Paper for dialogue session in topic 2a

Comparison of PWM operated Resonant DC-Voltage Link Inverters

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Abstract:

This paper compares three topologies of PWM operated Resonant DC-Voltage Link Inverters with respect of suitability for high power applications. The resonant circuits are analysed and compared under the aspect of semiconductor and passive element stresses. Simulation results are discussed. The final paper will give experimental results of the most promising topology.

Summary:

Increasing the switching frequency is one possibility to improve the line- and/or load- side characteristics of high power converters. The object of efforts in the power-semiconductor technology as well as in circuit design is to increase the switching frequency of high power converters. By introducing soft switching topologies, switching losses may be reduced, but some other drawbacks have to be accepted. In the literature, many proposals for soft switching inverters exist, each describing the favourable properties of the specific solution. The aim of our work is to compare some proposals and to find out, which is the best suited one for a predetermined power range. Only IGBT equipped Inverters are considered. As a result of a preselection, in the range of very high power, the Resonant Pole topology seems to be interesting, while in range of medium power, PWM operated Resonant DC-Voltage Link Inverters seem to be favourable. As there is one commutation circuit for each of the three phases, the count of individual components is clearly higher for the Resonant Pole Inverter than for the Resonant DC-Voltage Link Inverters. But Resonant Pole Inverters have the advantage, that they can generate true PWM-pulse patterns and that no increased switching frequency occurs in the commutation circuits. Therefore, the Resonant Pole Inverter may be interesting for a broad range from very high to medium power, but the Resonant DC-Voltage Link Inverter, which uses much less individual parts, seems to be the more cost efficient solution for the medium power range. To find out the upper limit of power for which the Resonant DC-Voltage Link Inverter should be used, in this paper some of the most promising Resonant DC-Voltage Link Inverter topologies are studied in detail and compared to each other. Resonant DC-Voltage Link Inverters can be classified as follows:

1.) Inverters, which use a continuously resonating commutation circuit. They need time-descrete gate control strategies, where switching of the power transistors is only allowed at descrete times defined by the resonance of the commutation circuit [Div87]. In this circuit, a considerable amount of energy permanently swings between the resonance capacitor and inductor at a frequency of about 50 kHz, which causes losses especially in the inductor. Another problem is a fast change from driving to breaking a machine. Then, despite of a clamping factor of 1.2, the IGBTs are transiently stressed with a voltage of approx. $1.8*U_{dc}$. Therefore, the Active Clamped Resonant DC-Link Inverter seems not to be attractive for medium to high power applications.

2.)Inverters using a commutation circuit, which performs only one resonant cycle each time the switching state of the inverter has to be changed. No (time descrete) restrictions exist for the start of such a resonant cycle [Moh90], [Bor91], [Sal95], [Sul95]. We concentrate on the latter three circuits, as they need only two IGBTs in the commutation circuit.

[Bor91] applies zero current switching (ZCS) for all transistors, [Sal95] employs zero voltage switching (ZVS) for all but one transistor, which uses ZCS. [Sul95] finally uses ZVS for all transistors. From literature [Kel91], [Sku92] it is known, that with IGBTs ZCS should produce slightly lower losses than ZVS.

At first, all three topologies have been simulated using ideal switches and the critical voltage- and current-stress on the devices has been pointed out. Then, some semiconductor effects like rise and fall time or tail current where taken into consideration in a simplified way. Finally, a test-stand for the most promising solution is under construction now and measurements will be included in the final paper.

