Analysis and Design of the Parallel Quasi Resonant DC Link Converter for Induction Motor Drive Application

Dimitar Stoilov Spirov and Nikolay Georgiev Komitov

Abstract – **A parallel quasi resonant DC link converter for induction motor drive application is analyzed and designed. The proposed soft-switching inverter is formed from the traditional pulse-width modulated (PWM) inverter by simply augmenting with auxiliary resonant circuits, and the soft switching is achieved through applying PWM switching control signals with suitable delays for the switches. The designed soft-switching inverter is used for powering an induction motor drive which is connected to drive the constant nominal load. The converter is designed to achieve the maximum voltage gradient and simultaneously to have low peak current and voltage stresses on the devices and thereby to reduce the losses.**

Keywords – **Induction Motor Drive, Parallel Quasi Resonant DC Link Converter**

I. INTRODUCTION

Variable speed drives using induction machines require power electronic circuits that are capable of producing sinusoidal voltages of varying frequency and magnitude [1]. The control of adjustable speed drives is done by the power converters. In hard-switched power converters switching losses limit the applicable switching frequency. Switching with large du/dt reduces the switching losses. Bigger voltage gradients combined with long feeders lead to high frequency parasitic effects, like over voltages at motor terminals, high common mode ground current, bearing currents, etc. In addition, electromagnetic interference increases and efficiency decreases. To overcome these problems, the application of soft switching techniques is essential [1-5].

The resonant DC-link inverter is the most commonly used one for induction motor drives, owing to its simplicity, but it possesses the disadvantage of having a high resonant link voltage, which is equal to or greater than twice the supply voltage [2].

Quasi-resonant (QR) inverters offer several advantages compared with resonant DC-link inverters with regard to resonant link design and control, device rating requirements and use of pulse width modulation (PWM) [3]. The QR inverter schemes generate zero-voltage instants in the DC link at controllable instants that can be synchronised with any PWM transition command, thus ensuring a zero-voltage switching condition of inverter devices. As a result, these inverters can be operated at high switching frequencies with high efficiency [3].

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A number of discontinuously resonant link circuits employing a parallel resonant link arrangement in conjunction with additional switches have been reported in the literature [1-7]. These have in common that the resonant link is only active when the bus voltage has to be reduced to zero in order to commutate the inverter switches. Two distinct advantages can be identified. The voltage across the dc link is resonated from supply voltage level down to zero, hence, the voltage stress for the inverter devices never exceeds the supply voltage. A resonant cycle can be initiated at any time which enables inverter switching at any desired instant.

These inverters can be designed not only for the soft switching but also for the voltage gradient reduction. In addition to switching loss reduction, the resonant circuit undertakes the filter's task of reducing voltage overshoot at motor terminals. It is important to minimize the peak value of the resonant current in order to reduce the stress on circuit devices.

The object of this work is to analysis and design a parallel quasi resonant DC link converter for a three-phase induction motor drive soft-switching inverter. The passive component values must be selected to meet specific design criteria, to reduce the level of the common mode voltage and to minimize the peak value of the resonant current.

A. Mathematical model

The parallel quasi-resonant dc link converter is presented in [5-7] (Fig. 1). The six switches of the bridge are represented by a single switch S_{inv} for the purpose of the analysis [5]. The proposed converter shown in Fig. 2 consist of an ideal current source I_o, equivalent switch S_{inv}, diode D_{inv} and resonant circuit. To turn on the equivalent switch S_{inv} means to turn on both the switches in one of the inverter legs simultaneously. The diode D_{inv} is conducting means both the diodes in one of the inverter legs are conducting.

