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BIDIRECTIONAL CONTROL OF RESONANT CONVERTER IN POWER ELECTRONIC TRACTION TRANSFORMER

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Abstract - *This paper proposes ,the model and working of LLC resonant converter which can achieve bidirectional power flow automatically. Power electronic traction transformer power cell is built to obtain the constant voltage for the traction application. MATLAB/Simulink model of the DC/DC resonant converter is built for the traction application in which superiority of the outcome validated.*

***Key Words*: Bidirectional power flow control strategy, LLC resonant converter, power electronic traction transformer (PETT),PI controller**

1. INTRODUCTION

In Recent Years, wide use of electrical equipment has forced strict demands for electrical utilizing energy and this development is constantly growing. The increasing efforts on pushing to high power density and high efficiency DC/DC converter have lead us to develop converters capable of operating at higher switching frequency with high efficiency[1]-[3]. For this reason, resonant converters have drawn lot of attentions due to high efficiency, high switching frequency and high power density.

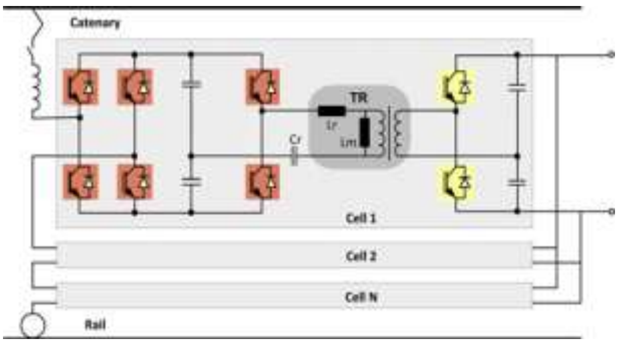

Fig-1: Power electronic traction transformer topology

Each of those converters has its pros and cons.For example, for SRC light load output voltage regulation is always a problem for the control design. For PRC, circulating energy will hurt the high line or light load efficiency. The development of power conversion technology, power density becomes the major challenge for front-end AC/DC converters[4]-[6]. Nowadays, dual active bridge DC/DC converter (DAB converter) is very popular in this application, because it can achieve an automatic transition between the forward mode and the backward mode through the phase-shift control[7]. Even so, the advantage of LLC resonant converter is still obvious, as its soft-switching capability is better than that of DAB converter. However, the conventional LLC resonant converter is a kind of unidirectional DC/DC converter, and few efficient bidirectional control strategies are suitable for LLC resonant converter to achieve automatic forward-backward transition. Especially, in power electronic traction transformer (PETT)[8]-[9] for locomotive ,with the transition between traction condition and regenerative braking condition of the train, the DC output voltage *Vo* of the DC/DC converter will drop and rise if output voltage control is not applied[8]-[9]. For locomotive, the transitions of traction conditions and regenerative braking conditions are usually random and frequent, it's hard to confirm when power flow is forward and when power flow is backward[10]. Therefore, to keep output voltage *Vo* constant, the power flow should be controlled automatically, that is, for PETT and other similar bidirectional DC/DC conversion, the system should have the ability to automatically adjust the power flow and keep the DC output voltage *Vo* constant.

2. WORKING OF LLC RESONANT CONVERTER:

The main control objective for the DC-DC converter in PETT is to automatically adjust the power flow and keep the DC output voltage constant. When LLC converter is used as the DC-DC converter in PETT, to achieve above control objective, a LLC-LC type bidirectional control strategy for LLC resonant converter is proposed.The characteristics and operation of this converter are different; despite of LLC has the same form as SPRC apart of magnetizing inductance. Three resonant components form the LLC converter (Lr , Cr and Lm) and two resonant frequencies are induced. Low frequency is induced by Cr and Lm + Lr and the high frequency by Cr and Lr .

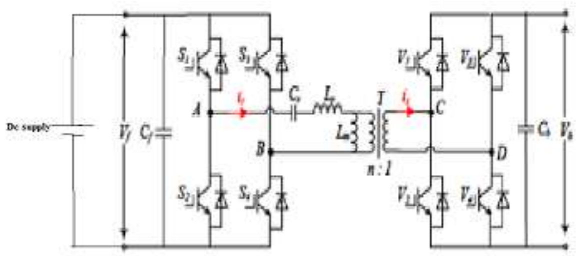

Fig-2: The topology of full bridge LLC resonant converter

In **LLC resonant mode (*t*1-*t*2)**, *V*1 and *V*4 are turned off at *t*1 and *is* falls to zero, so *V*1 and *V*4 can achieve zero-current turnoff. In this mode, *Lr*, *Cr*, and *Lm* constitute a resonant circuit and no power flows forward. *im*= *ir* and the corresponding schematic is shown in Fig. 4(b).

