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Power Converter Design for Electric Vehicle Applications

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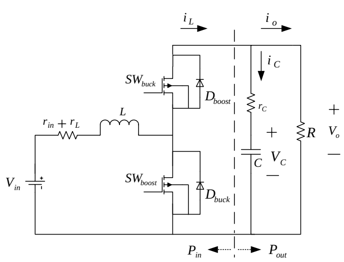
Graphical abstract



Non-isolated bi-directional dc/dc converter

Abstract

This paper presents the design of a power converter for electric vehicle (EV) applications energized by Li-ion battery (LiB) and supercapacitor (SC). The combination of these energy sources is a good solution for better performances of the EV. A single non-isolated bi-directional converter is proposed in order to get the lowest loss, weight and cost of total electric vehicle applications perspective. The battery voltage represents bus voltage of the power supply system connecting to the load. To control the dynamic of converter, state space averaging technique and power equation linearization are employed to get the transfer function for designing the PI controllers. In order to get the fast response of SC power energizing, the cascade controller is implemented to control current and SC voltage. MATLAB simulation is successfully verified the proposed power converter topology, configuration and controller design for EV. The result shows the capability to settling supply a significant amount of power for step load change within few milliseconds. Sudden load power demand can be drawn from SC. This can reduce the stress of battery as in case of the pure battery power supply system.

Keywords: Power converter; control design; bi-directional dc to dc converter; supercapacitor; Lithium-ion battery

Abstrak

Kertas kerja ini membentangkan reka bentuk sebuah penukar bagi aplikasi kenderaan berkuasa elektrik yang dipacu oleh sumber bateri Li-ion dan superkapasitor. Gabungan dua sumber tenaga ini menawarkan solusi yang amat baik bagi meningkatkan prestasi sesebuah kenderaan elektrik. Topologi penukar tak-terasing dwi-arah telah dicadangkan bagi meminimakan kehilangan kuasa, berat serta kos pembinaan. Voltan bateri mewakili voltan bus bekalan kuasa yang bersambung pada beban. Bagi mengawal dinamik litar penukar, teknik pemurataan ruang-keadaan dan penglinearan persamaan kuasa digunakan untuk menghasilkan rangkap pindah bagi tujuan reka bentuk pengawal PI. Bagi mencapai tindak balas pantas superkapasitor semasa pengecasan, pengawal kasakad digunakan untuk mengawal arus dan voltan superkapasitor. Simulasi MATLAB Simulink digunakan dan keputusan yang diperolehi membuktikan keupayaan topologi dan reka bentuk penukar yang dicadangkan. Keputusan yang diperolehi menunjukkan sistem yang direka bentuk ini mampu membekalkan sejumlah kuasa dari superkapasitor semasa berlakunya permintaan mendadak daripada beban. Keputusan ini membuktikan tekanan terhadap bateri dapat dikurangkan sekiranya bekalan bateri tunggal digunakan.

Kata kunci: Penukar kuasa; reka bentuk kawalan; penukar AT-AT dwi-arah; superkapasitor; bateri Lithium-Ion

■1.0 INTRODUCTION

The first electric vehicle (EV) was launched in 1830s and commercially trade in the end of 19th century. However, the success is not last long as the internal combustion engine vehicle (ICEV) came to the market, which provides longer driving range and taking short period of time to refuel. However, ICEV produces a major cause of the environment problems such as air pollution, petroleum resources depletion, global warming and others induced cost. These are serious topics that harm humanity at the present. At the same time, the energy and power capacity of electric sources have been researched and developed intensively to supply enough power and energy density for EV consumption. These turn EV to be a future transportation because of its characteristics; zero emission, high efficiency, quiet, smooth operation and safety. All of these characteristics are the main advantages over ICEV. However, refueling or charging period is a major drawback in EV.

EV is a vehicle powered by an electric power source or storage, driving the traction motor accommodating in a power train system. The ordinary Main Energy Source (MES) of EV today is fuel cell (FC) and battery. Supercapacitor (SC), solar cell, wind power and flywheels can be used as Auxiliary Energy Source (AES) to assist the main energy source to improve vehicle performance. At present, solar cell is not a good solution to be implemented in EV because of its highly cost per kW while producing low power density. In some literatures, solar cells are installed on the roof of vehicle for capturing the sun energy while parking in order to supply the power to grid. The same amount of energy will be charged the vehicle when it needed for future charging. This is not a large percentage implementation of hybrid solar vehicle as regarded reasons. Besides, wind power and flywheels are also debated of their suitability and safety in use. SC does not has any problems as in AES. SC has been directly developed to assist MES for many applications particularly for transportation. It has highly power density and extremely long life cycle.