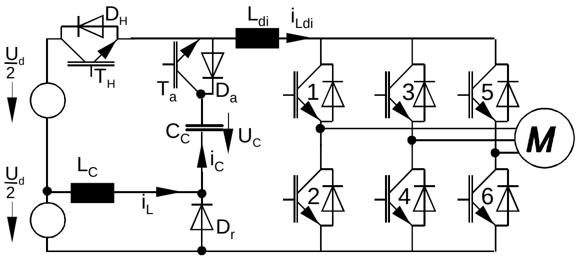

Fig. 1: Circuit for ZCS for all IGBTs

Figure 1 depicts a circuit, which realises ZCS for all IGBTs. Originally it was developed for GTO-Inverters with increased switching frequency. In the steady state the energy for the resonant operation is stored in the capacitor C_C which is charged up to U_d. The resonant cycle is triggered by turning on IGBT T_a. A resonant oscillation determined by L_C and C_C starts. The resonant oscillation drives a current against the DC-link current so that D_H starts conducting and T_H can be turned off under ZCS conditions. By this, the inverter bridge is separated from the DC-link. As soon as i_{Ldi} has discharged C_C to zero all IGBTs in the bridge are turned on and i_L increases sinusoidal. When i_L has passed its maximum and becomes negative the Diodes $D_1..D_6$ start conducting and the IGBTs can be turned off under ZCS conditions. Finally when the current distribution in the bridge has reached its final state, the IGBT T_H is turned on to charge C_C to U_d again. When u_C reaches U_d D_r starts conducting to demagnetize L_C. The new circuit state can be set while three diodes in the inverter bridge are conducting.

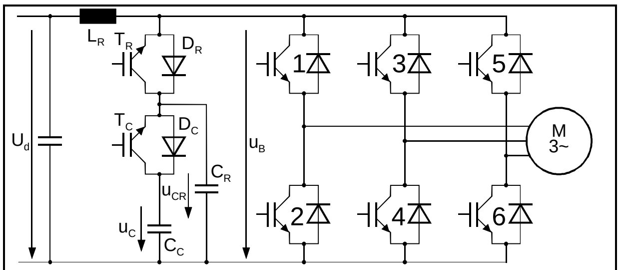

Fig. 2: ZVS for most IGBTs [Sal98]

The circuit shown in Figure 2 provides ZVS for the IGBTs in the inverter-bridge and T_C, T_R is switched off under ZCS conditions. The capacitors C_C and C_R are charged up to $1{,}2U_d$, the capacitance of C_c is about 100 times C_R. To trigger the resonant cycle the IGBTs in the resonant circuit T_C and T_R are turned on simultaneously, the voltage u_B is clamped to the capacitor voltage u_{CR}. A low frequency resonant oscillation determined by L_R and C_C starts. When i_{TC} reaches the level I_{TP}, the IGBT T_C is turned off, the current in T_C commutates to C_R and discharges it. When u_B reaches zero the IGBTs in the bridge can be switched under ZVS conditions within a short period of time which is determined by the conducting state of the diodes $D_1..D_6$. To restore the capacitor charge of C_R and C_C both IGBTs of one inverter leg are turned on together for a short time which is determined by the charge flowed out the capacitor C_C. When the new circuit state is set the capacitors C_R and C_C are charged up to $1{,}2U_d$ again.

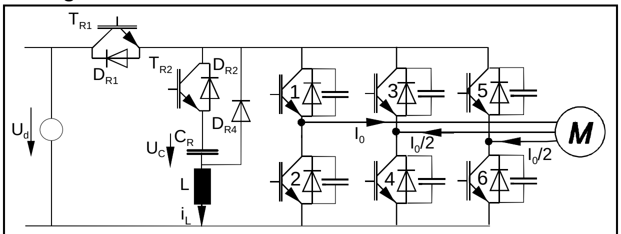

Fig. 3: ZVS for all IGBTs [Sul95]

The resonant circuit introduced by Sul is shown in Figure 3. In the steady state the resonant tank energy is zero, T_{R1} is closed and T_{R2} is open. The snubber capacitors provide ZVS switch off of the bridge IGBTs, independent of the resonant circuit. By turning T_{R2} on, a resonant cycle is started. The current in T_{R1} increases to feed energy into the resonant tank. As soon as i_L reaches I_{TP1} T_{R1} is opened and u_B is clamped to the snubber capacitor voltage u_C. i_L then discharges the snubber capacitors. When u_B reaches zero all the IGBTs in the inverter are turned on under ZVS conditions. i_L changes its direction and when it reaches the negative value i_{TP2} the new circuit state is set. The snubber capacitors are charged up to U_d and T_{R1} is turned on under ZVS conditions. C_R is discharged via D_{R1} and D_{R2}. When u_C reaches zero L is demagnetized via D_{R1} and D_{R4}.

