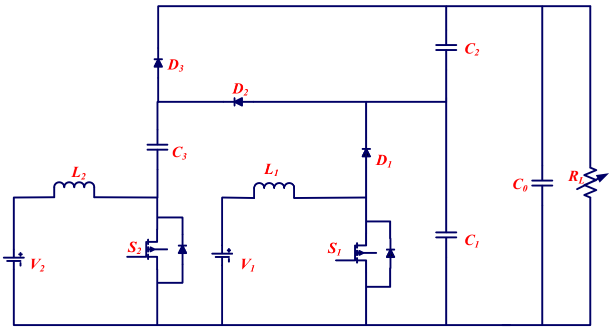

Fig. 20 – Multi-input converter proposed in Ref. [82].

In Refs. [97–99], Haimin Tao et al. proposed a triple half-bridge bidirectional DC-DC converter for fuel cell applications as shown in Fig. 25. The converter has two half bridges and one boost half bridge. To reduce the rms and peak values of current, phase shift plus pwm controller is used. The summary of magnetic couple multi-input converters is given in Table 8.

### *Electro-magnetic couple multi-input DC-DC converters*

In Ref. [101], H Tao et al. proposed a multi-input bi-directional DC-DC converter with a combination of magnetic coupling and dc link as shown in Fig. 26. In this converter two half-bridge converters are used. This converter draws the current continuously from the supercapacitor and fuel cell. The main advantages of this topology are only six switches are needed, high reliability and isolation is there between output and input of the converter and the drawback of this is soft switching is not available for switches $S_1$ and $S_2$.

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**Table 6 – Summary of electric coupled multi-input converters.**

| Author | Voltage conversion ratio | No. of semiconductors | No. of inductors | No.of capacitors |
|---|---|---|---|---|
| S Hou et al. [83] | $V_0 = \frac{3}{1-D}V_{in1}$<br>$V_0 = \frac{3}{1-D}V_{in2}$ | 4 diodes<br>2 switches | 2 | 5 |
| YM Chen et al. [70] | $V_0 = \frac{D_1}{1-D_2}V_1 + \frac{D_2}{1-D_2}V_2$ | 2 diodes<br>2 switches | 1 | 1 |
| K Gummi et al. [84] | $V_0 = \frac{D_1}{1-D_1-D_2}V_1 + \frac{D_2}{1-D_1-D_2}V_2$<br>$V_0 = \frac{D_1}{1-D_1}V_1 + \frac{D_2}{1-D_1}V_2$ | 3 switches | 1 | 1 |
| F Akar et al. [85] | $V_0 = \frac{V_1D_1}{1-D_{T0}} = \frac{V_2D_2}{1-D_{T0}}$ | 2 diodes<br>4 switches | 2 | 1 |
| Di Napoli et al. [2] | $V_0 = \frac{V_1}{1-D_2} = \frac{V_2}{1-D_4} = \frac{V_3}{1-D_6}$ | 6 switches | 6 | 3 |
| Gavri et al. [72] | $V_0 = \frac{D_1}{2-D_2}V_1 + \frac{D_2}{(2-D_1)(2-D_2)}V_2$<br>$V_0 = \frac{D_1}{2-D_2}V_1 + \frac{2D_2-D_1}{(2-D_1)(2-D_2)}V_2$ | 6 diodes<br>2 switches | 3 | 3 |
| MR Feyzi et al. [73] | $V_0 = \frac{V_1+D_4V_3}{1-D_1-D_4}$<br>$V_0 = \frac{V_2-D_3V_3}{1-D_2-D_3}$ | 2 diodes<br>4 switches | 2 | 1 |
| W Rang jang et al. [86,87] | $V_0 = \frac{1-D_1}{1+D_{dcm}-D_1}V_3$ | 1 diode<br>3 switches | 3 | 1 |
| MR Banei et al. [88] | $V_0 = \frac{V_2}{1-D_2} + \frac{D_1D_2}{(1-D_1)(1-D_2)}V_1$ | 2 diodes<br>2 switches | 2 | 2 |
| Y yuan-mao et al. [79] | $V_0 = V_1 + V_2 + V_3$ | 3 diodes<br>2 switches | 2 | 4 |
| A Delhimi et al. [82] | $V_0 = \sum_{i=1}^{n}\frac{V_i}{1-D_i}$ | 3 diodes<br>2 switches | 2 | 4 |

