Simulations and Analysis and Operating Regime as Rectifier with Power Factor Correction of Two - Quadrant Converter with RNSIC

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***Abstract*—In this paper, a new topology for a two – quadrant converter is presented. In the AC/DC transfer mode, the converter works as a rectifier with near sinusoidal input currents (RNSIC), while in the DC/AC transfer mode it works as a square-wave pulse switching inverter. We offer some suggestions for the converter design and realize a comparison with a two–quadrant PWM converter. The new converter is characterized by smaller power losses, reduced EMI problems and higher reliability.**

***Index Terms*—power quality, AC/DC power conversion, power converter, rectifier**

I. INTRODUCTION

Many applications use three – phase converters, for two – quadrant operation in AC power supplies where the objective is to produce sinusoidal current waveforms on the AC side. For example, in motor drives with regenerative braking, the power flow through the utility interface converter reverses during the regenerative braking while the kinetic energy associated with the inertias of the motor and load is recovered and fed back into the utility system [1 – 3]. Usually, in order to reduce higher current harmonics on the AC side, the three – phase converters for two – quadrant operation use PWM switching. Governments and international organizations have introduced new standards (IEEE 519 in the United States and IEC 61000 – 3 in Europe) which limit the harmonic content of the current drawn from the power line by rectifiers [4 – 6].

Figure 1a presents the most popular topology used in adjustable speed drives (ASD), uninterruptible power supplies (UPS), and more recently, in PWM rectifiers. This topology has the advantage of using a low – cost three – phase module with a bi-directional energy flow capability. Due to the rapid changes in voltages and currents of a switching converter, a PWM rectifier is a source of EMI. The PWM rectifier, even though it has near sinusoidal input currents, has important disadvantages as compared with the inexpensive three – phase rectifiers with diodes: larger switching losses, high per – unit current rating, poor immunity to shoot – through faults, higher cost and less reliability [1 – 2].

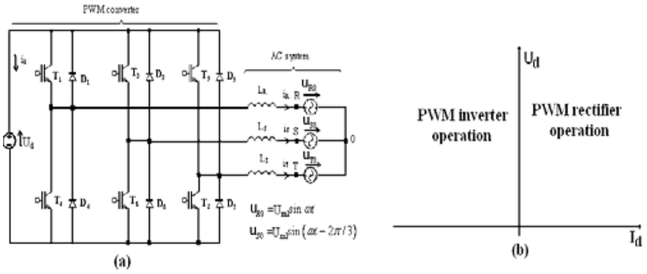

Figure 1. Converter for two – quadrant based on PWM principle; (a) Configuration; (b) Operation modes.

II. NEW CONVERTER FOR TWO – QUADRANT OPERATION

A new converter for two – quadrant is presented in this paper; it is equipped with 6 transistors (e.g. IGBT) having square-wave pulse switching (that is not PWM) operation, as shown in Figure 2a. When the energy is transferred from the AC side to DC side, the transistors are off and the converter works as a RNSIC (Rectifier with Near Sinusoidal Input Currents), as show in Figure 3 [7 – 9]. When the energy is transferred from the DC side to the AC side, the transistors are controlled to conduct for θ angles (square-wave pulse switching) and the converter works as inverter, as shown in Figures 2b, 5 and 6.

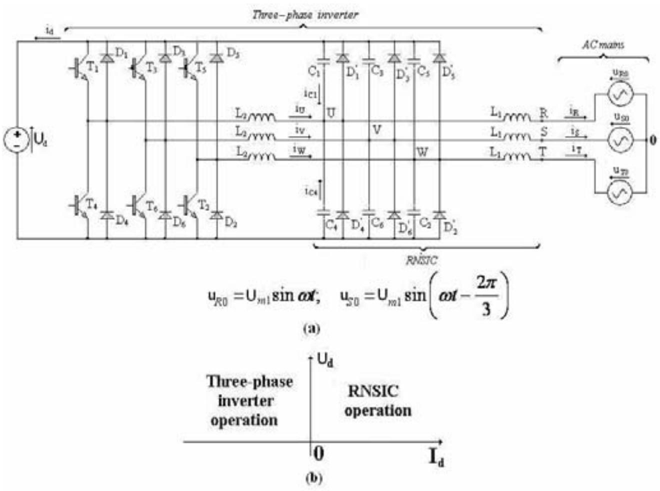

Figure 2. Converter for two – quadrant with RNSIC;

(a) Configuration; (b) Operations.

