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Design and Control Algorithms for Power Electronic Converters for EV Applications

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Abstract**—**The power electronic components within Electric Vehicles (EV) need to operate in several important modes. Some modes directly influence safety, while others influence vehicle performance. Given the variety of functions and operational modes required of the power electronics, it needs to meet efficiency requirements to minimize power losses. Another challenge in the control and construction of such systems is the ability to support bidirectional power flow. This paper considers the construction, operation, and feasibility of available converters for electric vehicles with feasible configurations of electrical buses and loads. This paper describes logic and control signals for the converters for different operations conditions based on the efficiency and energy usage bases.

Keywords**—**Electric Vehicles, Electrical Machines Control, Power Electronics, Powerflow Regulations.

I. INTRODUCTION

POWER electronic components play an essential role in the operation of Electric Vehicles (EV). The operation of the Energy Storage System (ESS) and other components and systems rely on converters and inverters characteristics of which depend on the systems' interactions and power requirements [1], [2].

EV power busses comprise separate buses depending on voltage level and power flow requirement. The high voltage bus connects and services systems with high peak power and energy consumption. These systems include drivetrain components, climate control system, and the main energy storage system. Other systems, such as media devices, safety components, comfort systems, and lights are connected to a low voltage bus with a peak voltage of 12V DC. The 12DC voltage level allows use of electrical components from conventional vehicles [3], [4].

Due to the different nature and power levels of the different buses, interconnection between different EV systems is minimal. The high voltage bus has bidirectional working environment and has continuous energy flow between the ESS and electric drive motor. The powertrain converter and controller needs to be able to handle this powerflow with requested power level in both directions, to be able to adapt to the external load on the powertrain and to the State of Charge (SoC) of the ESS. In addition, the converter and controller need to operate at high efficiency. The bidirectional nature of the high voltage power flow corresponds to the modes of the powertrain. One mode is where energy is supplied to the electric motor to rotate the wheels for torque and acceleration. In this mode, energy comes from the ESS through the converter according to the speed-load requirements. The opposing mode of the powertrain is the regenerative mode where the motor is working as a generator to supply power back to the ESS for recharging [3], [5], [6]. Another converter operates between the two buses. This converter is single directional and operates as a step down converter to supply 12V DC from the high voltage ESS. The reverse direction of the power for this converter is prohibited by a diode bridge so as to prevent current leakage from the 12V battery to the high voltage bus. Existing converter configurations follow the same rules, where a buck converter connects the low voltage battery to the main ESS and the low voltage bus is connected only to the battery. As a result, only one reference signal is required for the correct operation. For such construction, this is a SoC of the battery. Systems and components, and their energy usage has little influence on the operation of the high voltage bus as all energy comes from the battery as shown in Fig. 1.

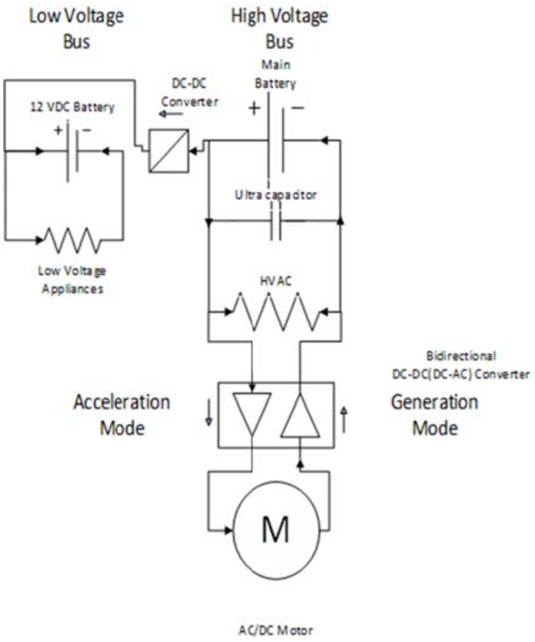

Fig. 1 EV Electrical System Architecture

EV Electrical System Architecture has low efficiency in energy conversion, seeing as energy which is stored in the high

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voltage energy system needs to be converted to charging energy for the low voltage battery and then this battery is powering the entire 12V systems. The main advantage of this approach is to use a single channel for the control signal. The SoC of the low voltage battery is the main feedback signal for the converter, and the control algorithm uses this signal to support required SoC level for all conditions [7], [8]. Another power electronic system in EVs is the voltage energy storage system. Modern storage systems consist mainly of Li-Ion or NiMH batteries with several cells to provide the required voltage and current. This system requires a suitable control algorithm for balancing the power flow in all cells of the battery. Other ESSs consist of other elements for energy storage such as ultra-capacitors and hydrogen fuel cells. To use these, additional converters are required to balance characteristics and SoC of the components. To achieve effective power flow and high efficiency, the converter between the powertrain and ESS needs operation conditions where both the ESS and powertrain are operating with the highest possible efficiency to provide energy supply and safety for the occupants in all sorts of environment. Given that capacitors provide high power density, for electric motors operating in generation mode with high braking torque, the energy generated should be stored in the capacitor rather than the batteries because of the different power charging characteristics of the elements.

