Switch Function Modelling of Bidirectional DC-DC Converter

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Abstract – **This paper proposes a generalized switched function model for a bidirectional DC-DC converters. Typical application for such converters is as a part of an electric vehicle power topology, where different architectures are available when more than one energy source is available. For this reason the model is general enough to incorporate a cascade or a parallel power architecture. The model includes switching and conduction losses of the semiconductor devices and ESR loss of the power inductor. The load of the model is based on the load requirements for a vehicle driving a standard Cycle WLTC.**

Keywords – **Power converters, modelling, switching function, bidirectional dc/dc converters.**

I. Introduction

The simulation of bidirectional converters for electric vehicles is a daunting task as it must include a model of the converter, the energy sources and the control system. In order to simulate the system the model must make a compromise between accuracy and speed. Usually the switching dynamics of the power converter are the ones with the fastest time constant and there is where the compromise must be made. Either behavioral or detailed mode simulation models are available [1]. If behavioral type model is chosen there are three available sub categories – full model of the switches, using a switching function and the average model [1]. The average model does not allow for accurate representation as it neglects high frequency components of the switching signal. It gives a good approximation if the state variables does not have large ripple. This is not necessarily the case for bidirectional converters, where large derivatives of the load can be observed.

For this reason this paper simulates a bidirectional converter using the switching function approach. It takes the converter equations and transforms them into a switching model. Typical applications of this types of converters are in electrical drivetrains. When used as part of such a topology this converter is connected to a supercapacitor or a battery and the motor. When a second energy source is available, there are two standard ways to connect this converter to the dc bus powering the electric motor. These are the cascode and parallel topology [2]. As a general switched function model that can accommodate the two is easily made, the paper then uses this to investigate some questions: How does the converter losses of the converter change with different supercapacitor size? What is the influence of the additional energy source?

The paper is structured as follows: In the next section the model used for simulation a bidirectional energy transfer system is presented – the converter, its control system and the loss model. Then in Section III some simulation results are given that can be used to optimize such a system for capacitor size taking into consideration the maximum current stress and switching losses in the power converter. In section IV a discussion of the obtained results is made and finally the paper concludes with Section V.

II. Converter Model

The model of the developed converter is shown in figure 1. The Bidirectional converter is shown in figure 2. It is connected between the supercapacitor and the motor voltage. As such a system includes a main energy source (a battery or a fuel cell) their influence is included in the model by adding a constant current source. For a more general representation this source can be added to charge the supercapacitor(SC) – cascade topology or directly to influence the dc bus on the motor- parallel topology. Both topologies can be modeled by setting one of the sources in the model to zero.

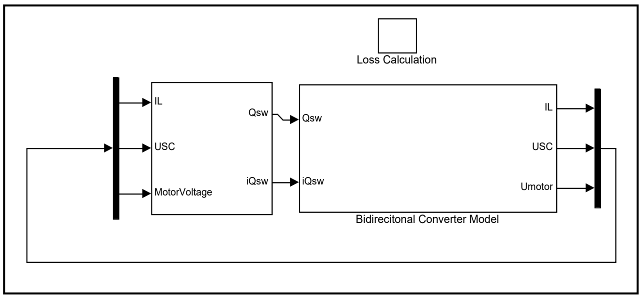

Fig. 1. Converter Model

The model of the bidirectional converter that is connected between a supercapacitor and the motor is based on equations (1) – (3).

$$\frac{du_{SC}}{dt} = \frac{1}{C_{sc}} \int \left(I_{ChgC} - I_{L_1} \right) dt + V_{scI} \quad (1)$$

$$\frac{dI_{L_1}}{dt} = \frac{1}{L_1} \int \left(U_{SC} - I_{L_1} R_{L1} - U_L \overline{Q_{sw}} \right) dt + I_{L0} \quad (2)$$

$$\frac{du_o}{dt} = \frac{1}{C_o} \int \left(I_{L1} \overline{Q_{sw}} + I_{ch} - \frac{U_L}{R_L} - I_{Load} \right) dt + V_{oI} \quad (3)$$