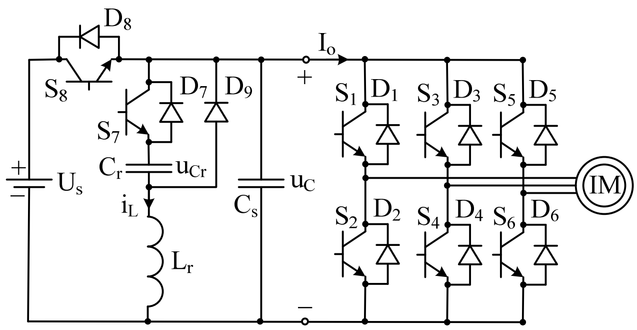

Fig. 1. Parallel quasi-resonant dc link converter

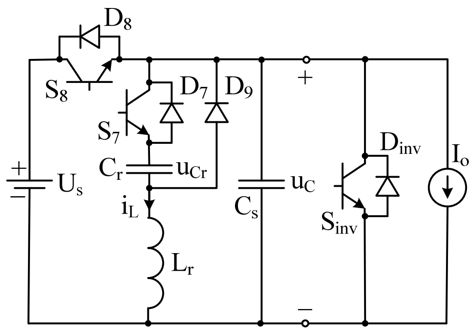

Fig. 2. Simplified circuit of the parallel quasi-resonant dc link converter

To simplify the analysis, all the components are assumed ideal. I_o is suddenly altered when the state of the inverter switches changes.

In Fig. 3, the main operational waveforms of the resonant circuit are shown.

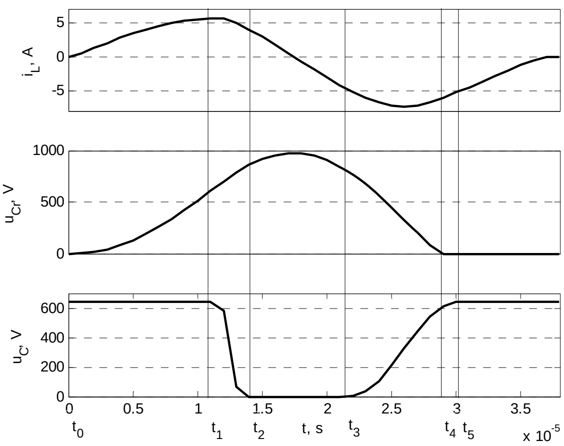

Fig. 3. Operational waveforms of the resonant circuit

The following notations will be used in the subsequent equations: $C_{rs}=C_r+C_s$; $C_e=C_rC_s/C_{rs}$; $k_s=C_r/C_{rs}$; $k_r=C_s/C_{rs}$; $\omega_r=1/\sqrt{(L_rC_r)}$; $\omega_s=1/\sqrt{(L_rC_s)}$; $\omega_e=1/\sqrt{(L_rC_e)}$; $Z_r=\sqrt{(L_r/C_r)}$; $Z_s=\sqrt{(L_r/C_s)}$; $X_{Cr}=1/(\omega_eC_r)$; $X_{Cs}=1/(\omega_eC_s)$; $X_{Ce}=1/(\omega_eC_e)$; $X_{Lr}=\omega_eL_r$.

In the steady state, the resonant tank energy is zero, S_8 is closed and S_7 is open.

$$\begin{aligned} &i_L(t)=0;\\ &u_{Cr}(t)=0;\\ &u_C(t)=U_s. \end{aligned} \tag{1}$$

An **energy storage interval** (t_0-t_1) is needed in order to store resonant energy in the resonant inductor L_r to ensure that the resonant link voltage does decrease down to zero, during the ramp down interval. The energy storage interval starts with turn-on of the resonant link transistor S_7 [5-7].

$$\begin{aligned} &\theta_0=\omega_r(t-t_0);\\ &i_L(t)=\frac{U_s}{Z_r}\sin\theta_0;\\ &u_{Cr}(t)=U_s(1-\cos\theta_0);\\ &u_C(t)=U_s. \end{aligned} \tag{2}$$

The energy storage interval is finished when the inductor current reaches the trip current $i_L(t_1)$.

$$i_L(t_1)=\frac{U_s}{Z_r}=i_L(t)_{\max}. \tag{3}$$

The duration of the energy storage interval is equal to

$$\Delta t_1=\frac{\pi}{2\omega_r}. \tag{4}$$

The **resonant link voltage ramp down interval**, (t_1-t_2) is initiated by turning off the resonant link series transistor S_8, forcing a discharge of the resonant link capacitor C_s [5-7].