The combination between two or more electrical energy sources is called hybrid electric vehicle (HEV). In many cases, Fuel cell Hybrid Electric Vehicle (FCHEV) is the vehicle that powered by FC and battery or SC. One of the significant drawbacks of FCHEV is that the FC starvations phenomena that need a carefully design rate of discharge current. Inappropriate design can lead to permanent damage of the highly cost fuel cell. Other type of EV is the battery electric vehicle (BEV) which is the vehicle powered by battery alone. BEV is a simple and efficient vehicle which have been interested and developed by many institutions. Because of the advanced battery technology, fuel tank could now be replaced by new era of Lithium ion battery (LiB) for EV application. The LiB has high energy and power density to supply solely to traction unit. Nonetheless, peak power design is not an appropriate design for BEV power system because of poor load factor design. Moreover, this design criterion may cause the battery supplies highly peak power for acceleration and recapture sharply peak power of regenerative braking. In this condition, high temperature of the battery while charging and discharging high current is the effect contributed by these operations which need to be concerned. In addition, life of the battery will be deteriorated from the peak load governed by the battery alone. To reduce the peak power supplies by the battery, SC could be utilized to supply and recapture the dynamic peak power. With this power sharing technique, base load will be supplied by the battery whereas fluctuating power will be supported by the SC as shown in Figure 1. The outcome of this combination will enhance driving range, acceleration cycle and prolong the battery life.

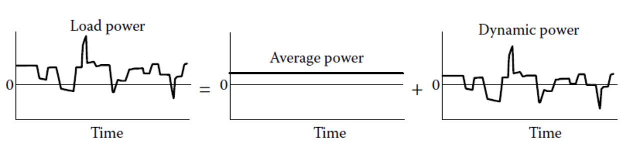


Figure 1 The load power demanded of a drive train

2.0 LITHIUM-ION BATTERY AND SUPERCAPACITOR

Lithium ion Battery (LiB) is a popular battery for many electronic equipment. It is one of the most preferable types of rechargeable battery having high energy density. It has no memory effect, and slow self-discharges. LiB is more expensive than NiCd batteries but having higher energy densities, with smaller size and lighter weight. Operating temperature and charging voltage must be taken care. In a very high temperature over the operating range the cell can lead to explode. On the other hand, when operating lower than 0 degree Celsius, the cell cannot recharge safely. Deep discharge may cause of cell short circuit. Fail-safe circuit must be added to shut down the battery before it operates beyond safety range. Normally, LiB has specific energy density between 110-250 Wh/kg and specific power density around 300 to 1500 W/kg. Life cycle is over 1000 cycles and self-discharging is about 5-10% per month which is lower than NiCd and NiMH. LiB can be considered as the most favorite choice for BEV application in the future. The summarized characteristic has shown in the following table.

Table 1 Battery characteristics

Character of Battery	LiB	NiCd	NiMH	Lead acid
Specific energy density (Wh/kg)	110-250	45-80	60-120	30-50
Specific power density (W/kg)	300-1500	125	200	250
Operating temperature (◦C)	-20 to 60	-40 to 60	-20 to 60	-20 to 60
Life cycle	>1000	~1200	~1000	>800
Recharge time	2-3 hr.	1 hr.	1 hr.	8 hr.
Self-discharging/ month	5-10%	20%	30%	5%

Supercapacitor (SC) is an electrochemical double layer capacitor which has high specific area of activated porous carbon to store huge amount of capacitance. The structure of electrode of supercapacitor is shown in Figure 2.