This paper aims to classify converters in EVs based on their operational principals and power requirements. The paper also describes the requirements of the converters and the influence of different electric bus designs to the efficiency of EVs. There are different approaches to the electric drive configuration and operation, so different drivetrain configurations have been selected and discussed. In addition, the layout of electric loads are taken into account, and energy consumption of the systems and the influence of their operation on the overall performance of the vehicle discussed.

II. DC-BASED DRIVETRAIN CONVERTERS

Drivetrain converters connect a EVs drive motors to the ESS. These power electronic converters operate continuously and mostly provide power for the high power load. Such converters need to be able to achieve reasonable performance due to required vehicular acceleration.

In contrast to conventional internal combustion powered vehicles, given their EV drivetrain characteristics, gearboxes are not an essential part of the system. High torque at low speed, flexibility in operational speeds, combined with high efficiency are the main advantages of electric motors.

The drivetrain torque and speed change as the load increases during the acceleration period. To obtain loading forces and the required power, (1)-(5) can be used

$$T_m = F_{resistance} * r_{wheels} + I\varepsilon \tag{1}$$

where

$$\varepsilon = \frac{a_{vehicle}}{r_{wheels}} \tag{2}$$

$$Fresistance = Froad + Fair \tag{3}$$

$$Fair = 0.5Cx\rho AV^2 \tag{4}$$

$$Froad = \varphi * mg * (1 + V) \tag{5}$$

and T_m is the required torque of the motor, r_{wheels} the radius of the wheels, I the moment of inertia of the rolling system's wheels, transmission, shaft of the motor, $a_{vehicle}$ the acceleration of the vehicle, C_x the drag resistance coefficient, ρ the air density, A the area of the vehicle in the direction of acceleration, V the velocity, φ the rolling resistance coefficient, m the mass of the vehicle, and g the gravity constant. After considering all variables, the torque required to overcome all resistive forces and to provide acceleration, will require the acceleration to be higher than the resistive line, as seen in Fig. 2. Fig. 2 is based on a model of a medium sized vehicle (1500kg) with C_x=0.28 and 1.5x1.8m.

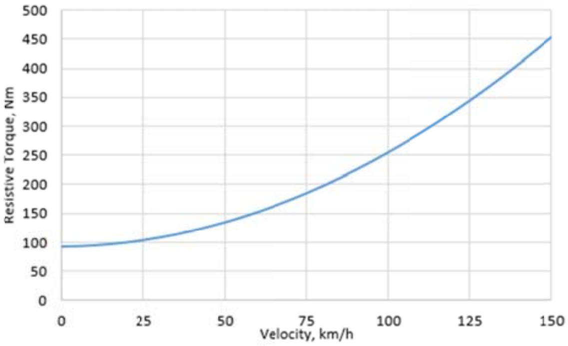

Fig. 2 Resistive Torque Behavior

The powertrain is supposed to provide the possibility to provide the requested performance in terms of variable speed and requested torque. Acceleration, as a main measurement of performance, cannot be constant due to the steadily increasing resistive torque which increases with the speed of the vehicle. Normally the highest acceleration is possible in the low speed region when resistance is low and greater generated torque can be used for acceleration.

Common drivetrains for EVs consist of either Permanent Magnet DC (PMDC) or AC Induction motors. Converters between the motor and battery can be considered as similar to the throttle of an Internal Combustion Engine. The operating point should, if possible provide increasing speed together with increasing motor torque. Increasing torque will provide additional acceleration performance for the vehicle, as all extra torque will transfer into acceleration [9].