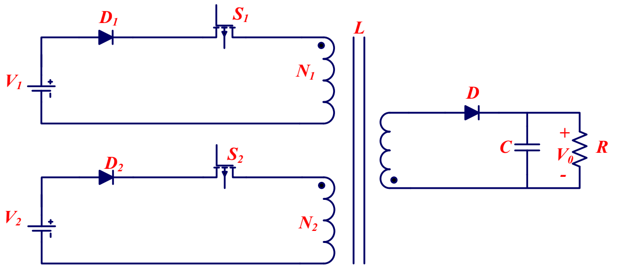

**Fig. 21 – Buck-Boost multiple input DC-DC converter [89].**

**Table 7 – Modes of operation of multiple input buck-boost converter.**

| Mode | $S_1$ | $S_2$ | D | Description |
|---|---|---|---|---|
| 1 | ON | OFF | OFF | $V_1$ charges inductor L |
| 2 | OFF | ON | OFF | $V_2$ charges inductor L |
| 3 | OFF | OFF | ON | Inductor L supplies the load |
| 4 | OFF | OFF | OFF | No operation |

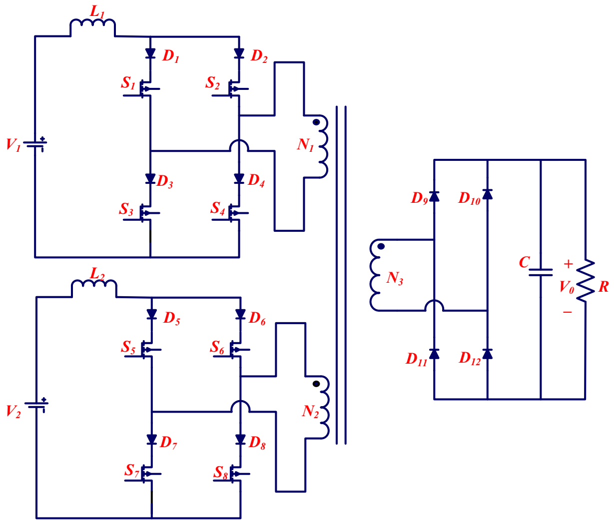

**Fig. 22 – Multi-winding multi-input converter [92].**

$$D = \frac{V_{DC} - V_{SC}}{V_{DC}} \tag{25}$$

$$V_{DC} = \frac{V_{load}}{n} \tag{26}$$

In [102,103], Hongfei Wu et al. proposed three-port half bridge converters for renewable applications as shown in Fig. 27. The converter has one input port, one isolated output port and one bi-directional port. In this topology single stage power conversion is achieved between any two ports. Compared to previous converter less number of switches are used in this topology. The main drawback of this topology is battery charging and discharging cycle is uncontrollable

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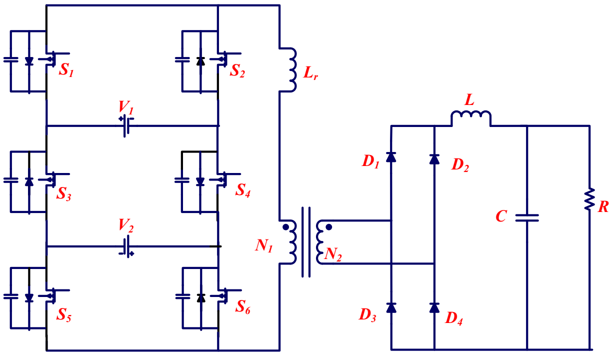