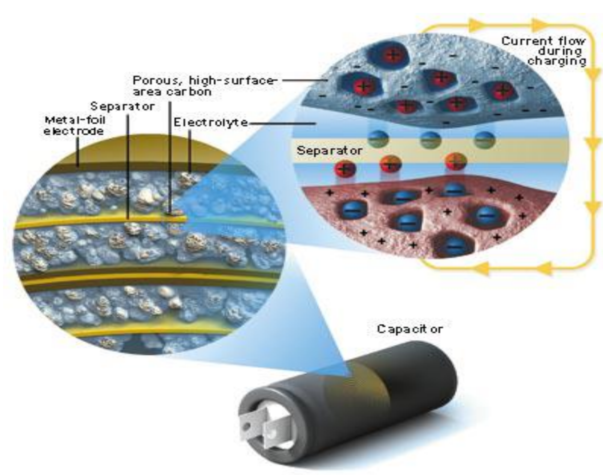


Figure 2 Structure of supercapacitor

The electric charge collection is occurred when the ions flow through the separated paper by connecting to the source. The carbon will transform to the porous material which has a lot of small crannies for keeping charge. The capacity of SC is depend on surface areas and very small distances of charge separated. This mechanism will be reversed when SC supply power to the load.

SC has vast of advantages and suitable to assist battery for supplying peak load demand. It has a decade more specific power density than LiB while lower of specific energy density about one hundredth. However, SC has a very high dynamic power response to the load, in a second unit, whereas the LiB is lower in power response but longer of energy supply period as shown in Figure 3.

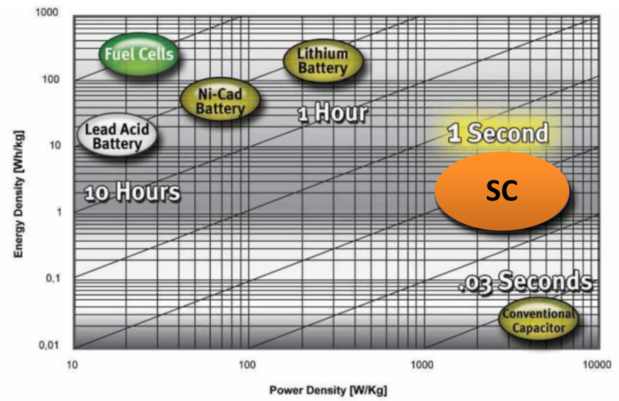


Figure 3 Energy sources performance

3.0 POWER TRAIN CONFIGURATIONS

Power train of a general vehicle is a system, which consists of power plant, clutch or torque converter, gear box, differential gear, drive shaft and drive wheel. In case of BEV, there are six possible configurations as shown in Figure 4.

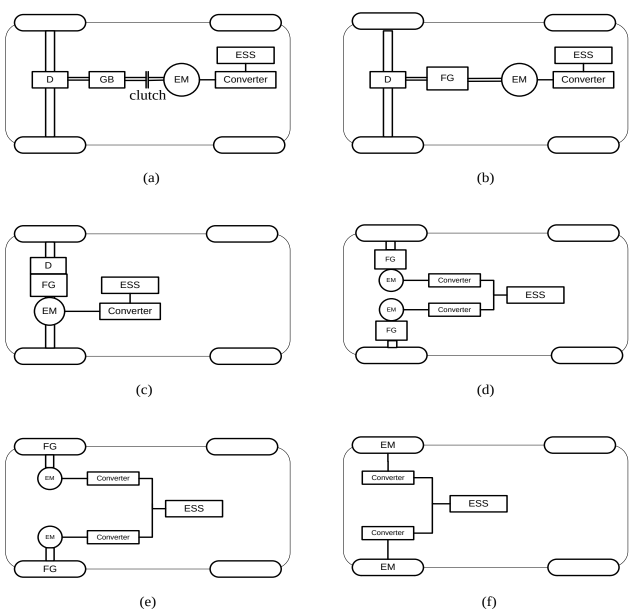


Figure 4 Possible configurations of BEV power train

Whereas: ——— Electrical link ═══ Mechanical link
EM = Electric Motor, ESS = Energy Source and Storage
FG = Fixed Gear

Referring to Figure 4(a), BEV composes of electric source connected to power converter supplying to traction unit. In this system, clutch and gear box is used for manual gearing system to power driven wheels through differential gear and drive shaft. If motor has wide constant power region, Figure 4(b) is generally implemented using fixed gearing instead of clutch and gear box. This reduces size, weight of mechanical components and increases overall vehicle efficiency. Figure 4(c) is the integrated mechanical component of electric motor, fixed gearing and differential which is more compact and simple. The electric motor can be individually powered to each drive wheel as shown in Figure 4(d) in order to separate control, decrease weight and size. In-wheel motor can be considered starting from Figure 4(e). The electric motors are connected to each wheel through a thin planetary gear set for reducing the motor speed. The planetary gear ratio can reduce the speed of motor effectively and allow inline configuration of drive shaft. Figure 4(f) is a fully reduction gearing transmission power system from electric motor to drive wheel. The in-wheel low speed motors are applied to each driven wheel. High starting torque and acceleration can be achieved by usage of the special out-rotor motor characteristic in order to control wide range of speed and torque.