During acceleration, the electric drivetrain operates in the first quadrant and electric machine is converting electrical energy from the ESS into mechanical energy moving the vehicle. The main inputs for this mode are the accelerator pedal position, speed of the vehicle, and wheel slip. Acceleration performance is not only limited by the torque provided to the power train, but also by friction of the wheels as all torque of the motor is converted into movement through the connection between wheels and driving surface. The converter between the ESS and DC motor can be based on several devices, such as MOSFETs or IGBTs. Due to advantages in efficiency and cost, IGBT based DC-DC converters are more commonly used for this application [1], [10].

As EV should be able to move forward and backwards, converters should be able to rotate magnetic flux in different directions. For this purpose, a four quadrant IGBT-based converter is better suited than a buck chopper, as a chopper consist of four IGBTs connected in pairs, as shown in Fig. 3.

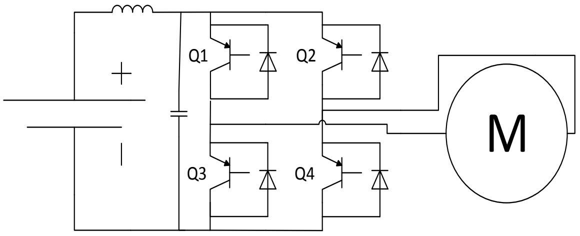

Fig. 3 Four-Quadrant Chopper

The control signal operates with all four IGBTs using a high frequency PWM signal. The frequency is dependent on configuration of the components, such as the required capacitor and inductor which increase efficiency of the circuit and decrease losses. The PWM signal controls the duty cycle of the IGBTs and allows the output voltage to the motor to be controlled. Increasing voltage achieves increasing operational speed of the DC motor (6). Signals to the IGBTs should simultaneously complement each other. For example, for movement forward, Q1 and Q4 should operate with the same duty cycle to prevent faults, where Q3 and Q2 are switched off, as power is not going through them. For reverse operation, it is possible to switch the polarity of the machine, where Q2 and Q3 operate as supplying switches for the machine. Duty cycle duration for acceleration acts similar to the throttle of an Internal Combustion Engine. The longer the duty cycle, the higher level of voltage supplied to the motor and, as a result, the higher the speed of rotation.

$$N = k_n(V_m - R_m I_a)/Ø \tag{6}$$

where n is the motor speed, k_n the speed equation constant, V_m the input DC voltage, R_m the armature resistance, I_a the armature current, and Ø the magnetic flux.

The four IGBT provide changing polarity and, as a result, changing magnetic flux in the windings, generation mode can be performed using this feature of the chopper. In this case, the motor will operate as a generator, as main rotation will be supplied by inertia of the vehicle and generator will apply braking torque, as rotation and magnetic flux will have opposite directions. In terms of switch operation, for forward generation mode, operational switches are Q2 and Q3 and Q1 and Q4 for reverse movements. The output voltage of the converter is represented in Fig. 4. The operation of the converter lies between 0 to 100% of the duty cycle, where 0% is a signal fully closed at Q1 and Q4 where Q2 and Q3 are fully opened. This curve was obtained from the experimental setup within the School of Engineering, Deakin University, comprising a PMDC 0.3kW motor, PWM controlled IGBT four quadrant converter with a switching frequency of 20 kHz based on the characteristics of the smoothing components. Testing speed and loads to dissipate created power were kept at the same level to see pure influence of the controlling signals for the converter. According to the proposed experimental setup, maximum voltages were obtained for the duty cycles of 0 and 100, but with switched polarities, as it was planned in the theoretical discussion.

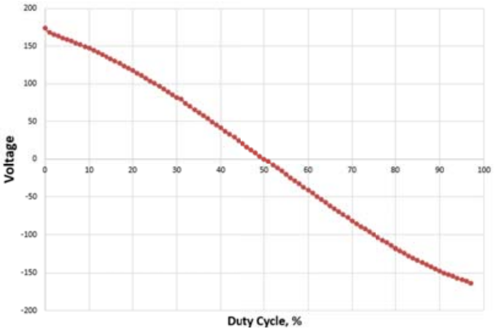

Fig. 4 Converter Output Voltage

During the braking process the most important characteristics is braking torque, as it slows down the vehicle. In addition, all this torque should be able to transfer through the tires and road surface, and therefore should not be greater. At the same time, during braking process, rotational speed is decreasing steadily as wheels are connected with rotor of the motor directly. DC generators have characteristics to decrease generated voltage level with the decreasing rotational speed. In these terms, generated voltage is important as this voltage is supposed to supply generated energy into ESS and their energy should be rated on the higher voltage, than the battery or other component of the ESS according to its characteristics, as shown on Fig. 5, for LI-Ion battery and in Fig. 6, for super capacitor systems. The converter is keeping voltage level on the certain level, where possible. Charging current affects braking torque and this influence should be considered in control signal for a converter.