**Fig. 23 – Two input converter [94].**

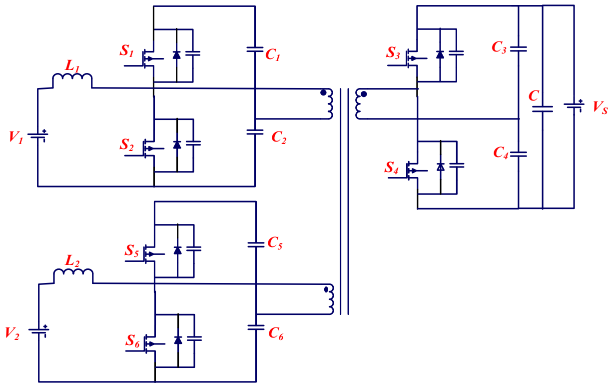

**Fig. 24 – ZVS bidirectional multi-input converter [96].**

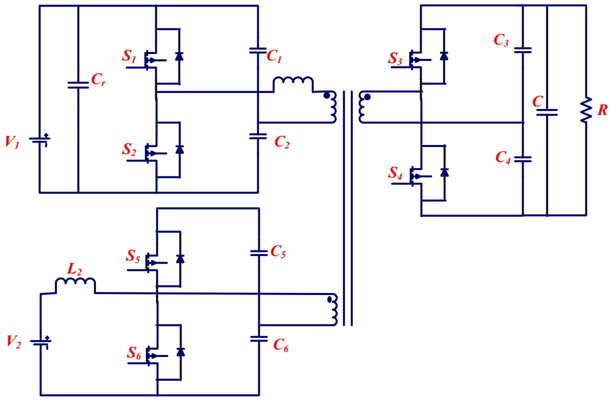

**Fig. 25 – Triple half-bridge DC-DC converter [97].**

which reduces the lifetime of battery. The relation between input-output voltages of the converter is given as

$$V_2 = \frac{D_1}{D_1 + D_2} V_1 \tag{27}$$

$$V_0 = 2nD_1V_2 \tag{28}$$

H Al-Atrash et al. proposed a tri-port half-bridge multi-input converter as shown in Fig. 28 [104]. In this topology, the duty cycles of switches controlled individually. Constant frequency PWM control is used for controlling the switches. The converter operates in three modes. When switch $S_1$ is ON, the positive voltage is delivered to the primary of the transformer. When switch $S_2$ is ON, the negative voltage is transferred to the transformer primary. When switch $S_3$ is ON, the transformer primary is shorted i.e. zero voltage applied. The main advantages of this topology are: soft switching, less stress on switching devices and possibility for battery charging and the main drawback is charge control of the battery is difficult. The relation between the input-output voltages of the converter is given as

$$V_2 = \frac{D_1}{D_1 + D_2} V_1 \tag{29}$$

$$V_0 = \frac{2D_1D_2}{D_1 + D_2} nV_1 \tag{30}$$

In Ref. [105], J Zeng et al. proposed a new multi-input DC-DC converter for simultaneous power transfer as shown in Fig. 29. In each port only one controllable switch is used in this converter at input side and there is no controllable switch at the transformer secondary side. The converter operates in three modes. In mode-1, the switches $S_1$, $S_2$ & $S_3$ are ON and the source inductors $L_1$, $L_2$ & $L_3$ are charged. In this mode the transformer primary has voltage of capacitor $C_1$. In mode-2, only one switch is ON and the remaining two switches are OFF. In this mode power is delivered to the load. In mode-3, all switches are OFF and all the input sources delivers power to the load.

S. Dusmez et al. proposed a multi-input three level DC-DC converter as shown in Fig. 30 [106]. The secondary side of the transformer may be either full bridge rectifier for high voltage output applications or a half bridge for low output voltage applications. The duty cycle of the controllable switches must be greater than 50%. The switches $S_1$–$S_4$ and $S_2$–$S_3$ have 180° phase shift with each other. The main advantages of this topology are output power of the converter is controllable and the isolation between output and input voltages and the main drawback is charge control of the

**Table 8 – Summary of magnetic couple multi-input converters.**

| Author | Voltage conversion ratio | No. of semiconductors | No. of inductors | No.of capacitors |
|---|---|---|---|---|
| H Matsuo et al. [89,90] | $V_0 = \frac{D_1V_1}{N_1(1-D_1-D_2)} + \frac{D_2V_2}{N_2(1-D_1-D_2)}$ | 3 diodes<br>2 switches | 0 | 1 |
| YM Chen et al. [92,93] | $V_0 = \frac{N_3V_1}{N_1} + \frac{N_2V_2}{N_1}$ | 12 diodes<br>8 switches | 2 | 1 |
| Yan Li et al. [94] | $V_0 = \frac{D_1V_1 + D_2V_2}{K}$ | 10 diodes<br>8 switches | 2 | 7 |
| Z Zhang et al. [100] | $V_0 = \frac{N_1}{2(1-D_1)} V_1$<br>$V_0 = \frac{N_2}{2(1-D_{21})} V_2$ | 8 diodes<br>8 switches | 2 | 2 |