4.0 CONVERTER TOPOLOGY AND CONFIGURATIONS

The converter topology for BEV normally used a non-isolated bi-directional dc to dc converter, as shown in Fig. 5, for control the power flow between energy source and load.

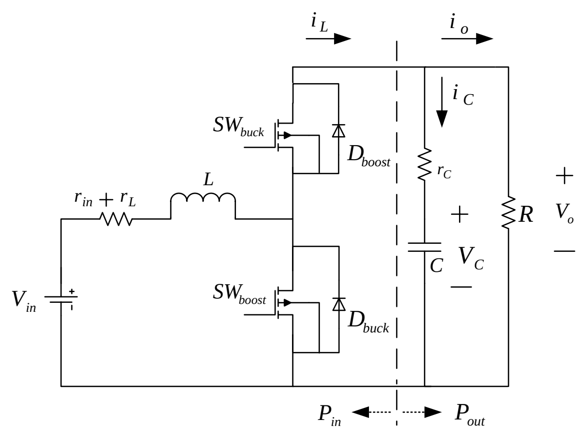


Figure 5 A topology for bi-directional dc to dc converter

Among converter topologies, non-isolated half bridge is the most suitable converter to be implemented in BEV. R. M. Schupbach *et al.* was noticed that half bridge converter has high efficiency, most compact, lowest cost and weight and simple control. These because of the converter need only half components compared to the cascade buck-boost, Cuk and SEPIC/Luo converter. The discontinuous output current is the main disadvantage of the converter. The output capacitor would be bigger than other converters.

To connect the converter to each of BEV energy sources, the effectiveness of the converter would be explained. Pay *et al.* the energy sources configuration, connecting through the converters and directly supply to the load, have been studied. As shown in Figure 6(a), with no implementation of the converter to both energy sources, the terminal voltage of SC will be fluctuated following the battery voltage. By this configuration, the power of SC cannot be controlled and effectively used. The power response is naturally shared according to internal resistance of each source. In Figure 6(b), the converter is connected to SC alone while the battery is floated. The function of the converter and controller are to control the amount and rate of charging and discharging power of SC. On the other hand, the battery is indirectly controlled by means of supplying the left of load demand. In case of connecting battery with a converter as shown in Figure 6(c), the converter size is smaller than previous configuration because it supplying the constant amount of power to the load, but the inverter must be specially designed in order to work with high variation of SC input voltage. This creates high losses and complexity, if compare with the aforesaid. The connection of both energy sources through the individual converter has been proposed by W. Jenn Hwa *et al.* as shown in Figure 6(d). Power demand and its dynamic are absolutely controlled individually but trade off with weight and cost. Moreover, the vehicle performance would be deteriorated.

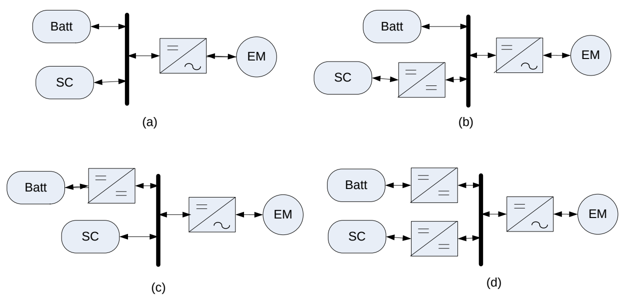


Figure 6 Possible Converter configurations for BEV

In this paper, the converter configuration for EV as in Figure 6(b) is designed and simulated in order to observe the steady state and dynamic behavior. Because of it has the ability to contribute the vehicle performance and cost effectiveness as regarded in many research developing control technique, studying losses model and others perspective.