Digital Object Identifier 10.4316/AECE.2009.03004

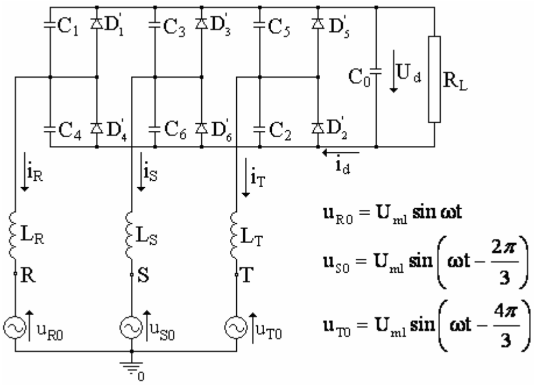

Figure 3. Configuration of RNSIC converter.

A. AC/DC operation mode

Figure 3 shows an AC/DC converter generating reduced higher order current harmonics in the mains, called for short in what follows RNSIC, and which is a module of the two quadrant converter in Figure 2a. The capacitors $C_1 - C_6$ have the same value C and they are DC capacitors. The inductors L_R, L_S and L_T have the same value, denoted by L_1, and they are connected on the AC side. L_1 and C fulfil the condition $0,05 \le L_1 C\omega^2 \le 0,10$ in order for the phase currents i_R, i_S, i_T to be practically sinusoidal (ω denotes the mains angular frequency), [7 – 9].

Considering that the currents i_R, i_S, i_T are practically sinusoidal and have the amplitude $I_{(1)}$, a function of the load resistor R_L, the current I_d of medium value can be calculated from the following relation:

$$I_d = \frac{3 I_{(1)}}{2\pi}\left(1 + \cos \omega t_1\right) \tag{1}$$

where ωt_1 is the turning on angle of the diodes $D_1' - D_6'$.

There are two extreme cases during RNSIC converter functioning. In the first case, if $R_L = 0$ (and so, Ud = 0 and $\omega t_1 = 0$), the capacitors $C_1 - C_6$ are short – circuited and the angle $\varphi = +90^0$ is inductive. In this case, the phase currents are sinusoidal and have maximum amplitude, equal to I_{max}. In the second case, if the voltage U_d exceeds the value $\sqrt{3}U_{m1} / \left(1 - 2L_1 C\omega^2\right)$, the diodes $D_1' - D_6'$ do not conduct any more and the angle $\varphi = -90$ is capacitive (and so $R_L = \infty$ $\omega t_1 = \pi$). For this latter case, the phase currents are also sinusoidal and the amplitude has a minimum value I_{min}, referred to as the holding current. The ratio I_{min} / I_{max} has the value:

$$\frac{I_{min}}{I_{max}} = \frac{2 L_1 C\omega^2}{1 - 2 L_1 C\omega^2} \tag{2}$$

Figure 4a shows the variation of the angle φ, the phase displacement angle between the phase voltage and the fundamental of the phase current, as a function of the mean rectified voltage U_d rated to the reference value $U_{ref} = \frac{3\sqrt{3}U_{m1}}{\pi}$ specific for the classical three – phase rectifier [1]. The voltage U_d can be established at a certain value by the load current.

Figure 4b shows the variations of the output voltage U_d rated to the reference value U_{ref} and the amplitude of the phase current $I_{(1)}$ rated to the reference value I_{max} as a function of the ratio R_L / R_{Lr} (R_{Lr} denotes the rated load resistor for $\varphi = 0^0$).

The rated operation of the RNSIC converter is defined for $\varphi = 0^0$ and $R_L / R_{Lr} = 1$. For this case, the variations of the rated angle $(\omega t_1)_r$, the angle corresponding to when diodes begin to conduct, and the ratio $R_{Lr} / L_1\omega$ are given in Figure 4c, as function of the parameter $L_1 C\omega^2$. The interval between 45^0 and 60^0 for $(\omega t_1)_r$ ensures a reduced content of higher harmonics for the input currents. One can design this converter using the diagrams in Figure 4c [9].