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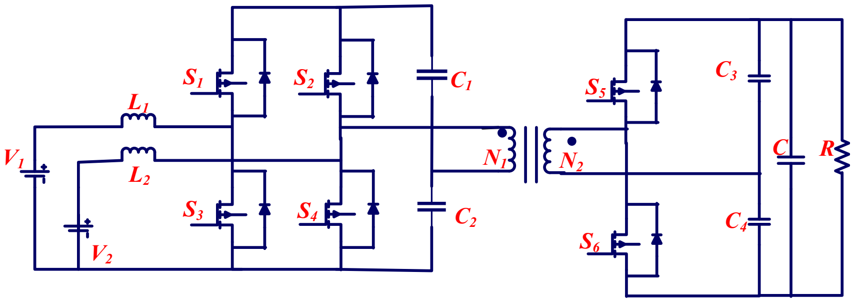

Fig. 26 – Multi-input bi-directional converter proposed in Ref. [101].

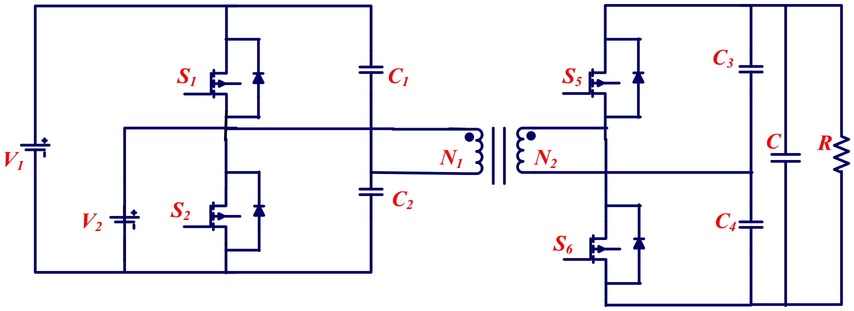

Fig. 27 – Three-port half-bridge converter [102].

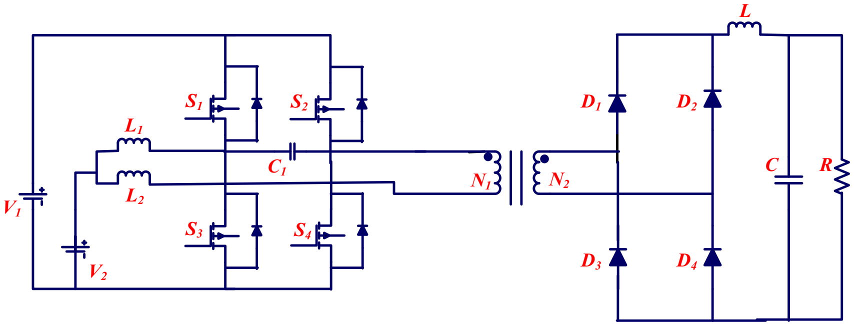

Fig. 28 – Tri-port half-bridge multi-input converter [104].

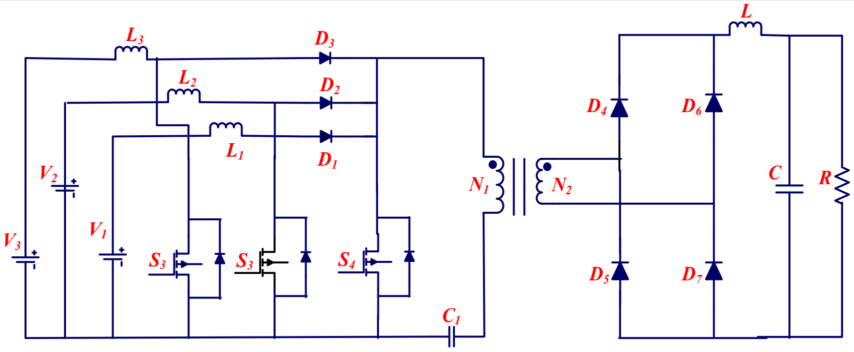

Fig. 29 – Multi-input DC-DC converter for simultaneous power transfer [105].

battery is difficult. The summary of electro-magnetic coupled multi-input DC-DC converters is given in Table 9.