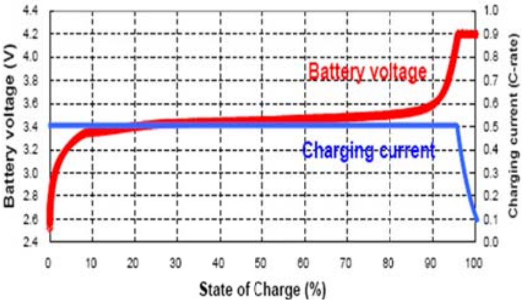

Fig. 5 Charging Characteristics of Li-Ion Battery [11]

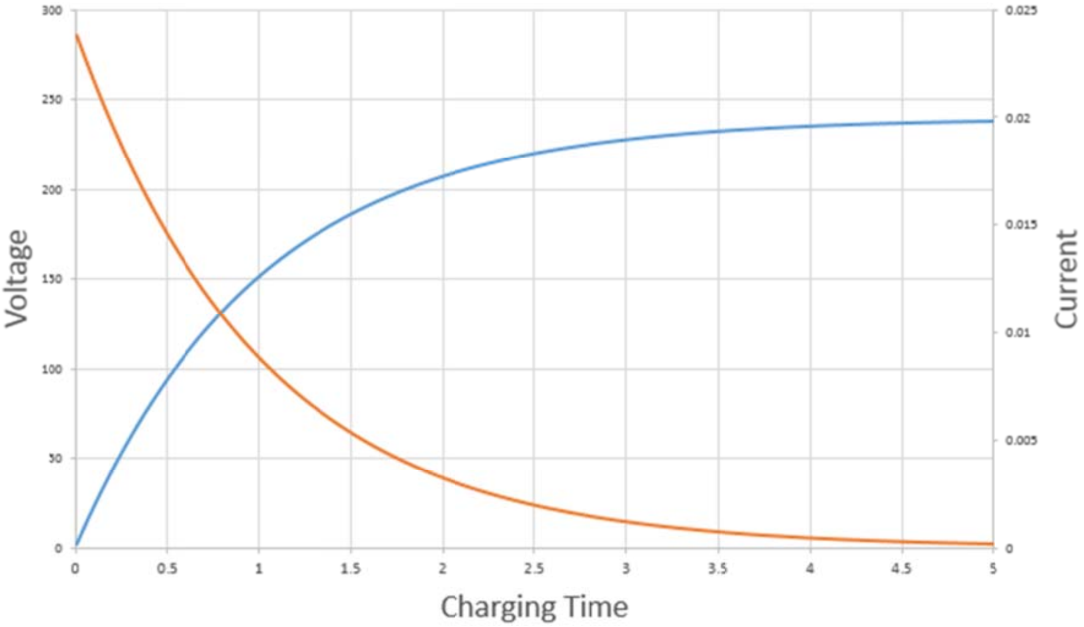

Fig. 6 Charging characteristics of Capacitors

III. AC-BASED DRIVETRAIN CONVERTERS

Induction Squirrel Cage induction motors are the most commonly used drivetrains for electric transport applications due to their low cost and high energy efficiency, in comparison with brushless DC machines. One of the main problems for such systems is the requirement of the continuous supply of the AC power when all ESS systems supply DC current. This applies some limitation on the design of the converter, as for this system converter supposed to supply AC current and it plays a role of inverter. Another requirement is bidirectional operational principal for recuperative braking process.

Operational principals of induction motors and controlling algorithms are different from the DC motor. DC motors response to the voltage changes where induction AC motors are controlled through the AC current frequency regulation. For these working conditions, it is possible to use IGBT based inverters, as it provides different frequency from the single DC bus voltage. Such converter consists of three pairs of IGBTs in parallel with diodes, Fig. 7. Controlling signal consists of complimentary command for each IGBT, as all of them are operating at the same time, in comparison with four quadrant chopper control [12].

To calculate synchronous operational speed of the induction brushless AC motor, (7) can be used

$$n = 120f/p - s \tag{7}$$

where n is the output speed of motor, f the frequency of the supplied AC power, p the number of poles of the motor, s the slip of the motor, which is reducing output speed according to the loaded torque and can't be avoided.