5.0 DYNAMIC MODEL OF CONVERTER

State space averaging method is a well-known technique for analyzing time-varying nonlinear systems or dynamic model as switch mode power supply. This method has been employed to get the transfer function of the converter in order to design the converter's controllers. The state equations can be achieved by using KVL for on and off state of the boost converter. To achieve CCM of the converter, complementary switching has been conducted to reduce current peak and saved active or passive components from dangerous stress. The converter state equations are shown in equation (1)-(2)

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_C \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\left(r_L + r_{in} + \frac{D'R \cdot r_C}{R+r_C}\right) & -\frac{D'R}{L(R+r_C)} \\ \frac{D'R}{C(R+r_C)} & -\frac{1}{C(R+r_C)} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{1}$$

$$v_o = \begin{bmatrix} \frac{D'R}{R+r_C} & \frac{R}{R+r_C} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{2}$$

Where D' is the off state of the converter's switch and others parameters are the converter's parameters according to Figure 5. Following equation (1)-(2), all of system matrices must be achieved first, then the equation can be arranged as Equation (3) for finding the duty ratio to output transfer function.

$$\frac{Y(s)}{D(s)} = C(sI - A)^{-1}[(A_1 - A_2)X + (B_1 - B_2)\,U] + (C_1 - C_2)X \tag{3}$$

Then Equation (3) can be transformed to Equation (4) as standardized by MATLAB transient response analysis.

$$\frac{Y(s)}{D(s)} = C_s \cdot (s \cdot I - A_s)^{-1} \cdot B_s + E_s \tag{4}$$

Where As, Bs, Cs and Es are the combinations of matrices or single matrix as shown in Equation (5).

$$\begin{cases} A_s = A \\ B_s = (A_1 - A_2)X + (B_1 - B_2)U \\ C_s = C \\ E_s = (C_1 - C_2)X \end{cases} \tag{5}$$

By doing so, duty ratio to output voltage and inductor current can be obtained. The duty ratio to inductor current transfer function can be achieved by changing Cs matrix to be [1 0].

Moreover, to find the inductor current to output voltage transfer function, the linearization of power equation between input power and output power of the converter as shown in Figure 5 has been introduced. This technique is used for finding the outer loop controller design of cascade control, while the inner loop transfer function, the duty ration to inductor current, is derived by the former method. The linearized power equation which ignoring any losses in the switch and diode has been declared as in equation (6).

$$P_{in} = P_{out}$$
$$V_{in} i_L - (r_{in} - r_L) i_L^2 - \frac{L}{2} \cdot \frac{di_L^2}{dt} = \frac{C}{2} \cdot \frac{dv_C^2}{dt} + r_C (i_L - i_o)^2 + R i_o^2 \tag{6}$$

After introducing the perturbations into any ac components, we will receive the inductor current to output voltage transfer function as in equation (7).

$$\frac{V_o(s)}{I_L(s)} = \frac{(CV_C r_C - LI_L)s + (V_{in} - 2r_{in}I_L - 2r_L - 2r_L I_L - 2I_L r_C + 2I_o r_C)}{CV_C\left(1 + \frac{r_C}{R}\right)s - \left(\frac{2r_C I_L}{R} - 2I_o - \frac{2r_C I_o}{R}\right)} \tag{7}$$

6.0 EXPERIMENTAL DESIGN OF CONVERTER AND CONTROLLER

The converter has been designed and simulated for 3 phase induction motor in traction unit rated 47 kW peak. Boost operation is used when supplying power to the traction system while buck operation will be availed when recapturing regenerative braking energy. As control of dynamic behavior of boost is more difficult to design than buck, the controller of boost will be analyzed first then buck is done afterward. The parameters for converter design for connection to the SC and also battery parameters, the dc bus voltage, have been shown in following table.

Table 2 Characteristics of each source

Characteristics	LiB	SC
Rated voltage (V)	300	200
1 C Capacity (Ah)	48	-
Energy density (Wh/kg)	170	6.0
Power density (W/kg)	870	12,000
ESR (mΩ)	300	0.29

- SCs initial voltage is 200 V, by 74 series connection of 3000 F, 2.7 V, 210 A. The SCs have capacity 41 F and ESR 21.4 mΩ in total.

- Battery output power has output voltage 300 V, equivalent series resistance (ESR) 300 mΩ and standard charging current is 48 A.
- The output voltage of the converter is 300 V supplying 152 A of peak load. This can be considered as load output of 2.96 Ω
- Inductance of the converter has been calculated and appropriate adjust to be 150 µH with ESR 10 mΩ.
- Output capacitor for lower 1% ripple voltage is calculated and selected as 4.7 mF with ESR 3.3 mΩ.