## Control techniques of DC-DC converter

The control techniques for DC-DC power converters are mainly classified into two main groups as current mode control (CMC) and voltage mode control (VMC) [109]. Besides these there are different control techniques has been designed such as sliding mode controller, digital controllers etc.

VMC is the basic controller technique used in DC-DC power converters due to its simple design and easy implementation. The block diagram of VMC of a power converter is shown in Fig. 31. VMC is a single feedback loop controller connected to the voltage reference [110]. In VMC, first the output voltage is measured and

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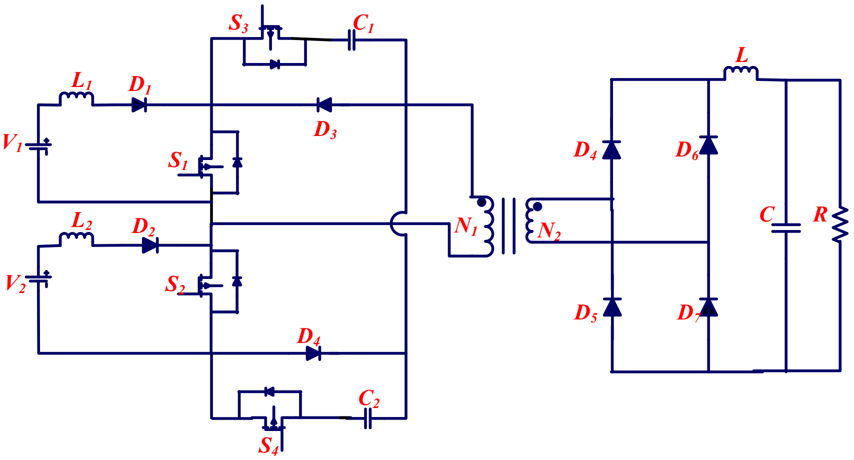

Fig. 30 – Multi-input three level DC-DC converter [106].

Table 9 – Summary of electro-magnetic coupled multi-input DC-DC converters.

| Author | Voltage conversion ratio | No. of semiconductors | No. of inductors | No.of capacitors |
|---|---|---|---|---|
| W. Hongfei et al. [102,103] | $V_2 = \frac{D_1}{D_1 + D_2} V_1$<br>$V_0 = 2ND_1V_2$ | 4 switches | 0 | 5 |
| H. Al-Atrash et al. [104] | $V_2 = DV_1$<br>$V_0 = 2\Psi_{eff}NV_1$<br>$\Psi_{eff} = \min(\Psi, D, 1 - D)$ | 4 diodes<br>4 switches | 3 | 2 |
| H. Al-Atrash et al. [107] | $V_2 = \frac{D_2}{D_1 + D_2} V_1$<br>$V_0 = \frac{2D_1D_2}{D_1 + D_2} NV_1$ | 3 diodes<br>3 switches | 1 | 3 |
| W Hongfei et al. [108] | $V_1 = \frac{D_1}{D_2} V_2$<br>$V_0 = 2ND_3V_2$ | 4 diodes<br>4 switches | 4 | 2 |
| Z Jianwu et al. [105] | – | 7 diodes<br>3 switches | 4 | 2 |
| S Dusmez et al. [106] | – | 8 diodes<br>4 switches | 3 | 3 |

then it compared with the reference voltage by using an error amplifier. And then, a PWM signal is generated by comparing this error signal with a sawtooth waveform. The generated PWM signal is used as gate signals to the DC-DC converter. VMC requires a compensation network to improve the closed-loop phase margin. The advantages of VMC are high noise tolerance and simple design and the major drawbacks of this controller are: i. Amplifier and compensation network slowdowns the response of feedback loop. ii. Less reliability and stability of main switch. iii. The response of the system is very slow [111].