$$\begin{aligned} &\theta_1=\omega_e(t-t_1);\\ &i_L(t)=(k_sI_o+i_L(t_1))\cos\theta_1+\\ &+\frac{U_s-u_{Cr}(t_1)}{X_{L_r}}\sin\theta_1-k_sI_o;\\ &u_{Cr}(t)=k_r(u_{Cr}(t_1)-U_s)\cos\theta_1+\\ &+X_{C_r}(k_sI_o+i_L(t_1))\sin\theta_1+\\ &+k_rU_s+k_su_{Cr}(t_1)-\frac{I_o(t-t_1)}{C_{rs}};\\ &u_C(t)=k_s(U_s-u_{Cr}(t_1))\cos\theta_1-\\ &-X_{C_s}(k_sI_o+i_L(t_1))\sin\theta_1+\\ &+k_rU_s+k_su_{Cr}(t_1)-\frac{I_o(t-t_1)}{C_{rs}}. \end{aligned} \tag{5}$$

The ramp down interval is finished when the resonant link voltage reaches zero.

During the **zero voltage interval** (t_2-t_3) the resonant link voltage is clamped to zero, first by the converter freewheeling diodes and then by the converter transistors [5-7].

$$\begin{aligned} &\theta_2=\omega_r(t-t_2);\\ &i_L(t)=i_{Lr}(t_2)\cos\theta_2-\frac{u_{Cr}(t_2)}{Z_r}\sin\theta_2;\\ &u_{Cr}(t)=u_{Cr}(t_2)\cos\theta_2+\\ &+Z_ri_{Lr}(t_2)\sin\theta_2;\\ &u_C(t)=0;\\ &i_{Dinv}(t)=i_L(t)+I_o. \end{aligned} \tag{6}$$

The zero voltage interval is finished when the diode current i_{Dinv} reaches zero. The duration of the zero voltage interval is equal to

$$\Delta t_3=\frac{1}{\omega_r}\arctan\left(\frac{X_{C_s}i_L(t_2)}{u_{Cr}(t_2)}\right) \tag{7}$$

The equations valid for the **resonant link voltage ramp up interval** (t_3-t_4) are given below [5-7].

$$\theta_3 = \omega_e(t - t_3);$$
$$i_L(t) = (k_s I_o + i_L(t_3))\cos\theta_3 - + \frac{u_{Cr}(t_3)}{X_{L_r}}\sin\theta_3 - k_s I_o; \quad (8)$$

$$u_{Cr}(t) = k_r u_{Cr}(t_3)\cos\theta_3 + X_{C_r}(k_s I_o + i_L(t_3))\sin\theta_3 + k_s u_{Cr}(t_3) - \frac{I_o(t - t_3)}{C_{rs}};$$
$$u_C(t) = k_s u_{Cr}(t_3)(1 - \cos\theta_3) - X_{C_s}(k_s I_o + i_L(t_3))\sin\theta_3 - \frac{I_o(t - t_3)}{C_{rs}}. \quad (9)$$

The resonant link voltage ramp up interval is finished when u_{Cr} reaches zero. The duration of this interval is equal to

$$\Delta t_4 = \frac{1}{\omega_e}\arcsin\left(\frac{X_{C_s} I_o}{u_{Cr}(t_3)}\right) \quad (10)$$

During the **resonant energy recovery interval**, (t_4-t_5) the excess energy stored in the resonant inductor L_r is transferred back to the DC link voltage sources U_s via the resonant link series diode D_8. Furthermore, this also implies that the resonant link voltage is clamped to the DC link voltage level. During the energy recovery interval the resonant link series transistor S_8 is turned on, to be able support the current fed to the converter during the off resonance period. The equation valid for this mode is thus written [5-7]

$$\theta_4 = \omega_s(t - t_4);$$
$$i_L(t) = (i_L(t_4) + I_o)\cos\theta_4 + \frac{u_{Cr}(t_4)}{Z_s}\sin\theta_4 - I_o;$$
$$u_{Cr}(t) = 0; \quad (11)$$
$$u_C(t) = u_{Cr}(t_1)\cos\theta_4 - Z_s(I_o + i_L(t_4))\sin\theta_4.$$

The resonant energy recovery interval is finished when u_C reaches U_s.