In **dead time mode (*t*2-*t*3)** ,*S*1 and *S*4 are turned off at *t*2. Because *ir* is equal to *im* at *t*2 and their values are usually very small, *S*1 and *S*4 can achieve low-current turn-off. In this mode, power begins to flow forward through the resonant circuit consisted of *Lr* and *Cr*, the schematic is shown in Fig. 4(c). When the power flow is backward, it can be divided into two working modes in a half switching period: LC resonant mode (*t*0-*t*2), and dead time mode (*t*2-*t*3).

In **LC resonant mode (*t*0-*t*2)**, *S*1, *S*4, *V*1, and *V*4 are turned on at *t*0. The resonance between *Lr* and *Cr* begins and transfers backward power flow. Since *ir* is negative, the current will flow through the parallel diodes of *S*1 and *S*4, thus zero-voltage turn on can be achieved. Meanwhile, *is* is zero at *t*0, and *V*1 and *V*4 can achieve zero-current turn-on. *V*1 and *V*4 are turned off at *t*1. As *is* is larger than zero and flows through the parallel diodes of *V*1 and *V*4, zero-voltage turn-off of *V*1 and *V*4 can be achieved. After that, the resonance between *Lr* and *Cr* continues and transfers forward power until *S*1 and *S*4 are turned off. The schematic in this mode is expressed in Fig. 4(a).

In **dead time mode (*t*2-*t*3)**, *S*1 and *S*4 are turned off at *t*2 and all the switches are on off-state. The resonance between *Lr* and *Cr* begins through the parallel diodes of *S*2, *S*3, *V*1, and *V*4, whose corresponding schematic is shown in Fig. 4(d). In this mode, *ir* and *is* decrease rapidly until *ir*=*im*, *is*=0. Then *is* will keep zero until this mode is over at *t*3.

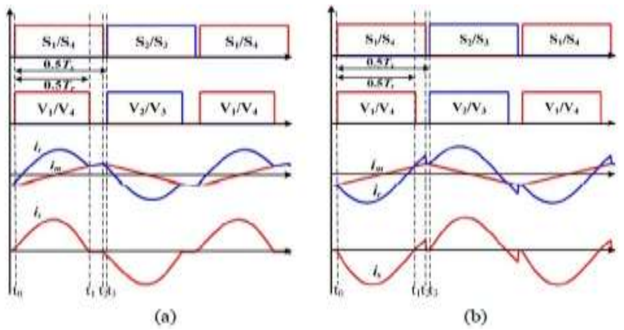

Fig-3: The modulation method and corresponding theoretical waveforms of LLC-LC type bidirectional control strategy. (a) Forward mode. (b) Backward mode.

Operating Modes:

Based on the above analysis, it can be concluded that in the whole switching period, by using the proposed LLC-LC type bidirectional control strategy, when the converter works in forward mode, zero-voltage turn-on and low-current turn-off can be achieved for the primary-side switches, zero-current turn-on and turn-off can be achieved for the secondary-side switches. when the converter works in backward mode, zero voltage turn-on and low-current turn-off can also be achieved for the primary-side switches, zero-current turn-on and zero voltage turn-off can be achieved for the secondary-side switches.