Current control mode (CMC) is another basic controller for DC-DC converters. The block diagram of CMC of a power

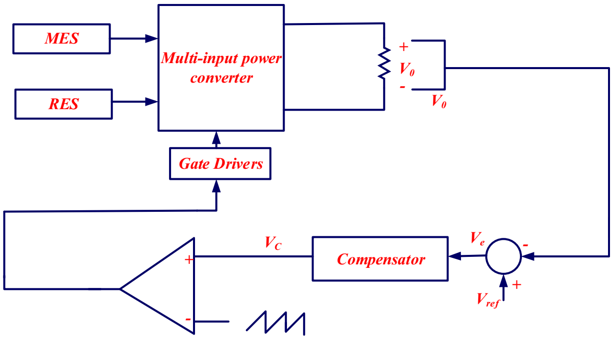

Fig. 31 – Block diagram of VMC.

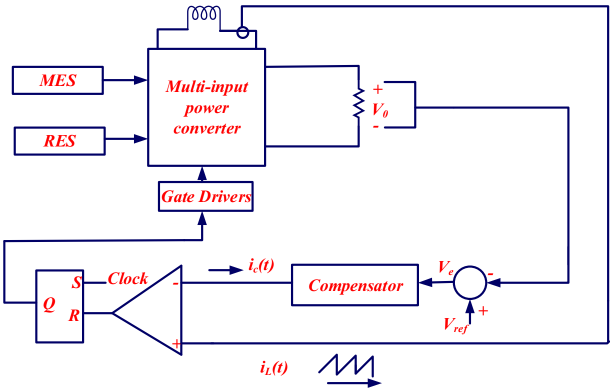

Fig. 32 – Block diagram of CMC.

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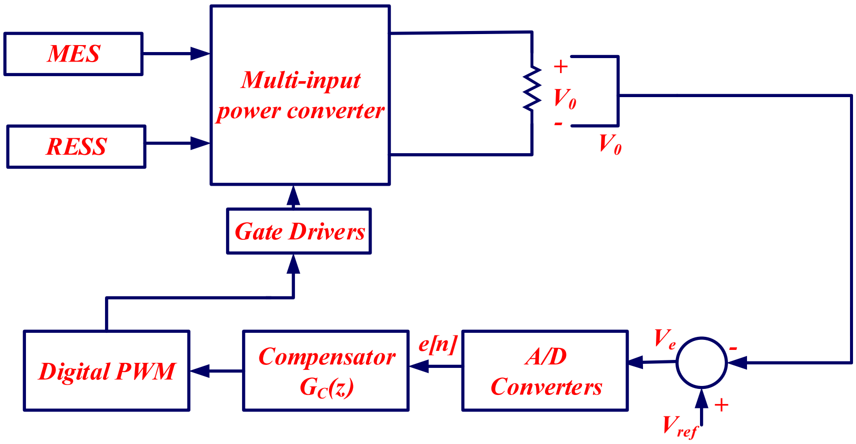

**Fig. 33 – Block diagram of digital controller.**

converter is shown in Fig. 32. CMC has two feedback loops including current and voltage control loops. Compared to VMC, CMC provides an extra inner current loop control [112]. The inner current loop senses the inductor current. The error signal $V_e$ is generated by comparing the output voltage of the converter $V_0$ with a reference voltage $V_{ref}$ and this error signal $V_e$ is used to generate a control signal $i_c$ [113]. After that, the control signal $i_c$ is compared with inductor current to generate PWM signals to drive the switches of the power converter. Total response of the system depends on the feedback loop position. If the loop is closed $V_0$ becomes equal to $V_{ref}$ and the inductor current is proportional to the control signal.

Sliding mode controller (SMC) is a nonlinear controller and it is mainly used to control the variable structured systems. Compare to other nonlinear controllers SMC is very easy to implement [114]. SMC consists of two modes, reaching mode and sliding mode. In reaching mode from any initial point the trajectory moves towards the sliding line. In sliding mode, along with state trajectories the switching line moves towards the origin. SMC is graphically represented as shown in figure. The phase plane is divided into two main regions by the sliding line. If the trajectory comes at the system equilibrium point then the system is considered as stable system [115,116]. The advantages of SMC are fast dynamic response, high robustness, high stability and easy implementation. The major drawbacks of this controller are, the switching frequency of the converter varies and the output voltage is affected by steady-state errors.

