DESIGN CONSIDERATIONS FOR ELECTRIC VEHICLE POWER CONVERSION SYSTEMS

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Abstract
One of today's key challenge is reducing the emissions and improving the fuel economy of vehicles. To meet this goal the automotive industry is developing electric vehicles based on different technologies including batteries or on-board power generation in case of fuel cells. Power electronics is an enabling technology for the realization of environmental friendly vehicles. It allows to implement various electrical architectures to achieve the best performance. In this paper aspects of the design of electric vehicle power conversion systems regarding the current ripple distribution are discussed.

Keywords: electric vehicles, fuel cell, power conversion, multiple drive system.

INTRODUCTION

Electric vehicles (EVs) promise improved fuel economy and reduced emissions compared to conventional internal combustion engine [1]. Still there are some key challenges to overcome. First reduced emission can only be achieved if the electric energy is generated by alternative energy sources. Second the effective range of EVs is still low due to the limited storage capacity of traction batteries. Third prices for EVs are still to high. Therefore the vehicle technology success relies on customer acceptance both from a performance and economic standpoint [2]. In general EVs can be classified into different groups [3], [4]. Pure electric vehicles with one traction battery. Hybrid vehicles realized either as parallel hybrids which have been introduced already into the market or serial hybrids recently announced as extended range electric vehicle. Fuel cell vehicles powered by hydrogen are proved to offer the greatest potential as an alternative to today's ICE [5]. Common to these technologies is that several electric consumers, the traction drive as well as ancillaries like fans, pumps or the A/C compressor, are supplied by one DC energy source, the battery or the fuel cell. The aim of this paper is to discuss some design considerations of the electric power conversion system of EVs in particular the interaction of multiple drives operating on one DC bus.

SYSTEM DESIGN

According to the system engineering approach the development of an vehicle is established by an top down design starting with the vehicle technical specification (VTS).

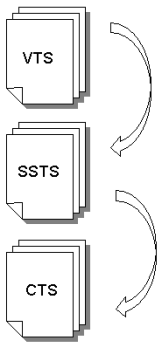


Fig. 1. *Design flow*

In the VTS all basic vehicle requirements like top speed, acceleration, mass and range are defined. In a next step in the subsystem technical specification (SSTS) all requirements of the mechanical, electrical, electro-chemical and control subsystems are defined, e.g. battery cell number, DC bus voltage, power

consumption of the traction drive and the ancillaries. Finally in the component technical specification (CTS) the hardware and software of the components itself is defined. Fig. 1 shows the simplified design flow. This requirement management is essential for the functionality of the entire vehicle.

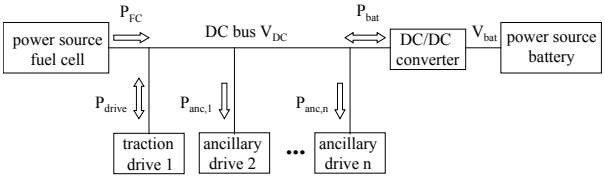


Fig. 2. *Electrical architecture*

Fig. 2 shows the general block diagram of the electrical architecture of an electric vehicle including a fuel cell as a primary power source. If required the system can include a secondary battery which is connected to the DC bus via a bi-directional DC/DC converter [6]. In case of a pure electric vehicle or a hybrid vehicle the system will include only one traction battery as the primary power source.

According to the described design the requirement management will define the voltage range of the DC bus V_{DC} and the battery V_{bat} as well as the power flow of the power conversion system for any arbitrary operating condition of the vehicle, e.g. acceleration, top speed etc. . The traction drive as the major power consumer indicated by drive 1 will provide a bi-directional power flow due to regenerative braking, P_{drive} [7]. The ancillary drives (pumps, fans) indicated by drive 2 … n are characterized by an uni-directional power demand, $P_{anc,1}$ $P_{anc,n}$. The DC/DC converter which consists of an cascaded buck-bust unit will also provide a bi-directional power flow P_{bat} to enable charge and discharge of the battery [8], [9]. In this way the design ensures that each component will operate correctly and the vehicle performance can meet the requirements defined in the VTS.