Bode plot of duty ratio to inductor current shows in Figure 7 that the bandwidth is too high and need a controller to regulate the cutoff frequency following the system requirement. In Figure 8, inductor current to output voltage transfer function has been declared and found the gain margin is too low, also a controller is needed to improve per design purpose.

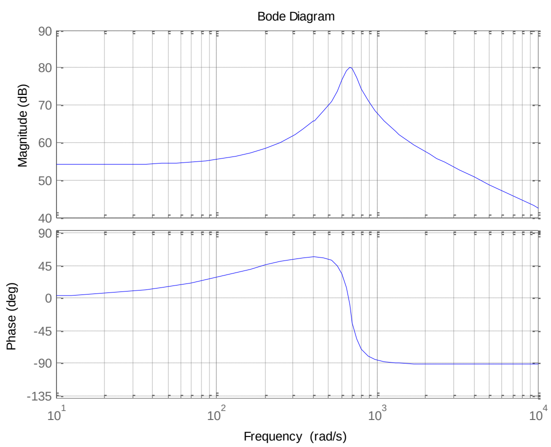


Figure 7 Duty cycle to inductor current transfer function

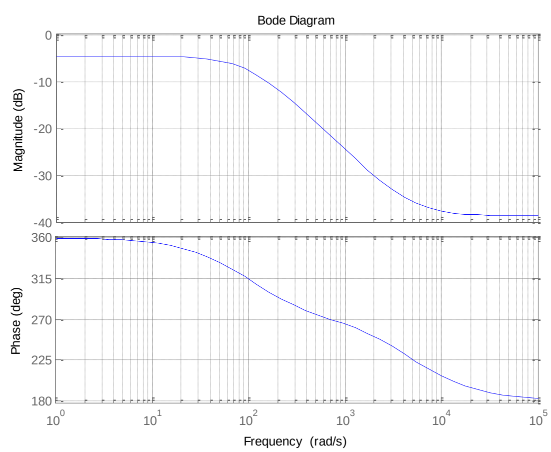


Figure 8 Inductor current to output voltage transfer function

The controller design based on the cascade control has been proposed to improve its performance, stability, and reject disturbances. The inner inductor current loop controller and the output voltage loop controller result the better performance comparison with single loop control because of the inner current loop control is an inherent feed forward of the outer voltage loop control for regulating output voltage following reference voltage. The compensator or error amplifier parameters of each control loop have been simplifying designed by MATLAB/SISO toolbox.

The switching frequency selection is 20 kHz to suppress the audible noise and suitable for equipment frequency range. Cutoff frequency of inner loop control is selected at 1 kHz which is one tenth of sampling frequency, 10 kHz, of dSPACE controller board. PWM comparator gain depending on peak-to-peak voltage of saw-tooth waveform is simplifying designed to be 1. Simulink blocks of cascade PI control loops are shown in Figure 9. By using PID tuning tool of MATLAB, P and I value can be received. In Figure 10 shows bandwidth of tuned response of duty cycle to inductor current which adjusted the bandwidth to 6.28 krad/s. A stability and high DC gain for cancelling the noise can be achieved. The outer control loop has been tuned to one tenth of the inner loop that the cutoff frequency is 628 rad/s with a stability and high gain also. Bode plot of the outer loop tuned response shows in Figure 11.