Power converters are more complicated due to the nonlinear and time-varying nature of power switches and fluctuations of load input voltage and load current. Hence, it is difficult to design the exact model of the power converter system. Generally in analog controller technique, the power converter is designed by using linear models. So, it is difficult to design the control algorithms with high performance by using analog controllers. To overcome this problem, digital controllers are designed for the power converters. The block diagram of digital controller of a power converter is shown in Fig. 33. Compared to digital controllers analog controllers have the advantages of reduced design time, better flexibility, improved system reliability, programmability and easier system integration. Advanced power management system depends on integration of power control and conversion functions with digital systems. Digital controllers have inherently lower sensitivity to process and parameter variations. The real-time digital control can be implemented by using different technologies: basically,

i. Digital signal processors (DSP) [117,118].
ii. Field programmable gate arrays (FPGA) [119–121].

## Future scope

As the sources of conventional fossil fuels are decreasing day by day, fuel cell hybrid electric vehicles with multi-input converters can play an important role in the future vehicle market. However, there are some disadvantages by using these vehicles and are listed below:

a. The capital cost of the fuel cell hybrid electric vehicles is very much high compared to internal combustion engine vehicles.
b. The size of fuel cell is also a major drawback in these vehicles.
c. The reliability and durability of fuel cell system is less compared to internal combustion vehicles, especially in some temperature and humidity ranges.

If these drawbacks are conquered, fuel cell hybrid vehicles can become a best alternative for internal combustion engine vehicle.

## Conclusion

Hybrid Electric vehicle technology is a trending subject today due to its low emissions, less fuel consumption, low noise and low operating cost. This paper gives state-of-art overview of electric vehicle technology, the possible energy sources and the different multi-input converter topologies used HEV applications. Energy storage device is the major problem in all EVs. In recent years, there is a lot of advancement in energy storage devices which offers better promise in terms of power density and energy density. But none of these energy storage devices provides the required combination of all the following features: high energy density, high power density, low cost and long life. So the concept of combining energy sources (hybrid energy sources) is introduced to obtain the better features.

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This paper also briefly discusses about the different multi-input converter topologies used electric vehicles. In this paper the multi-input DC-DC converter topologies are divided into three groups such as electric, magnetic and electromagnetic coupled multi-input converters. Literature suggests that compared to electrical coupled and magnetically coupled multi-input converters the combined electromagnetic coupled multi-input converters offers high voltage gain. Hence, electromagnetic coupled multi-input converters are best option for electric vehicle applications. The use of multi-input converters in EV applications has reduced switching losses, reduced the cost of integration and increased the power security and reliability. Simultaneous utilization of two or more energy sources is possible. With a clear insight, the multi-input DC-DC converter can be a better choice if one has to integrate two or more energy sources to EVs. The additional advantages of these converters are listed below:

a. Size of the converter is small.
b. Converter cost is less due to the utilization of less semi-conduct or devices.
c. Better monitoring on the energy resources.

## Appendix

**Table 1 – Different commercial electric vehicles available in market.**

| Vehicle model | Type | Energy source | Fuel economy MPGe (Highway/city) | Annual fuel cost in $ (per 15,000 miles) |
|---|---|---|---|---|
| BMW Active E 2011 | BEV | Electric | 96/107 | 600 |
| Honda Fit 2014 | BEV | Electric | 105/132 | 500 |
| Nissan Leaf 2015 | BEV | Electric | 101/126 | 550 |
| Mitsubishi i-MiEV 2016 | BEV | Electric | 99/126 | 550 |
| Ford Focus Electric 2016 | BEV | Electric | 99/110 | 600 |
| Honda Insight 2014 | HEV | Gasoline | 44/41 | 850 |
| BMW Active Hybrid3 2015 | HEV | Gasoline | 33/25 | 1500 |
| Toyota Prius 2015 | HEV | Gasoline | 48/51 | 700 |
| Ford Fusion Hybrid FWD 2016 | HEV | Gasoline | 41/44 | 850 |
| Toyota Prius 1.8 2015 | PHEV | Gasoline-Electric | 50/95 | 650 |
| Chevrolet Volt 2015 | PHEV | Gasoline-Electric | 93/101 | 800 |
| Audi A3 E-tron 2016 | PHEV | Gasoline-Electric | 83/83 | 950 |
| Honda FCX clarity 2014 | FCEV | Hydrogen | 60/58 | – |
| Hyundai Tuscon Fuel cell 2016 | FCEV | Hydrogen | 51/49 | – |
| Toyota Mirai 2016 | FCEV | Hydrogen | 66/66 | – |
| Toyota FCHV adv | FCHEV | Hydrogen | 43/39 | – |
| Audi Sportback A7h-tron Quattro 2014 | FCHEV | Hydrogen | 62/62 | – |