However this design only covers the DC current flow through the power conversion system. According to the power request under steady state conditions average current values are defined, for transients e.g. acceleration current ramps are defined. In addition to DC currents AC currents generated by the switching behavior of inverters will flow through the DC bus. The situation can be analyzed by taking a look at the schematic of a voltage source inverter, Fig. 3, and the corresponding current waveforms of a PWM controlled inverter, Fig. 4. The DC link current $I_{DC,link}$ is impressed by the PWM control, the content of the AC current flowing through the DC link capacitor C depends on the input current I_{DC} and the DC link current $I_{DC,link}$ itself.

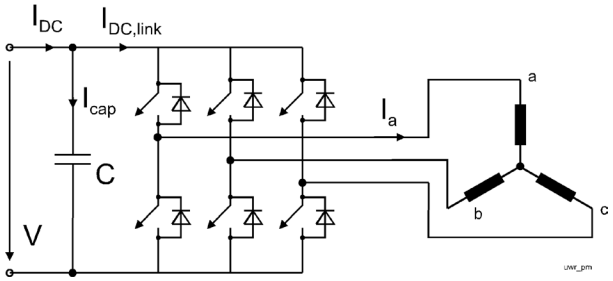


Fig.3. *Voltage source inverter*

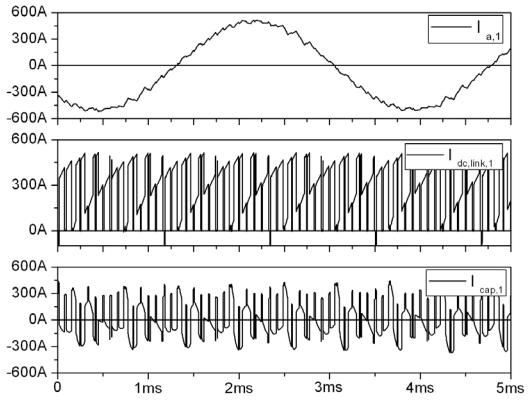


Fig. 4. *Current waveforms*

In dependence on the impedances of the DC bus a more or less portion of an AC current produced by one inverter can flow unintended through the DC bus into other inverters. The problem can be explained by taking a closer look to the power conversion system in Fig. 5. Each drive inverter (1 … n) is connected to the DC source by interconnecting cables (line 1 … n). The DC voltage source could be either a fuel cell or a battery connected via a DC/DC converter to the bus. Power is supplied from the voltage source through the bus to each drive, according to the power demands DC currents $I_{DC,1}$ … $I_{DC,n}$ will flow. Due to the

mode of operation in each inverter a DC link current will flow. For example we look at $I_{DC,link,1}$. One part of this current flows through the DC link capacitor C_1 , $I_{cap,1}$, the other part flows into the power supply line, $I_{AC,1}$.

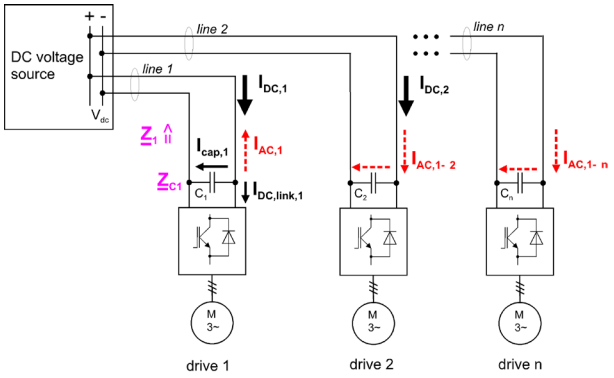


Fig. 5. *Current ripple distribution*

At the nodes in the power distribution this current is divided into the portions $I_{AC,1\text{-}2}$ … $I_{AC,1\text{-}n}$. The problem now is that a capacitor C_n of any other drive n consumes a higher current ripple than it has been originally designed for. The additional current is indicated by dashed arrows. As a consequence this additional ripple leads to an increased self heating of the capacitor [10]. Depending on the ambient temperature this self heating can damage the capacitor and reduce the lifetime of the drive [11]. Fig. 6 shows the situation for drive 1 and 2 [12]. At the beginning only drive 1 is in operation, the input current $I_{DC,2}$ is about 50A. The DC bus voltage is about 330V, the ripple content on both inputs, V_1 and V_2, is the nearly the same. At t = 0.25s drive one starts operation, the input current $I_{DC,1}$ ramps up from 0 to 200A.

