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IFAC PapersOnLine 51-2 (2018) 331–336

Control oriented modeling of DCDC converters

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Abstract: DCDC converters are widely used in different fields of applications to interface between DC voltage buses. A common structure of such converters is based on a resonant topology in which the working frequency of the converter should be close to the concerning resonance frequency. Therefore, a control scheme with a suitable model to design a controller is needed. Within this manuscript a nonlinear model of a CLLC DCDC converter is derived by means of the extended describing function method and a dq decomposition. Afterwards, this model is linearized to allow for a small signal analysis of the system. Both models are compared to a simulation of the DCDC converter in MATLAB Simscape and show good agreement.

Keywords: Control oriented models, circuit models, control system analysis, circuit simulation, control nonlinearities, describing functions, differential equations, dq decomposition

1. INTRODUCTION

In electrical power systems DCDC converters are widely used in different fields of applications to interface between DC voltage buses. These applications include, but are not limited to, battery-chargers, renewable energy and smart grid power systems (see Schulz (2017), Chuang and Ke (2008), and Wang et al. (2009)). Within all these applications, the requirements for DCDC converters, regarding efficiency and its power density, are increasing due to statutory specifications.

One possibility to achieve higher performance is to use a resonant topology. In the corresponding converters the switching devices operate at zero voltage or current crossing. This reduces losses drastically (Kazimierczuk and Czarkowski (2012), Tabisz and Lee (1989)), because the converter works at a certain resonance frequency ω_r. Changing the load of a DCDC converter shifts its resonance frequency. Thus, a control scheme is needed to keep the input frequency close to the resonance frequency ω_r.

The “standard” PWM control scheme, where a constant frequency with a change of the control signal’s duty cycle of the switching devices is used, cannot be applied. Due to that, the common modeling technique “State Space Averaging” is inappropriate to derive an accurate small signal model to design a controller as proposed in, e.g., Mahdavi et al. (1997).

Applying a high accurate model of the system in terms of direct physical modeling (for instance in MATLAB Simscape), the simulation time gets very long and needs powerful hardware. Furthermore, methods of control theory cannot be used. Also approaches based on neural networks to model power systems including converters, as proposed in Mercorelli and Terwiesch (2003), suffer from same problems. However, to design a control scheme for DCDC converter in resonant topology, a model of the system to analyze its dynamical behavior is necessary.

Within this manuscript a nonlinear state space model of a CLLC resonant converter is derived by means of the extended describing function method and a dq decomposition. To allow for a small signal analysis and an observer and controller design, the model is linearized. Both models are compared to a simulation of the complete converter in MATLAB Simscape and show good agreement. The presented modeling strategy can also be used for other types of converters, frequency or duty cycle controlled or even both (Kazimierczuk and Czarkowski (2012)).

2. GENERAL STRUCTURE OF DCDC CONVERTERS IN RESONANT TOPOLOGY

As depicted in Fig. 1 all types of DCDC converter have in general the same structure (Kazimierczuk and Czarkowski (2012)). The first element is a DC source, followed by an active input bridge, which transforms a DC signal to an AC one. Generally, it consists of MOSFETs or other transistors. The AC signal passes a RLC resonance circuit with low pass characteristic, called resonant tank. Afterwards, the signal is transformed into a DC signal by means of a rectifier. To provide a pure DC signal at the sink a low pass suppresses high frequency components of the rectified signal. (In case of a bidirectional DCDC converter, the rectifier has to be also an active bridge of transistors.) To derive a suitable model for the DCDC conversion, certain elements of the converter can be combined.

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10.1016/j.ifacol.2018.03.057

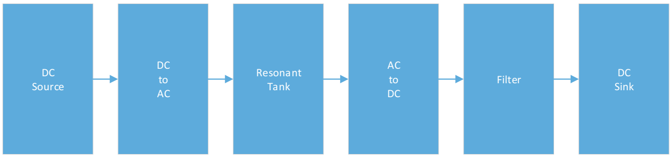

Fig. 1. General scheme of a DCDC converter in resonance topology.

The DC source and the input bridge can be merged to an equivalent AC source, which represents the input of the resonant tank. The corresponding output signal of the bridge is described by its Fourier series. At the output of the resonant tank a matching resistance R'_e is connected. It can be seen as the simplest approach to match the AC signal with the DC one at the sink of the converter. The whole circuit model is shown in Fig.2.

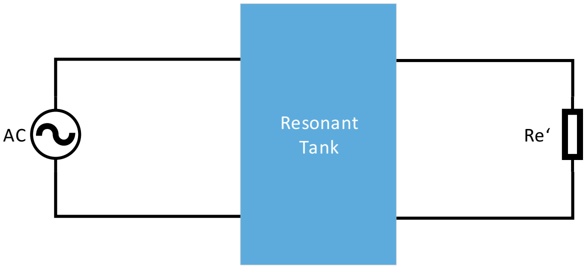

Fig. 2. Circuit model of the merged DC source and input bridge, resonant tank and matching resistance.