**Table 2 – Characteristics and applications of different types of batteries.**

| Energy storage type | Specific energy (Wh/kg) | Specific power (W/kg) | Life cycle | Efficiency (%) | Applications |
|---|---|---|---|---|---|
| **Lead acid battery** | | | | | Grid energy storage, UPS, Electric vehicles, lighting and ignition. |
| lead acid | 35 | 180 | 1000 | >80 | |
| Advanced lead acid | 45 | 250 | 1500 | – | |
| Metal foil lead acid | 30 | 900 | 500+ | – | |
| **Nickel battery** | | | | | Digital cameras, electric vehicles<br>Portable electronics and toys. |
| Nickel-iron | 50–60 | 100–150 | 2000 | 75 | |
| Nickel-zinc | 75 | 170–260 | 300 | 76 | |
| Nickel-cadmium (Ni–Cd) | 50–80 | 200 | 2000 | 75 | |
| Nickel-metal hydride (Ni-MH) | 70–95 | 200–300 | <3000 | 70 | |
| **Lithium battery** | | | | | Electric vehicles, smartphones, laptops, electric toys, digital cameras. |
| Lithium-ion | 118–250 | 200–430 | 2000 | >95 | |
| Lithium-ion polymer (LiPo) | 130–225 | 260–450 | >1200 | – | |
| Lithium-iron phosphate (LiFePO4) | 120 | 2000–4500 | 42000 | – | |
| Lithium-iron sulphide (FeS) | 150 | 300 | 1000+ | 80 | |
| Lithium-titanate | 80–100 | 4000 | 18000 | – | |
| **ZEBRA battery** | | | | | Automobile applications. |
| Sodium-sulfur | 150–240 | 150–230 | 800+ | 80 | |
| Sodium-nickel chloride | 90–120 | 155 | 1200+ | 80 | |
| **Metal-air battery** | | | | | Grid storage and electric vehicles. |
| Aluminum-air | 220 | 60 | – | – | |
| Zinc-air | 460 | 80–140 | 200 | 60 | |
| Zinc-refillable | 460 | – | – | – | |
| Lithium-air | 1800 | – | – | – | |

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**Table 3 – Fuel cell characteristics and applications.**

| Fuel cell type | Electrolyte type | Cell voltage (V) | Operating temperature (°C) | System output (kW) | Efficiency (%) | Applications |
|---|---|---|---|---|---|---|
| AFC | Aqueous solution of potassium hydroxide soaked in a matrix | 1.0 | 90–100 | 10–100 | 60 | Military, Space |
| PEMFC | Solid organic polymer poly-perfluorosulfonic acid | 1.1 | 50–100 | < 1-250 | 53–58 | Backup power transportation, Small distributed generation, Portable power |
| PAFC | Liquid phosphoric acid soaked in a matrix | 1.1 | 150–200 | 50–1000 | >40 | Distributed generation |
| MCFC | Liquid solution of lithium, sodium and/or potassium carbonates soaked in a matrix | 0.7–1.0 | 600–700 | < 1-1000 | 45–47 | Large distributed generation, Electric utility |
| SOFC | Yttria stabilized zirconia | 0.8–1.0 | 600–1000 | < 1-3000 | 35–43 | Large distribution generation, Electric utility, Auxiliary power |

**Table 4 – Ultracapacitor characteristics and applications.**

| Ultracapacitor type | Electrode materials | Cell voltage (V) | Specific energy (Wh/kg) | Specific power (W/kg) | Life cycle | Efficiency (%) | Applications |
|---|---|---|---|---|---|---|---|
| EDLC | Activated carbon | 2.5–3 | 5–7 | 1–2 M | 40 years | >95 | UPS, Electric toys, Electric vehicles. |
| Pseudocapacitor | Metal oxides | 2–305 | 10–15 | 1–2 M | 40 years | >95 | Low power applications. |
| Hybrid capacitor | Carbon/metal oxide | 2–3.3 | 10–150 | 1–2 M | 40 years | >95 | Digital wireless communication devices, Space shuttle, Satellite phone. |

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