The circuits mentioned above have been simulated. Comparing the simulation results, we decided to build up an experimental set-up, based on [Sul95] for the following reasons:

- An estimation on power losses in the resonant circuit during one resonant cycle shows, that due to rather long conducting times, the ZCS solution [Bor91] will produce higher losses than the ZVS solutions.
- The voltage stress of semiconductors is in the circuit [Sal95] is higher than in [Sul95].
- In order to achieve ZVS, an extreme precise gate timing seems to be necessary with [Sal95]. [Sul95] is less sensitive in this respect.
- The snubber-capacitors allow a ZVS turn off any time irrespective of the link voltage
- In [Sul95] the IGBT T_{R1} can be used to separate the inverter-bridge from the DC-link in case of an fault.
- In [Sul95] the resonant tank energy is stationary zero, so there is no need for controlling it
- Overvoltages produced by parasitic inductances are damped by the snubber capacitors.

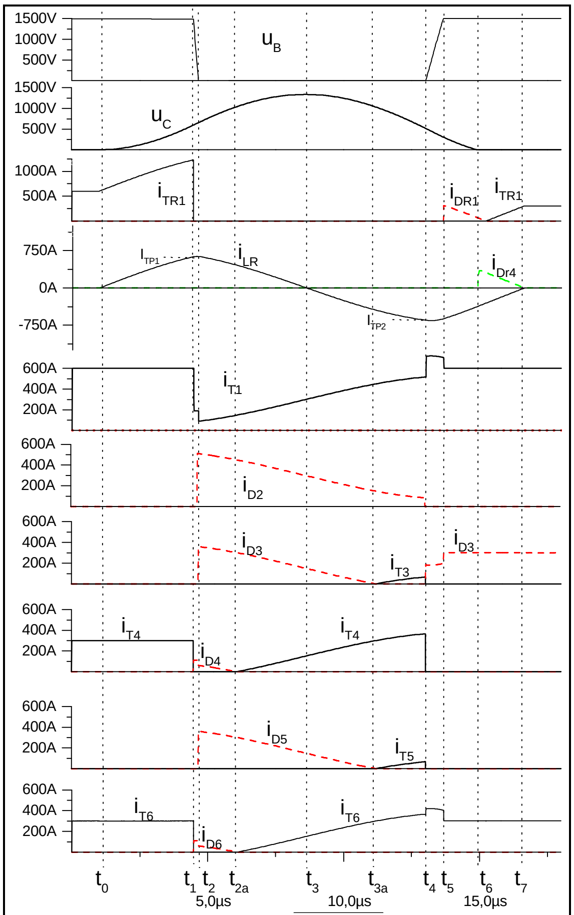

Fig. 4: Commutation process in [Sul95]

Figure 4 depicts the simulation results using the resonant circuit from Sul shown in figure 3. In this simulation a change from voltage-vector {1} to {2} is examined. The load-side currents are assumed to be constant for the time the resonant operation takes. The resonant operation is triggered at t_0. At t_1 T_{R1} has to switch off a current that is about two times the load-current in this example. This is a disadvantage of [Sul95], but this problem can be solved by using two parallel IGBTs to realise T_{R1}. The maximum current of the IGBTs 1-6 is close to the maximum load current.

As long as (in the mentioned case) D_2 conducts the inverter bridge transistors can be switched under ZVS conditions. At the end of the resonant cycle the diode D_{R4} feeds the surplus of resonant tank energy back into the DC-link.

The final paper will present experimental results using a resonant circuit (1.5KV, 150A) according to [Sul95] and discuss the differences of the three circuits in more detail.

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