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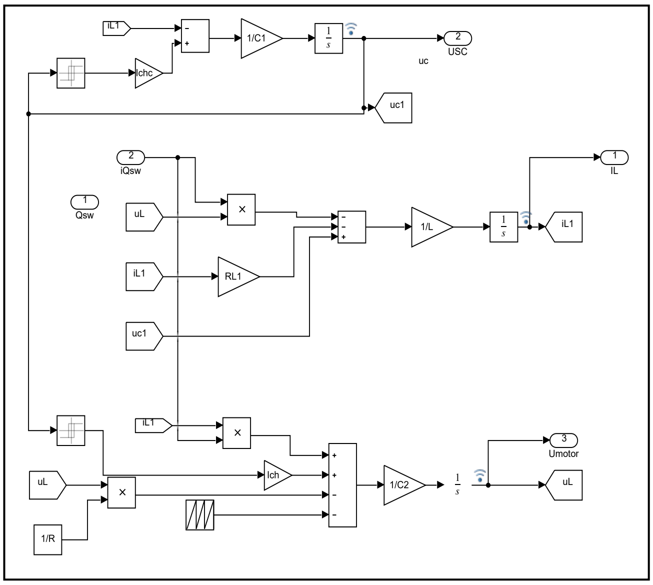

Fig. 2. Bidirectional Converter Model

The various used subscripts and their values are given in table 1

TABLE 1. PARAMETERS USED

Parameter	Symbol
Initial SC voltage	V_{scI}
Charge current for cascode configuration	I_{ChgC}
Switching function inverse	$\overline{Q_{sw}}$
ESR of the power inductor	R_{L1}
Charge current for parallel configuration	I_{ch}
Load current profile	I_{Load}
Initial output voltage	V_{oI}
Load resistive component	R_L

The load of the converter is a combination of a fixed resistive component to take into account the static consumption of the motor control driver and a constant current source, which models the power needed by (or supplied by) the motor if used in an electric vehicle driven according to a standard cycle. A waveform of the current required from such a vehicle are shown in figure 3. The model of the vehicle was presented in [2], and the data shown here are scaled in time (1:100) in order to obtain reasonable simulation times.

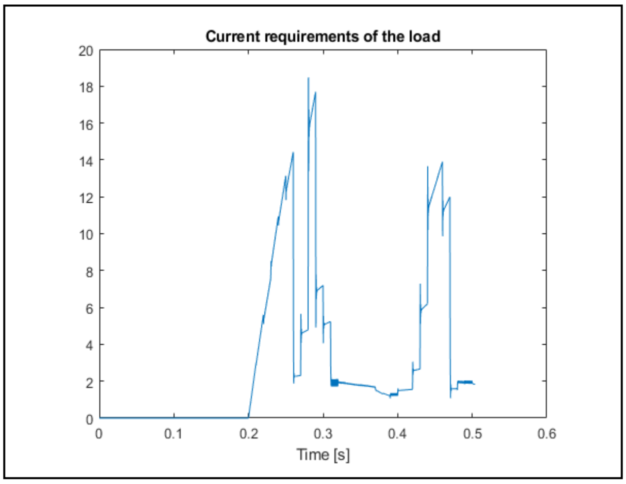

Fig. 3. Scaled Current Requirements of the load

When the supercapacitor voltage goes above its maximum value the Ichg (for cascade) or Ich (for parallel topology) source is turned off. This is true until the supercapacitor discharges to a certain voltage.

The control system for the bidirectional converter is shown in figure 4. It consists of a main voltage regulator that sets the voltage on the motor bus constant. An internal hysteresis current regulator is added to obtain better dynamics. A logic is implemented that enables the output of the hysteresis controller to generate the switching function only if the supercapacitor voltage is above a certain value. This is necessary as the peak transistor current stress can be very high in order to achieve very high boosting of the supercapacitor voltage.