For AC based powertrain, smoothing inductor and powerful capacitor are necessary parts of the inverter construction. The main reason for installing these elements is for smoothing out the fluctuation in DC voltage output, when the motor is operating as a generator and AC power flow is generated by the generator and transferred to the ESS. In addition, due to the frequency fluctuation in the controlling signal, according to the speed and torque requests from the driver, duty cycle, as a main controlling signal for IGBTs, fluctuates during the time to supply required input power.

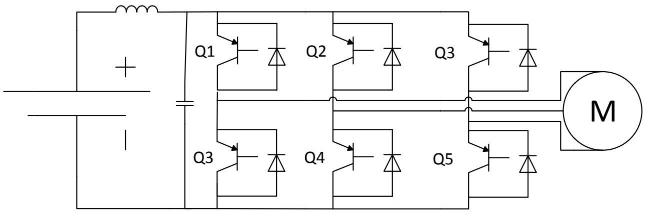

Fig. 7 Inverter Design for AC Induction Motor Operation

In comparison with controlling algorithms for industrial induction motors, the EV application requires different approaches in controlling principals, as most of the industrial induction machines operate with the constant speed and changing torque environment. For EV this option is not ideal as additional transmission system, such as gearbox, is required to control output speed of the motor with such control functions. These mechanical systems increase the cost of the powertrain system and decrease efficiency and increase energy consumption, which leads to the lower distance range on one charge.

Difference between DC and AC operation for drivetrain application in EVs is fundamental. When looking at DC powertrain operations, it is possible to get good output characteristics with supplying constant duty cycles of the several IGBT switches. Whereas For AC control, frequency regulation is required for complimentary six independent IGBTs, through changing duty cycle of switches, it is possible to obtain changes in frequency of the output current and voltage and, as a result, in the rotational speed of the motor.

Generation control of induction motor is also based on the frequency regulation of the AC power on the motor side of the inverter. Induction motor is operating as a generator, when shaft speed is higher than the synchronous speed of the machine, calculated with (7). The higher the difference between the frequencies is, the higher braking torque can be achieved and more energy can be recovered during the process and stored in the ESS.

IV. LOW VOLTAGE BUS SUPPLYING CONVERTERS

In comparison with supplying power to the powertrain, low voltage buses have pure electrical nature of powerflow. The main challenge of this bus is low predictability of the energy usage from the systems, which are operating within this bus, as their usage is dependent on the driver's behavior in terms of using of features and external conditions, such as weather or time of the day [13].

Changing of the energy consumption of this bus have influences on the voltage level similar to the power grid operations. As this bus is operating within certain voltage range, converter should supply exact level of voltage and provide possibility to regulate power flow to compensate voltage drop when voltage of the bus level decreases due to the high energy demand.

In conventional design, converters connecting ESS consisting of low voltage battery, follow the logic of supporting the programmed SoC of the low voltage power source and all features are interacting directly with it. An approach, which is proposed in this article, will allow controlling the power consumption through the voltage monitoring and supplying required amount of energy through converter without charging the additional battery. This approach provides opportunity of the fast response within the required range of the loads and also increases efficiency of the overall systems.

Low voltage battery is required in this construction to add electrical inertia in the system for providing faster response and supplying important safety components, as most of the passive safety components, such as airbags and strain sensors, operate within low voltage to decrease cost of transition from the conventional vehicles. Another additional proposed system is a second converter to supply 12V DC energy. This converter can operate as a single buck converter and supply energy from the motor, when it is operating as a generator for recuperative to the braking process. This converter covers two functions at the same time. First function is to supply energy during the braking process to backup battery, supply load without discharging the battery and increasing the energy outcome from the generator, as not all of the energy generated is able to be stored in the ESS system or dissipate through the power consumed, like in the HVAC system.

The proposed system requires two separate converters with difference logic of control for each of them. The first controller has the same output voltage and is working as a charger for low voltage battery and transferring energy from the main ESS. Construction can be applied as a simple one directional DC buck chopper with relatively low power rating, as shown in Fig. 8. In Fig. 8, the controlling signal is coming from the SoC of the battery and when the signal is dropping below the several preset levels and the main ESS has enough energy, this first converter is pumping energy from the high voltage bus into the battery. Another working mode for this converter is network charging of the EV. During night charging, when energy is stored into the main battery, this converter is supplied with energy from the battery. As a low battery can be discharged through the leakage of the energy into the main high voltage bus, this converter will have single direction of energy flow.