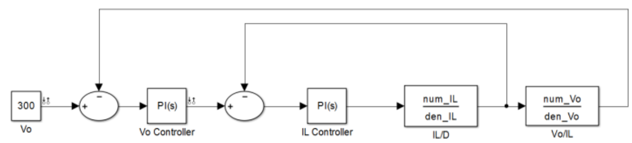


Figure 9 Cascade control for the power converter

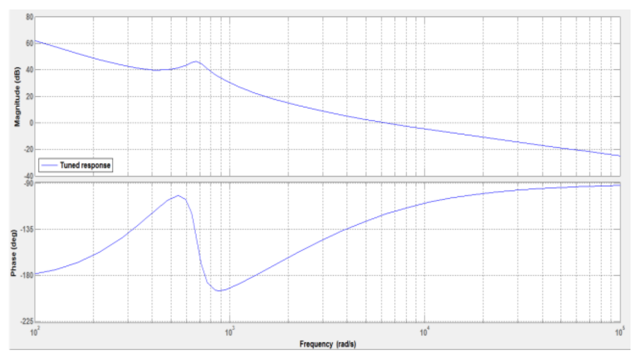


Figure 10 Bode plot of tuned I_L/D close loop transfer function

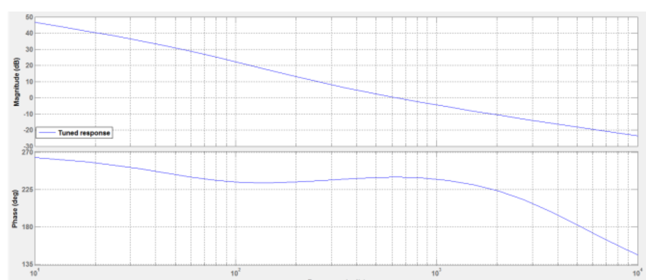


Figure 11 Bode plot of tuned V_o/I_L close loop transfer function

7.0 SIMULATION RESULTS AND DISCUSSION

Large signal simulation has been conducted to verify the controllers' performance. Step load change has been implemented to observe the dynamic response of the converter sharing load power from the battery. Two resistors, 4 Ω each, have been used for the simulation by stepping the second resistor at t = 0.2 s as shown in Figure 12. The results show in Figure 13 which described as following;

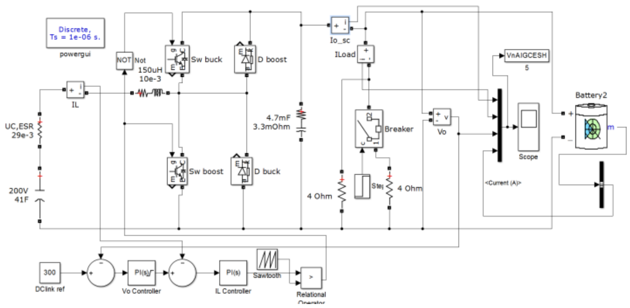


Figure 12 Simulink blocks of large signal simulation

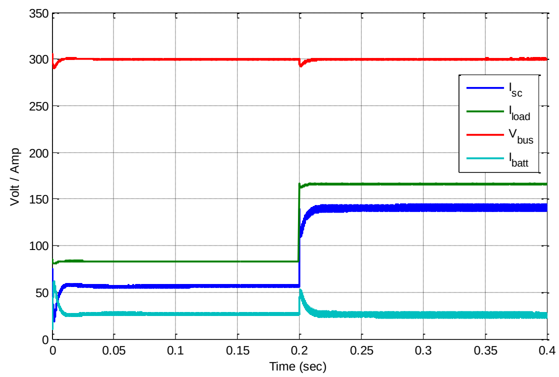


Figure 13 Simulation result of output voltage and current

- Load current is supplied by SC and battery current in which SC supplied higher as designed.
- At t = 0.2 s, load was step from 4 to 2 Ω and SC current was suddenly injected into the power system that cause of stabilizing voltage bus at 300 V, the reference voltage.
- The step load current, 166 A, was shared by battery current and SC current per designed.

This is clearly declared that the controllers have capability to maintain output voltage and power requesting by the load. The battery current supplies the rest amount of current and can maintain its terminal voltage, the bus voltage, even in high pulse power requiring. Battery life can be prolonged and temperature can be reduced which make easier for designing the cooling system.

■8.0 CONCLUSION

This paper presents a design of 47 kW power converter for electric vehicle applications. The energy source is a combination of Lithium battery (LiB) and Super capacitor (SC). These sources have been reviewed in detail. Bi-directional dc to dc converter is utilized for managing the power flow in both directions for each source for energizing EVs. The dynamic behavior of the boost converter has been analyzed by state space averaging method. Cascade PI controllers have been designed for regulating output voltage according to the reference voltage. The power converter output voltage and inductor current have been simulated by using MATLAB/Simulink software. The simulation result declared the controller performance; regulation the output voltage in few milliseconds after load disturbance and supplied correctly the amount of current according to the design. Moreover, the battery supplied a small amount of power if compared with the battery alone system that has to be supplied the whole power demanded.

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