The output of the AC to DC rectifier can be modeled as an AC current source and represents the input of the filter and the DC sink (see Fig. 3). The corresponding current is determined by the rectified value of the AC current at R'_e, where R'_e depends on the resistance of the switched transistors, the filter and the DC sink. Filter and DC sink can be modeled as linear elements and are described by linear differential equations.

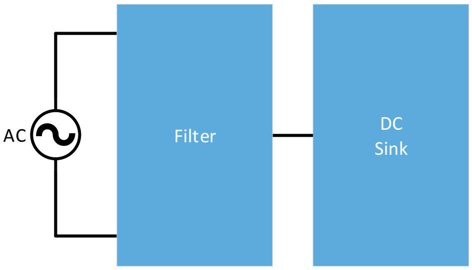

Fig. 3. Circuit model of the rectifier as AC current source, filter and DC sink.

3. STATE SPACE MODEL

In this section a general approach, known as describing function method (see Chang et al. (2012),Yang (1994),Rim et al. (1990)), to model the dynamic behavior of resonant converters is applied. Therefore, a full order dynamic model of the whole converter has to be derived.
One of the main challenges concerning DCDC converter modeling is to model their switching elements, due to their non-linearity. Several methods have been proposed in literature to overcome this problem. One of them is based on describing functions and utilizes a dq decompensation of all AC signals in the resonant tank (Rim et al. (1990), Areerak et al. (2008)), which allows a simpler coupling between resonant tank model and the filter and sink model. It leads to a high order nonlinear model, where the dynamic behavior of the rectifier is included (see Duerbaum (1998)).

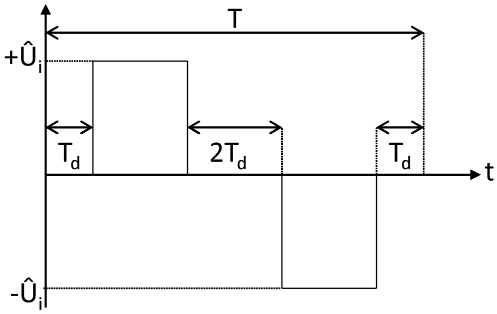

Fig. 4. Input signal $u_\mathrm{i}(t)$ of the resonant tank.

As an example, we considered a CLLC bidirectional converter. Due to the fact that the modeling approach remains the same for both directions, only one direction will be investigated here. The voltage $u_\mathrm{i}(t)$ of the equivalent AC source, mentioned in the previous section, is a certain square wave as shown in Fig. 4. T_d is the delay between the firing signals of the transistors to avoid short circuits within the input bridge due to reverse recovery of the transistors. $\hat{U}_\mathrm{i}$ is the voltage amplitude. This square wave represents the output of the DC to AC conversion bridge and its Fourier series is given by

$$u_\mathrm{i}(t) = \frac{4}{\pi}\hat{U}_\mathrm{i}\sum_{n=1}^{\infty}\frac{cos((2n-1)\omega T_\mathrm{d})}{2n-1}\sin((2n-1)\omega t)\ . \quad (1)$$

Typically, a resonant tank in a CLLC converter contains a transformer, which can be model by the so called T model (see for example Zastrow (2010)). The complete equivalent lumped element circuit model is depicted in Fig. 5. All parameters of the circuit elements are known by data sheets or can be measured, except R'_e. To determine R'_e, we assume, that the route mean square value of the dissipated power in R'_e equals the dissipated DC power in the resistance of the switched transistors R_tr, the filter R_f and the sink R_L (see Fig. 6):

$$R'_\mathrm{e}I^2_{2,\mathrm{RMS}} = (R_\mathrm{L} + R_\mathrm{f} + R_\mathrm{tr})I^2_0\ . \quad (2)$$

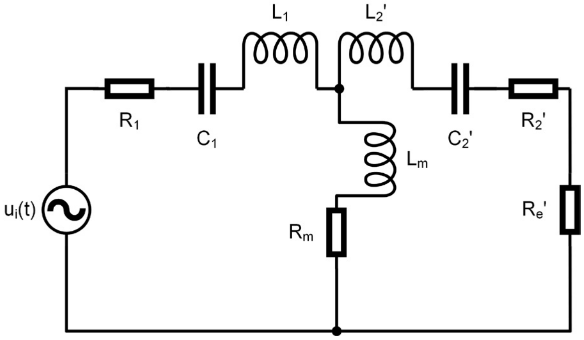

Fig. 5. Equivalent circuit of the resonant part (Merged as shown in Fig.2)