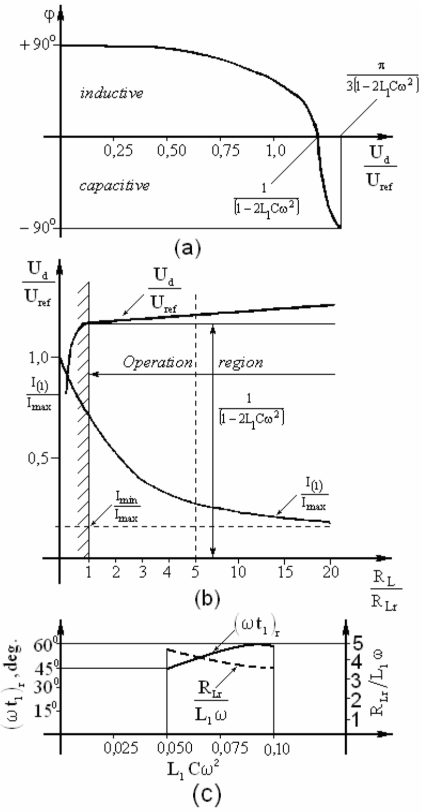

Figure 4. Characteristics of RNSIC converter.

Angle φ as a function of ratio U_d / U_{ref}; (b) Ratio U_d / U_{ref} and $I_{(1)} / I_{max}$ as a function of R_L / R_{Lr}; (c) Rated angle $(\omega t_1)_r$, and the ratio $R_{Lr} / L_1\omega$ as a function of $L_1 C\omega^2$.

B. DC/AC operation mode

In what follows we describe the operation of the converter in Figure 2a as an inverter. The control programme of the transistors is shown in Figure 5 and the corresponding waveforms in Figure 6. During the first stage, which starts at t_0, the transistor T_1 begins to conduct and the capacitor C_1, charged at initial voltage U_{in}, is discharged to final voltage, U_{end}, while capacitor C_4, initially charged at voltage $(U_d - U_{in})$, is charged to $(U_d - U_{end})$ by means of the oscillatory processes in which transistor T_1 and inductor L_2 take part. After the blocking of the transistor T_1, made at t_1, the second stage begins, when the energy accumulated in inductor L_2 is rapidly transferred to DC and AC sources through diode D_4. Finally, in the third stage, which lasts between t_2 and t_3, the current i_U is zero, and the current i_R has a practically sinusoidal waveform, flowing through capacitors C_1 and C_4. At the end of this stage, capacitor C_4 is charged at voltage U_{in}, and C_1 at voltage $(U_d - U_{in})$. Inductors L_2 have two times smaller values than L_1. In the case of inverter mode operation, the voltage U_d is considered to be 15-25 % greater than in the case of rectifier system operation. Diodes $D_1^{'} - D_6^{'}$ are chosen according to the RNSIC component design specification, while the diodes D_1 – D_6 are rated for much smaller average currents, [12, 14].

According to the phasor diagram in Figure 6b, current i_R is given by:

$$i_R = \frac{u_{U0} - u_{R0}}{j\omega L_1} \tag{3}$$

while its active value, i_{Ra} , is given by :

$$i_{Ra} = \frac{U_{m2}}{\omega L_1}\left[\sin\left(\omega t + \alpha\right) - \frac{U_{m1}}{U_{m2}}\sin\omega t\right] \tag{4}$$

The active power transferred to the AC source is given by:

$$P = \frac{3}{2\pi}\int_0^{2\pi} i_{Ra} U_{m1}\cos\omega t\, d\omega t = \frac{3U_{m1}U_{m2}}{2\omega L_1}\sin\alpha \tag{5}$$

In order to obtain a unitary power factor at the AC source, it results from formula (4) that:

$$\cos\alpha = \frac{U_{m1}}{U_{m2}} \tag{6}$$

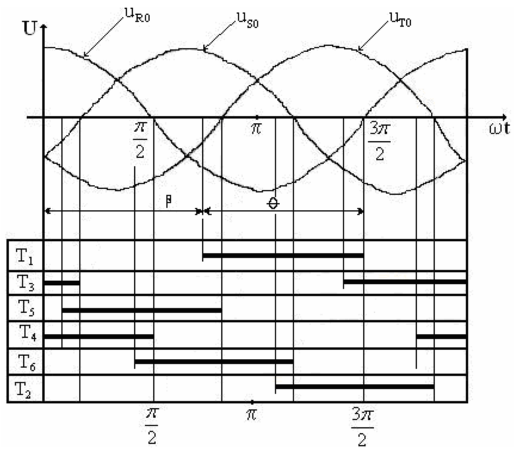

Figure 5. Control Programme of the transistors.