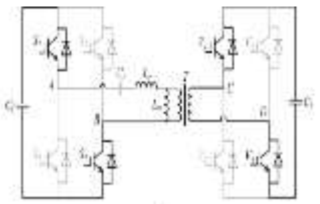

Fig-4(a): Mode 1

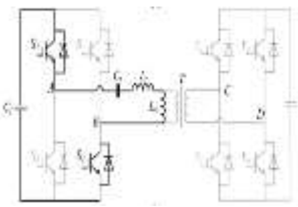

Fig-4(b):Mode 2

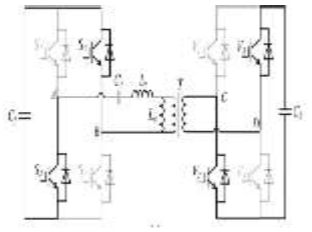

Fig-4(c): Mode3

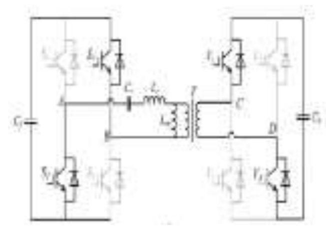

Fig-4(d): Mode4

Fig-4:Working schematic of LLC resonant converter

2.3 Control block of proposed control strategy:

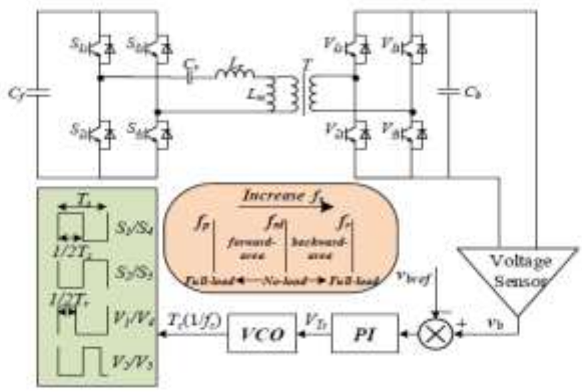

Fig-5: The control block diagram of the proposed control strategy

The control block diagram is shown in Fig. 5. In Fig. 5, with the calculation of a PI controller, a voltage signal *VTs* is obtained from the difference between output dc voltage *vb* and its reference value *vbref*. Then use a voltage controlled oscillator to convert the voltage signal *VTs* to the final switching period *Ts*, where *Ts* =1 *fs* . By frequency adjusting, the output voltage can be hold constant no matter forward or backward mode. It's not hard to find that the no-load frequency *fnl* is a key point to connect forward mode and backward mode of LLC resonant converter, which can be seemed as a junction point of forward power flow and backward power flow. It should be pointed that *fnl* is the switching frequency when active power is zero, which can be called no-load frequency. If other parameters is chosen as rated values, then *fnl* is a fixed value which can be calculated. If *fp* < *fs* < *fnl*, LLC resonant converter is working at forward mode and if *fnl* < *fs* < *fr,* LLC resonant converter is working in backward mode.

3. SIMULATION MODEL FOR PROPOSED WORK:

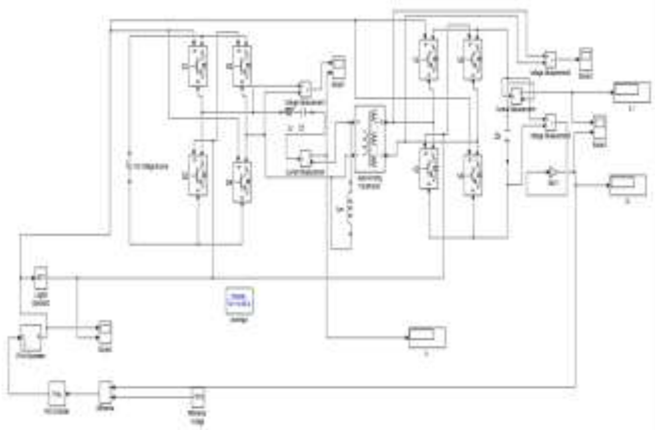

Fig-6: Simulink model of LLC resonant converter

The switches in the primary side are S1,S2,S3 and S4 and at the secondary side V1,V2,V3 and V4 in the simulated model as referred from the figure 2 full bridge LLC resonant converter .The input dc voltage of 25kv is given from the front end of the model to achieve the dc/dc conversion. The resonant capacitor(Cr) and resonant inductor(Lr) and mutual inductance (Lm) are connected in such a way to form LLC resonant converter to achieve resonance. Full bridge is formed by the combination of switching devices on both primary and secondary side of the transformer. The output voltage from the LLC resonant converter can be sensed by PID controller ,the reference voltage is set to generate the signals for the switches from the PWM generator.

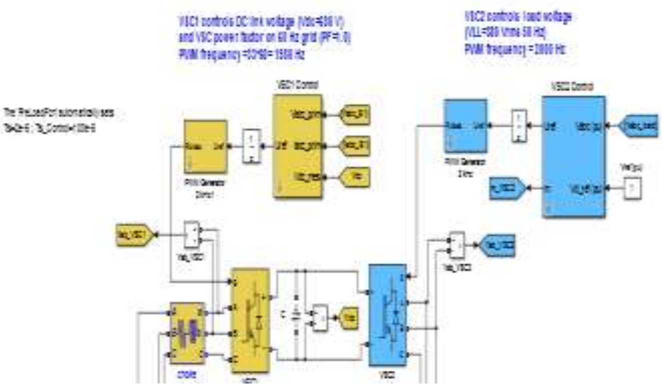

Fig-7: AC-DC-AC converter

The dynamometer is an AC-DC-AC converter which consists of a three-phase rectifier and a three-phase inverter to control the induction motor M1 and another three-phase inverter is used to control the induction motor M2. The whole starting process is stable and no over current occurs. It should be pointed that the starting process is always at closed-loop mode so the output voltage can be controlled constant.