The inductor current i_L goes back to zero from a negative value. The equation valid for this mode is thus written [5-7]

$$i_L(t) = i_L(t_5) + \frac{U_s}{L_r}(t - t_5);$$
$$u_{Cr}(t) = 0; \quad (12)$$
$$u_C(t) = U_s.$$

The duration of this interval is equal to

$$\Delta t_5 = -L_r\frac{i_L(t_5)}{U_s} \quad (13)$$

B. Design Considerations

A good design of the resonant elements is important in order to reduce the peak voltage stress and the peak current stress on the devices [5]. The specifications to design the quasi resonant dc link inverter circuit parameters are as follows [5, 6]:

- The inverter input voltage must be pulled down to zero for zero voltage switching (ZVS) and again boosted to the DC link source voltage;
- The trip currents should be as small as possible in order to reduce the circuit power loss;
- It is important to minimize the peak values of the resonant voltage and the resonant current in order to reduce the stress on circuit devices;
- The rising and falling slope of the inverter output voltage must be low for long cable drives;
- The resonant transition interval must be designed to be much shorter than inverter's switching frequency cycle time.

The peak resonant voltage $u_{Cr}(t_{ucr.max})$, peak inductor current $i_L(t_{ir.max})$, falling time of the voltage u_C - Δt_f and resonant transition interval T_s are to be obtained from the equations, derived for different modes.

$$t_{ucr.\max} = \frac{1}{\omega_r}\arctan\left(\frac{Z_r i_L(t_2)}{u_{Cr}(t_2)}\right) + t_2 \quad (14)$$

$$t_{ir.\max} = \frac{-1}{\omega_e}\arctan\left(\frac{u_{Cr}(t_3)}{X_{Lr}(i_L(t_3) + k_s I_o)}\right) + t_3 \quad (15)$$

It is difficult to obtain an analytical solution for the falling time of the voltage u_C - Δt_f and resonant transition interval T_s due to complex modes. The "root" function of the software product Mathcad is used to determine these functions [8]. The result is obtained in the form: *root(f(var1, var2, ...),var1, [a, b])*. The "root" function returns the value of *var1* lying between *a* and *b* at which the function *f* equal to zero. Fig. 4 shows the variation in peak resonant voltage $u_{Cr}(t_{ucr.max})$ for different values of the L_r^*, C_r^* and C_s^*. The quantities shown in Fig. 3 are normalized, where the L_r, C_r and C_s base values are the optimal values L_{rb}=L_{ro}=800μH, C_{rb}=C_{ro}=60nF, C_{sb}=C_{so}=20nF.

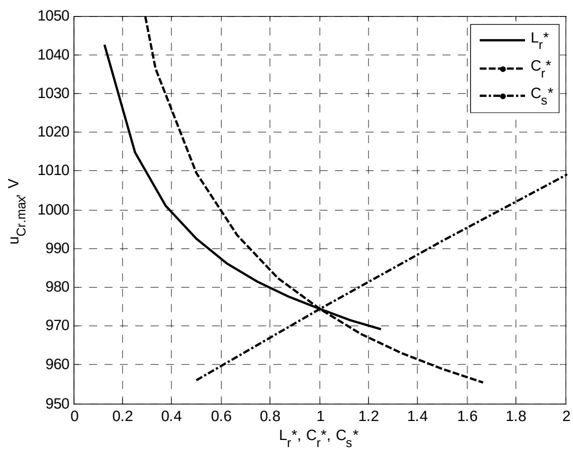

Fig. 4. Dependences $u_{Cr.max}$=f(L_r^*), $u_{Cr.max}$=f(C_r^*), $u_{Cr.max}$=f(C_s^*)

Fig. 5 shows the variation in peak inductor current $i_L(t_{ir.max})$ for different values of the L_r^*, C_r^* and C_s^*.

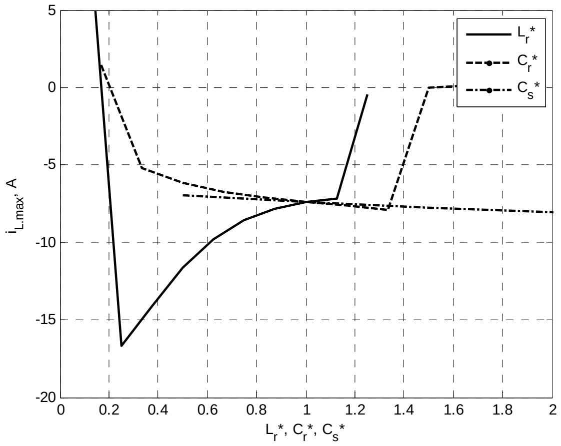

Fig. 5. Dependences $i_{Lr.max}$=f(L_r^*), $i_{Lr.max}$=f(C_r^*), $i_{Lr.max}$=f(C_s^*)

Fig. 6 shows the variation in falling time of the voltage u_C - Δt_f for different values of the L_r^*, C_r^* and C_s^*.