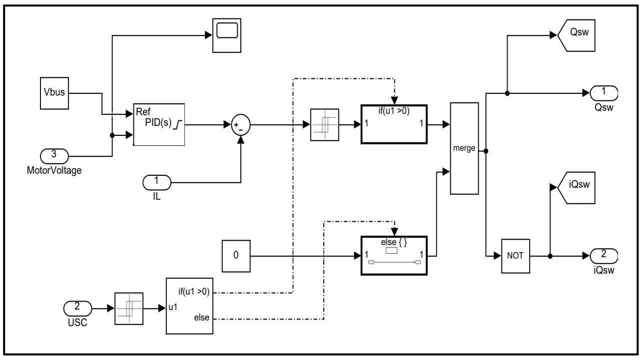

Fig. 4. Regulator Model

In order to compare different optimal values of the supercapacitor voltage, the charging current (for the parallel or cascade topology) an elementary loss model of the system is added – given in figure 5. It takes into account three types of losses – the losses in the two switches and the loss in the power inductor.

The losses in the power switches, that realize the bidirectional converter (which are assumed to be identical) are calculated as the sum of the conduction and switching losses for inductive load – eq (4) and eq (5) for SW1.

$$P_{Sw_1} = \frac{1}{2} U_{SC}.RMS\left(I_{L1}\overline{Q_{sw}}\right).\left(T_{on}+T_{off}\right).f_{sw} \quad (4)$$

$$P_{cond1} = RMS\left(I_{L1}\overline{Q_{sw}}\right)^2 R_{ds} \quad (5)$$

The loss in SW2 are calculated similarly but the inverse switching function is taken.

For the inductor the losses in the ESR are only taken into consideration – eq (6)

$$P_L = RMS\left(I_{L1}\right)^2 .R_L \quad (6)$$

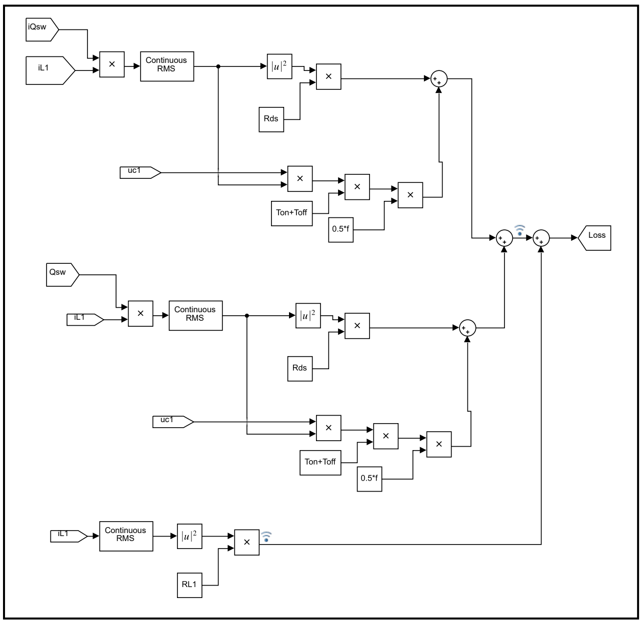

Fig. 5. Switching Loss Model

III. Simulation Results

The circuit is simulated with data given in Table 2, while for the loss calculations were modeled for TK65G10N Nmos transistor from Toshiba Corporation and the inductor was modeled after 74436410470 from Wurth Elektronik.

TABLE 2. LOAD PARAMETERS

Parameter	Value
Supercapacitor Initial voltage	10V
Motor Voltage	36V
Load resistive component	80 Ohm
Peak Motor current	18A

As already stated the time simulation was scaled (1:100), compared to a normal driving cycle, so naturally the supercapacitor values used were scaled accordingly.

A waveform showing the Semiconductor and Inductor losses as a function of the Charge current for the Parallel topology are shown in figure 6 and figure 7. For these the supercapacitor value is kept constant at 0.8F.

Figure 8 shows the converter losses as a function of the Capacitor size for the parallel topology with constant charging current of 5A.