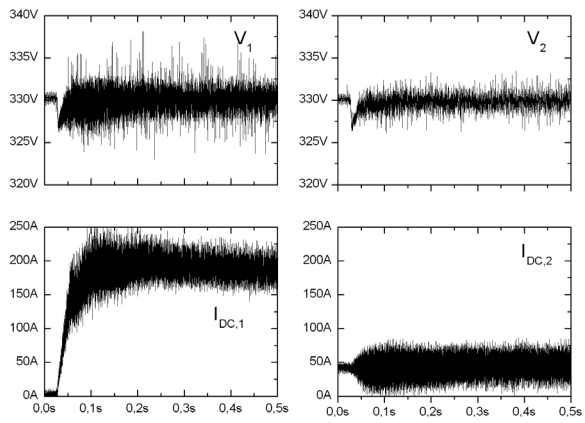


Fig. 6. *Two drives in operation*

As a results the voltage ripple on the DC bus increases, due to the voltage drop of the line impedances the ripple content of the input voltages V_1 and V_2 is different. The current ripple of $I_{DC,2}$ increases although the operation of drive 2 stays unchanged. This indicates that the DC link capacitor C_2 must withstand a certain current ripple caused by the drive inverter 1. The observed effect underlines the significance to understand the current ripple distribution. During the design phase the stress of the DC link capacitors C_i in the power conversion system needs to be evaluated.

Under perfect conditions the current ripple produced by drive 1 should completely flow through the capacitor C_1, the ripple current into the supply line is zero. In this ideal case no other drive would be stressed by the ripple current of drive 1. Under real conditions this assumption is not given. The actual current distribution depends on the relationship of the capacitor impedance $\underline{Z}_{C1}$ and the impedance $\underline{Z}_1$ at the connecting point of drive 1 described by the current divider law:

$$I_{AC,1} = I_{DC,link,1} \cdot \frac{\underline{Z}_{C1}(j\omega)}{\underline{Z}_{C1}(j\omega) + \underline{Z}_1(j\omega)} \qquad 1$$

The above equation shows that for a good design $\underline{Z}_{C1}(j\omega)$ needs to be less than $\underline{Z}_1(j\omega)$ at the switching frequency. The value of $\underline{Z}_{C1}(j\omega)$ depends on the type of the capacitor (capacitance, equivalent series inductance ESL, equivalent series resistance ESR), the value of $\underline{Z}_1(j\omega)$ depends on the line inductance of the connecting cable between the power distribution and drive 1 as well as on the impedances of the other inverters in the system. Another essential aspect is the harmonic content of the DC link current. Drive inverters are typically controlled by a PWM (pulse width modulation) switching pattern [13]. A characteristic of the PWM control is that the major harmonic of the DC link current occurs at a frequency which is twice the switching frequency f_S [14]. Fig. 7 illustrates the results of a harmonic analysis of the DC link current of an inverter operating at a switching frequency f_S = 10kHz. The major harmonic occurs at f = $2f_S$ = 20kHz. For this reason Equation 1 should be fulfilled at $\omega=2\pi\cdot(2\cdot f_S)$. The design of the electrical system shall follow

the simple design guideline of Equation 1 for each component of the multi-inverter system.

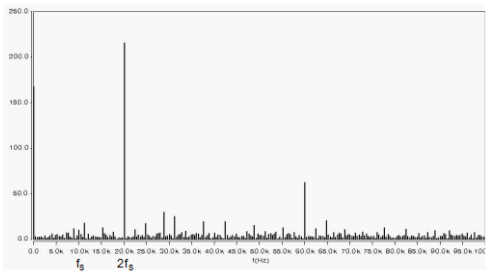


Fig. 7. *Harmonic content DC link current*

SMALL SIGNAL MODEL

Due to the complexity of the described system and the high number of design parameters which can be varied (line inductance, capacitor type, capacitance, filter inductor, switching frequency) the analysis can be supported by a simulation model. A small signal analysis of the simplified circuit diagram depicted in Fig. 8 has to be performed.