It results that the value of the power transmitted to the AC source could be varied by modifying the amplitude U_{m2} (thus the angle θ) and the angle α (thus the angle β), as show in Figure 5.

The switch of the converter in Figure 2a from the inverter operation mode to the rectifier operation mode and the reverse can be rapidly accomplished during a utility grid cycle $T = \frac{2\pi}{\omega}$.

1) 2.2.1Possible applications

This is a 4th Order Heading Possible application of the converters for two – quadrant operation with RNSIC which is used in static frequency converters with DC voltage link, designed for supplying variable voltage and frequency to the three – phase induction motor drives, as shown in Figure 7.

For the time intervals when the induction motor drive is in the motoring regime, the input converter becomes a RNSIC converter. In this case, the transistors T_1 – T_6 are off. The output switch – mode converter operates as a PWM inverter [10 –12]. The energy is transmitted from the power supply to the motor and the voltage on the filtering capacitor C_0 is less than $U_{d0} = \sqrt{3}\,U_{m1}\big/\left(1 - 2L_1C\omega^2\right)$.

During the time interval while the induction machine (IM) is operating in breaking mode, the energy received from the motor is transmitted to the power supply. The switch – mode converter operates as a rectifier and the voltage across C_0 is greater than $(15 - 25\%)U_{d0}$. Further on, the energy is transmitted into AC mains by means of a three – phase inverter made up of transistors T_1 – T_6, three inductors L_2, diodes D_1 – D_6 and RNSIC. One must also observe the fact the total duration of operation as a generator for the asynchronous machine is much smaller as compared with the total motor functioning duration.

Having in view that the wind energy is non-polluting, a significant growth of its importance in electrical power generation is expected in the future. Although, in the last years, remarkable technological progress has been achieved, currently, the power produced according to this principle is not yet totally competitive from the economic point of view. A wind-energy-conversion system has to draw maximum power when the speed of wind varies over a wide range, [1 – 2], [13], [15]. The energy produced by the generator is transmitted in the distribution grid by means of a frequency converter with DC voltage link [16]. The output inverter which connects to the grid can be conveniently chosen according to the variant in Figure 2a, having the semiconductor devices controlled over continuous time intervals. Such an inverter can be adopted also for small hydro interconnections with induction generators. Slightly modifying the angles α and θ, according to Figure 6c, we can vary the active power delivered in the distribution grid with unity power factor.

III. SIMULATION RESULTS

The RNSIC is composed of six diodes, three inductors L_1 with inductance 25mH and six DC capacitors C_1-C_6 with capacitance 30uF. For the three inductors L_2 we have adapted the value 6,25mH. Figures 8a and 8b present the waveforms of the phase current i_R, the transistor current i_{T1}, and the DC current i_d when the induction machine is operating in breaking mode. The value of the power transmitted to the AC source could be varied by modifying the angles θ and β.

IV. CONCLUSION

One of the advantages of the continuous functioning of the controllable switches (in square-wave pulse and not PWM switching), is that each inverter switch changes its state only twice per cycle, which is important at high power levels where the solid – state switches generally have slower turn – on and turn – off speeds.

The proposed converter has increased safety due to the fact that controllable switches have much smaller total conducting durations, being blocked while the converter operates as RNSIC.