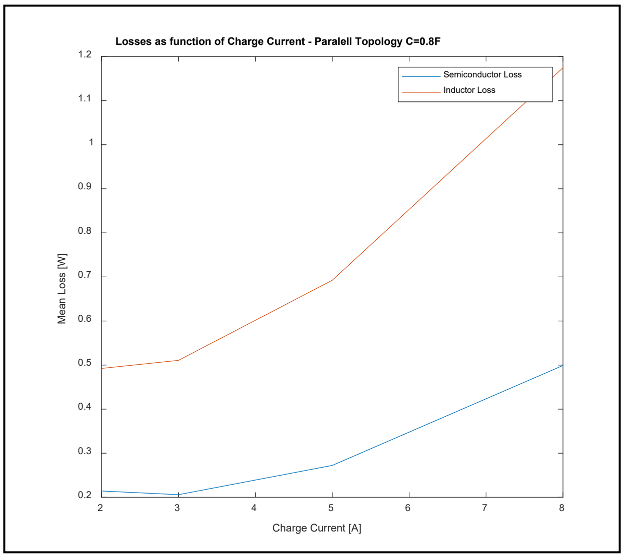

Fig. 6. Losses as function of charge current for Parallel Topology

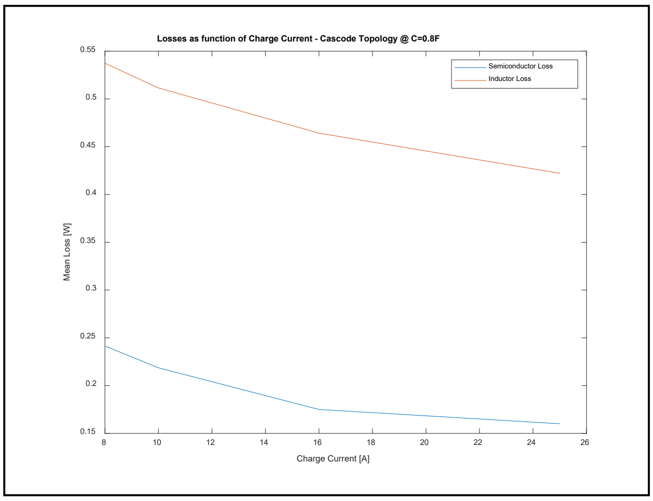

Fig. 7. Losses as function of charge current for Cascode Topology

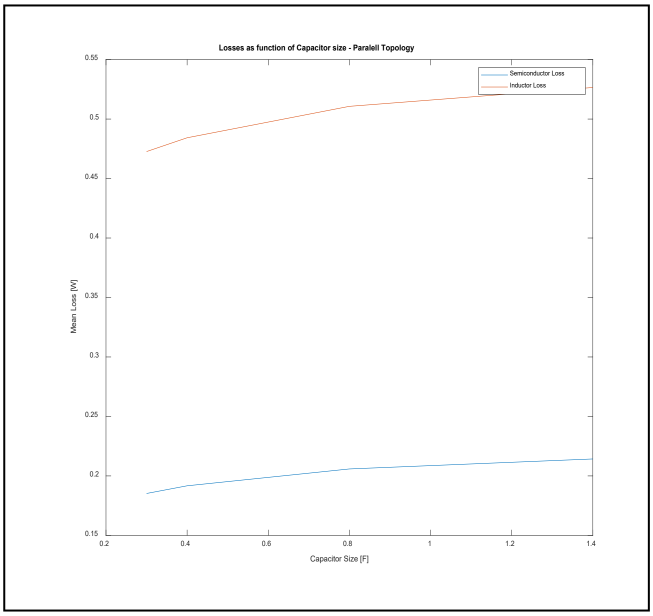

Fig. 8. Losses as function of capacitor size for Parallel topology

IV. Discussion

The load voltage was kept at 36V for all simulation results, and the regulator was kept the same. In order for the system to be able to keep the output voltage constant the minimum charging current for the cascade topology had larger than that for the parallel topology, as can be seen from figure 6 and figure 7. This can be explained by the slower dynamics of the control circuit, when rapid derivative of the load voltage is required.

The losses for the converter are lower when used in a cascade topology, when compared with the parallel one as can be seen in figure 6 and 7. The more interesting observation is that the losses are decreasing when the charge current increases for the parallel topology, but they have the opposite relation for the cascode topology.

As can be seen on figure 8 with increasing supercapacitor size the losses increase slightly for the cascode topology.

IV. Conclusion

The paper considered a load scenario for direct comparison between a parallel and cascade topology when loaded by a typical power profile. This profile is obtained by driving an electric vehicle with a WLTC cycle.

The paper proposed a switching function model of the converter between the supercapacitor and the motor along with its control system and power components loss model. The model was general enough to be able to have the current from the secondary energy storage as a design variable.

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