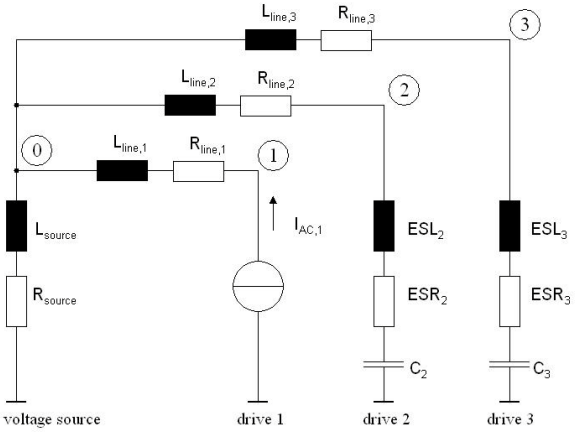


Fig. 8. *Small Signal model, drive 1*

For this example a system with three drives operating on the DC bus will be explained. The voltage source could be either a battery or a fuel cell represented by the internal resistance R_{source} and the inductance L_{source}. In this small signal model each DC link capacitor is represented by the capacitance C_i, the equivalent series resistance and inductance, ESR_i and ESL_i respectively. The interconnecting cables are described by the line inductances $L_{line,i}$ and the line resistances $R_{line,i}$. The amplitude response of the impedance at the connecting point of a drive is generated by replacing the inverter by a current source.

How the model can be used to support the design with respect to the power conversion system behavior is demonstrated first for the traction drive, in this example drive 1 operating at a switching frequency of f_S = 10kHz. In the model at connecting point 1 the capacitor is replaced by a current source. An AC analysis is performed by setting the AC amplitude to 1A. In this way the amplitude response of the impedance can be easily established for a defined frequency range. In the performed example for the lines the inductance values $L_{line,1}$ = 0 nH, $L_{line,2}$ = 500 nH, and $L_{line,3}$ = 1000 nH have been used. Further more it is assumed that drives 2 and 3 are ancillaries with aluminum electrolytic capacitors C_2 = 560µF (ESR_2 = 45 mΩ, ESL_2 = 14nH) and C_3 = 330µF (ESR_3 = 240 mΩ, ESL_3 = 20nH).

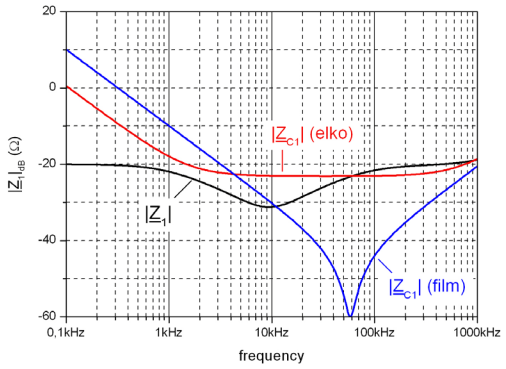


Fig. 9. *Results small signal analysis, drive 1*

With this assumptions the amplitude response of the line impedance $|\underline{Z}_1|$ at the connection point of drive 1 can be analyzed, Fig. 9. One important design aspect is the choice of the DC link capacitor of the traction drive. If for example an aluminum electrolytic capacitor C_1 = 1500µF (ESR_1 = 70mΩ, ESL_1 = 15nH), V_R = 450V [15], suitable for traction application is selected, the small signal analysis shows that the impedance $|Z_{C1}|$ (elko) at f = $2f_S$ =20kHz is much higher than $|Z_1|$. As a result the major content of the AC current produced by drive 1 will flow into the power supply line and stresses other components. This will be a poor design. If a film capacitor C_1 = 500µF (ESR_1 = 1mΩ, ESL_1 = 15nH), V_R = 450V

[16], is used instead, the analysis shows that at twice the switching frequency $|Z_{C1}|$ (film) is about 20dB lower than $|Z_1|$, thus the major content of the AC current will flow through this DC link capacitor as desired.