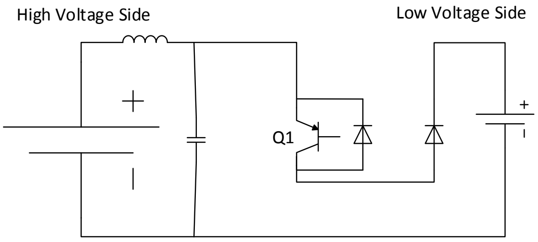

Fig. 8 Low Voltage Battery Charging Converter

Second converter proposed in this design scheme is operating in between drive motor and low voltage appliances, such as lights, safety systems, and media system of the vehicle. In comparison with battery charging buck converter, which is operating based on the SoC of the battery and ESS, this converter has more variables, as it is providing all required power for the appliances and it should react to the changing of the amount of loads it is supplying. In addition, it should react on the SoC of the main ESS and mode of the drivetrain.

In order to increase efficiency of the recuperative braking, the converter acts as a load for the generator and through energy consumption, it has influence on the braking torque. As a result of this influence, this converter should get controlling signal from not only appliances control unit, but also from the ABS control system, as ABS system is operating with the braking torque of the drivetrain.

Power fluctuations are the normal working conditions for this converter. To prevent shocking modes, in the bus line design, this converter is following the bidirectional converter for the drivetrain, as shown in Fig. 9.

As all appliances are working with low voltage DC, an additional converter is supplying DC energy and due to the proposed position of this converter, input voltage is also DC, as it is coming from the high voltage DC bus.

Peak power requirements are not as high, as main bidirectional converter is providing the required power, but this requirement is higher than for the charging buck chopper battery. All appliances in the low voltage bus have total power consumption of approximate 8 kW when all of them are in use. As not all of them are being used continuously, for example seats heaters or windows lifting systems, the converter adjusts output power. Also, some lights are not working during whole time of the operation, for example stop lights are only working during the braking process. To improve the performance of the converter, it is a possibility to unite onboard systems in the single central controlling unit. For effective interactions with drivers, this controlling system can interact as a single board with all controllers and switches on it. Such systems are available for a long time in automotive, but in EV applications such systems will have higher influence on the performance and usability through smart control and power consumption prediction and control.

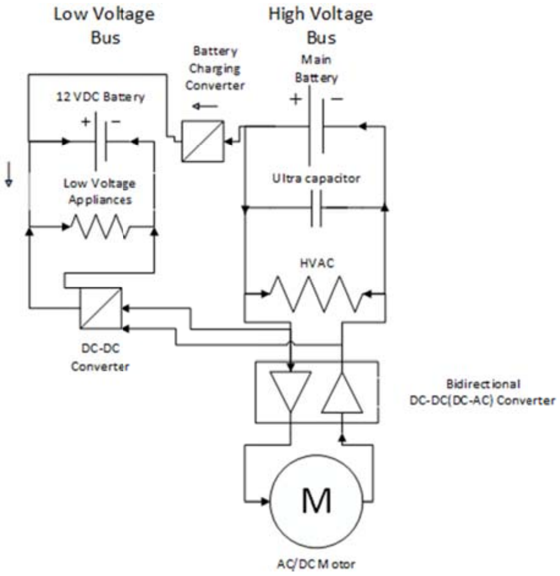

Fig. 9 Proposed Architecture

V. CONCLUSION AND WORK IN PROGRESS

This paper highlighted converters for EV application for different design approaches and drivetrain configurations. Also, different working modes and converters operations were highlighted and the supply required in the operations of the PMDC motors and induction DC drive motors were discussed. The new proposed controlling design is aimed to unite two relatively separate buses in conventional EV architectures- high and low voltage buses with an additional converter. This converter will give allow support not only to low voltage appliances directly from the high voltage side of the electrical architecture but additionally increase efficiency and controllability of the regenerative braking process, as controlling units will have more ways to dissipate generated power, as it can be used for supplying loads in the low voltage bus. Another application of such converters can be smart control of the usage of the power as it can react directly to the request. In the proposed circuit, a low voltage battery is working as an additional unit to increase the inertia of the whole low voltage bus and supply safety systems with reduction in possible faults. Energy efficiency of the proposed system is higher, as an additional converter is not storing energy in the battery, like in the traditional EV architecture. In addition cost efficiency as one of the key elements, as it is not an issue due to the dc-dc single direction nature of additional converters.

Current research activities are focused on developing an efficient logic algorithm for smart energy consumption systems for EV and operational logic for converters as a main parts of the systems. Smart grid and micro grid principals of the energy management are the foundation for the developing the algorithms.

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