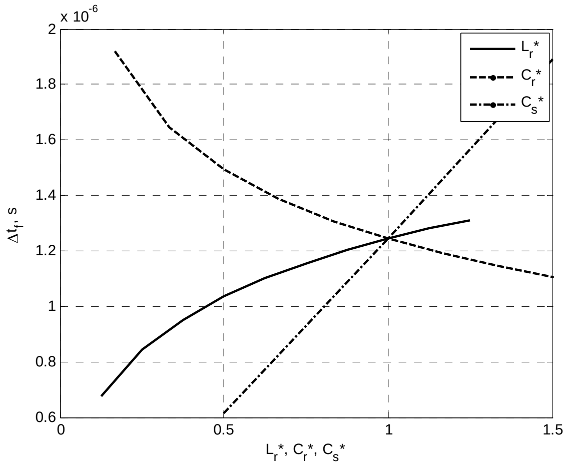

Fig. 6. Dependences Δt_f =f(L_r^*), Δt_f =f(C_r^*), Δt_f =f(C_s^*)

Fig. 7 shows the variation in resonant transition interval T_s for different values of the L_r^*, C_r^* and C_s^*.

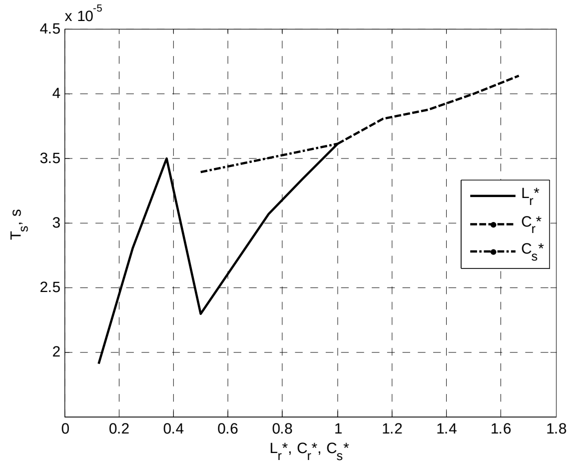

Fig. 7. Dependences T_s =f(L_r^*), T_s =f(C_r^*), T_s =f(C_s^*)

The converter is designed to achieve the maximum voltage gradient and at the same to have low peak current and voltage stresses on the devices and thereby to reduce losses. The selected parameters for this resonant converter were summarized in Table 1.

TABLE 1. THE SELECTED PARAMETERS FOR THE RESONANT CONVERTER

Resonant Inductor L_r	800μH
Resonant Capacitor C_r	60nF
Parallel Capacitor C_s	20nF

The basic circuit of the proposed scheme consists of a three phase induction motor type AO-90S-4 having ratings as 1,1kW, 380V, 50 Hz which is connected to drive the constant nominal load. The parameters used in the simulation were U_s=640V, I_o=5A. The Mathcad model of proposed soft-switching converter for powering of the three phase induction motor drive has been developed.

The peak resonant voltage, peak inductor current, falling time and resonant transition interval for the selected parameters were summarized in Table 2.

TABLE 2. PEAK VALUES, THE FALLING AND RESONANT INTERVAL TIME

Peak resonant voltage $u_{Cr.max}$, V	974,27
Peak inductor current $i_{Lr.max}$, A	-7,371
Falling time of the voltage u_C - Δt_f, μs	1,24
Resonant transition interval T_s, μs	36,13

II. CONCLUSION

A parallel quasi resonant DC link converter for induction motor drive application is analyzed and designed. Link waveforms and operation modes are analyzed to reveal various soft switching characteristics. The converter is designed to achieve the maximum voltage gradient and simultaneously to have low peak current and voltage stresses on the devices and thereby to reduce the losses.

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