In the next step the amplitude response of the line impedance $|\underline{Z}_2|$ at the connection point of drive 2 can be analyzed by replacing the capacitor with a current source, Fig. 10.

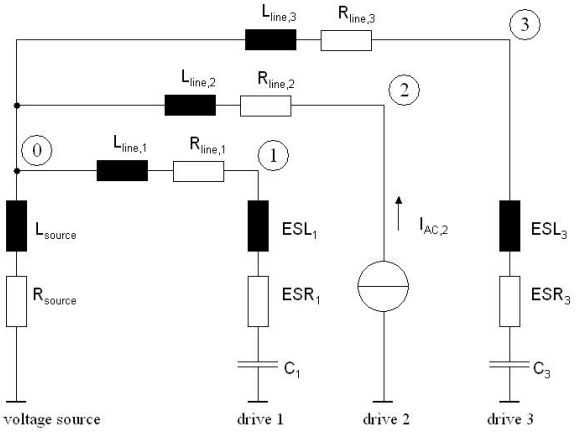


Fig. 10. *Small signal model, drive 2*

Fig. 11 shows the results of the small signal analysis. In this example for drive 1 the 500µF film capacitor as described above has been used.

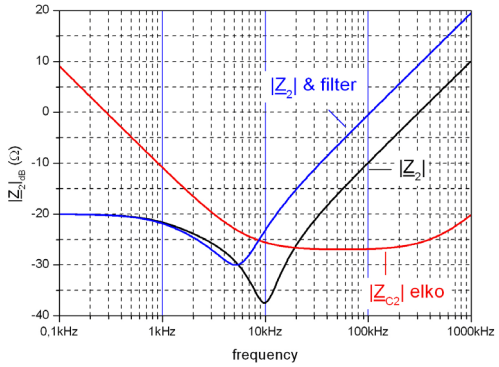


Fig. 11. *Results small signal analysis, drive 2*

Assuming that drive 2 will operate at a switching frequency of f_S = 10kHz the use of the aluminum electrolytic capacitor C_2 = 560µF will result in a poor design. At the frequency $2f_S$ = 20kHz the impedances $|Z_2|$ and $|Z_{C2}|$ (elko) are nearly the same, as a consequence only one half of the major harmonic content will flow through the DC link capacitor C_2, the other half will flow into the power supply line. The design can be improved by the use of another capacitor type or by the use of a small filter inductor in the power supply line 2. Fig 11. shows the amplitude response of the line impedance $|\underline{Z}_2|$ with an additional filter inductor of L_{filter} = 1µH. With this simple measure an increase of $|\underline{Z}_2|$ of more than 20dB at $2f_S$ = 20kHz can be achieved. Thus drive 2 will inject no noticeable AC current in the system.

It is obviously that the design for the third drive can be analyzed in a similar way. It is also possible to add a DC/DC converter in the model, the procedure remains the same. However it is an iterative process if parameters (capacitor type or filter elements) of any other drive or converter needs to be changed as a result of the optimization. Still it is an easy to handle guideline, all required parameters can be derived from data sheets. In this way the small signal analysis of the entire power conversion system allows an accurate prediction of the AC current distribution and ensures a proper component and system design.

CONCLUSION

In this paper the power conversion system of electric vehicles has been discussed. The typical design process of an vehicle according to the system engineering has been summarized. It was shown that the conventional requirement management does not cover the interaction of components operating on one DC voltage bus as it occurs in all electric architectures of EVs. It was demonstrated how the system perturbbation caused by an unintended AC current flow through the system can stress capacitors. To overcome this problem a small signal model has been introduced capable to predict the AC current distribution of a multi drive system. The explained method can be used for any kind of electric vehicle, hybrid or fuel cell vehicle with a multi inverter / converter architecture. The method provide simple guidelines which can be easily added to the conventional design.

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