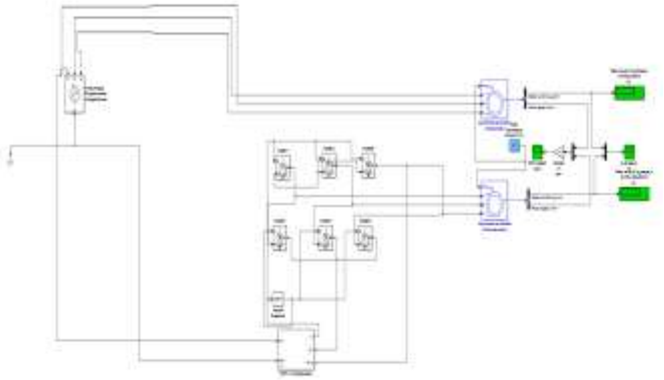

Fig-8: SIMULINK model of LLC resonant converter with load

In order to verify the validity of the proposed control strategy, an simulink model of a PETT power cell is built. Also, a reciprocal power-fed test system is built to achieve forward mode and backward mode of LLC resonant converter. PETT is composed of a single phase rectifier and a bidirectional LLC resonant converter which can provide 1500V DC bus voltage for the reciprocal power-fed test system. Meanwhile, the reciprocal power-fed test system is made up of a dynamometer, an inverter, and two reciprocal induction motors.

4. RESULTS AND DISCUSSIONS

Input to the resonant converter is 25kv,the switches on the front end in the circuit model are S1,S2,S3 andS4 and the switches on the secondary are V1,V2,V3 and V4.The controlled signals from the PWM generator are given to the switches to operate the switches with the switching frequency 100kHz. With no load ,the output voltage 1500v of the LLC resonant converter is shown below

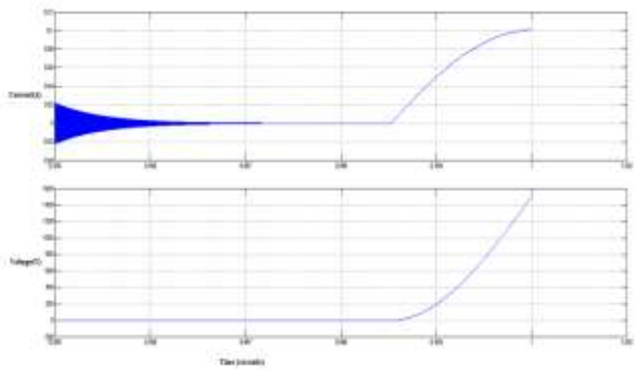

Fig-9: Current and Voltage waveform of LLC resonant converter

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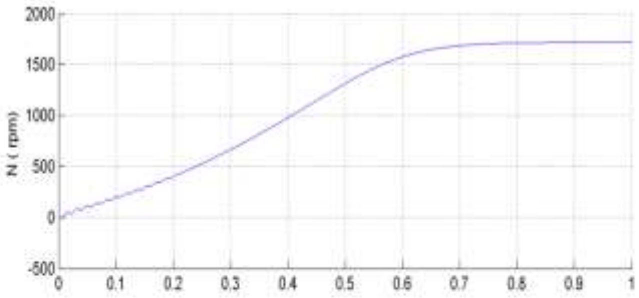

Fig-10: Rotor speed of the Induction motor

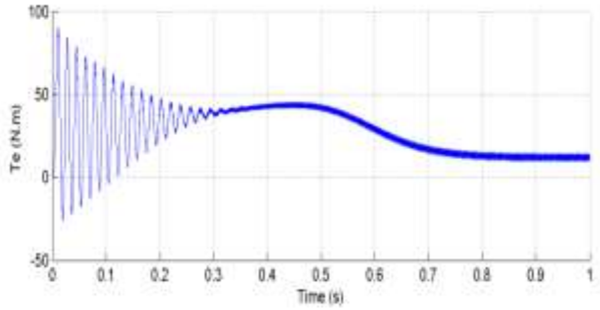

Fig-11: Torque of the induction motor

The figure 10 shows the machine's speed going from 0 to 1725 rpm (1.0 pu). The second graph shows the electromagnetic torque developed by the machine. Because the stator is fed by a PWM inverter, a noisy torque is observed. However, this noise is not visible in the speed because it is filtered out by the machine's inertia, but it can be seen in the stator and rotor currents.

5. CONCLUSION:

In conclusion, the proposed model can achieve automatically bidirectional power flow and also keep good soft-switching characteristic which is beneficial to improve the converters efficiency and power density. The output from the LLC resonant converter maintained constant i.e,1500V using feedback control strategy and the proposed efficiency-optimized switching strategy can minimize the power loss and maximize the system efficiency. The voltage-current waveforms, rotor speed and torque waveforms are captured and verified using MATLAB/SIMULINK model.

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