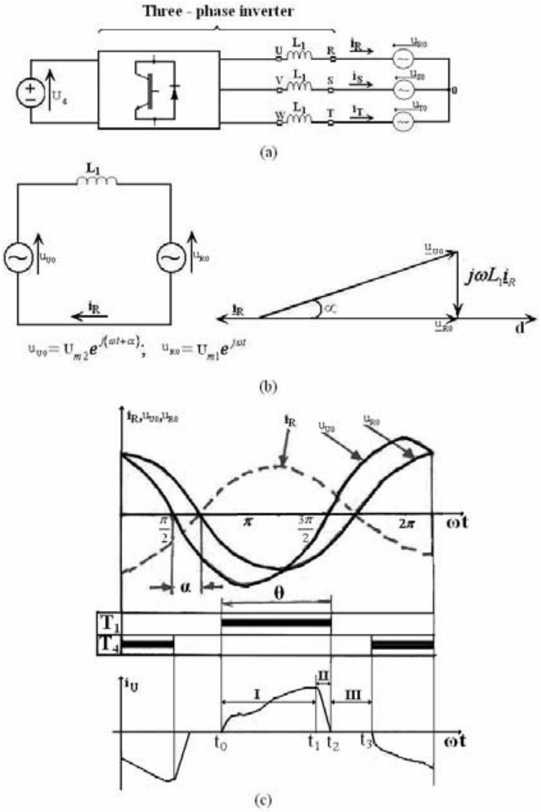

Figure 6. Inverter operation mode of the two – quadrant converter with a RNSIC ; (a) Simplified representation; (b) Phasor diagram at unity power factor; (c) Waveforms of the currents and voltage.

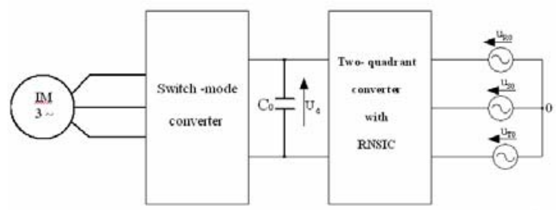

Figure 7. Static frequency converter for two – quadrant with RNSIC.

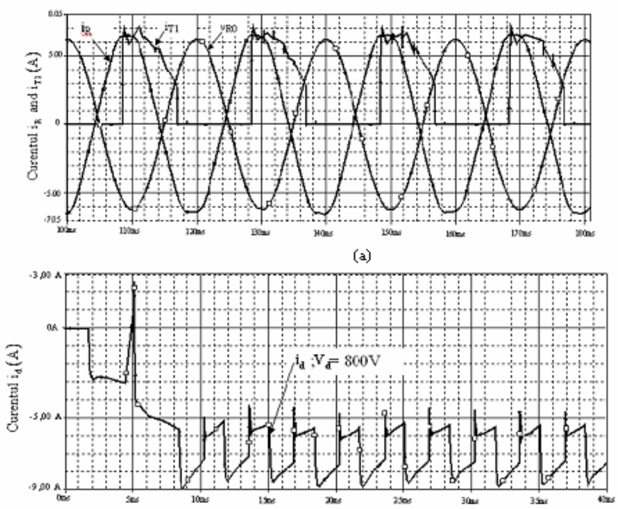

Figure 8. Characteristics for proposed converter with a RNSIC for inverter operation with V_d = 800 V; (a) Waveforms of the phase current i_R, the transistor current i_{T1} and the phase voltage v_{R0}; (b) Waveforms of the DC current i_d

In the case of DC to AC conversion, for the same values of the voltage Vd and AC inductances, the proposed converter provides larger output voltages VU0, VV0 and VW0 and thus allows a more efficient energy transfer (obviously, at the PWM inverter, the fundamentals of the output voltages are smaller and, thus, the transferred energy is smaller).

The simulation and experimental results proved that the fifth current harmonic is the most significant one generated in the AC mains and that its value situates within the limits imposed by the IEEE Standard 519/1992.

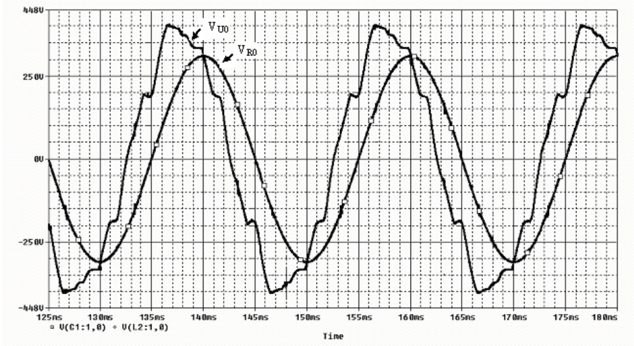

Figure 9. Inverter mode operation: waveforms of the V_{r0} and V_{U0} voltages according with the Figure 5.

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