A NEW UNIFIED APPROACH TOWARDS THE ANALYSIS OF SEMICONDUCTOR R L C INVERTERS

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Abstract

A new unified approach towards the steady - state analysis of inverters based on power semiconductor devices and containing resistors, inductors and capacitors, which form a serial R L C circuit is proposed. The transistor RLC inverter with free - wheeling diodes is considered, taking into account its dual correspondence with the thyristor parallel current - fed inverter and its coverage of the voltage - fed inverter. The main parameters of the inverter circuit, namely the load coefficient and the load power factor are introduced. The conditions for different regimes of inverter operation are derived. A generalized diagram is obtained which determines the areas for typical modes of operation of the inverter circuits and helps their classification.

The unifying of the analysis of different types of inverter circuits built with half - controlled or fully - controlled power semiconductor devices has been a strong tendency in the field of power electronics for a long time [1], [4].

In this article a new unified approach towards the steady - state analysis of inverters based on power semiconductor devices containing resistors, inductors and capacitors, which form a serial RLC circuit of second order at most is proposed. This has been made possible by the comparison between the transistor RLC inverter with free - wheeling diodes and the thyristor parallel current - fed inverter, whose bridge circuits are given in Fig.1 and Fig.2 respectively.

Applying the duality theory [6] this two circuits can be considered dual, which means that the voltages and currents of the transistor inverter correspond to the currents and voltages of the thyristor inverter, and vice versa, and the resistance corresponds to the conductance, the inductance - to the capacitance, and vice versa [7]. Therefore it is sufficient to analyze only one of the already mentioned inverters and transfer the obtained results to the other inverter circuit.

On the other hand the thyristor parallel current - fed inverter is fully analyzed only for purely active load, while for the more widely applied active - inductive load the well known analysis [5] is based on the assumption that the output voltage is purely sinusoidal. At the same time the analysis of the thyristor RLC inverter with free - wheeling diodes working in resonant mode with capacitive reaction of its diagonal serial RLC circuit is fully considered without a simplifying assumption concerning the shape of its output current for the steady - state condition in [4]. The same results can be applied to the analysis of the transistor RLC inverter with free - wheeling diodes working in a resonant mode with inductive reaction of its diagonal serial RLC circuit which is actually entirely equivalent to the thyristor parallel current - fed inverter working with capacitive reaction of its parallel diagonal RLC circuit. In that case the only difference that must be taken into account is the opposite sign of the initial current flowing through the diagonal RLC inverter circuit, which leads to an opposite sign in the expression for the "a" coefficient and some important changes of the signs in the expressions for the average currents through the devices and that drawn from the supplying source. The investigation of transistor RLC inverters with free - wheeling diodes working in aperiodical or critically - aperiodical regime is given in [8] and [9] respectively. The comparison of the expressions for the variables of the transistor RLC inverter working in different modes (resonant, aperiodical or critically - aperiodical) shows that to the trigonometrical functions contained in the equations for the resonant mode correspond hyperbolic trigonometrical functions for the aperiodical regime or simple linear functions for the critically - aperiodical regime, which of course is natural.

It should be noted that the transistor voltage - fed inverter can be considered as a partial case of the transistor RLC inverter with free - wheeling diodes working in periodical mode with the assumption that $C=\infty$.

Consequently, the analysis of transistor RLC inverter with free- wheeling diodes, whose bridge circuit is given in Fig.1, covers without simplifying assumptions cases of the current - fed, the voltage - fed and other resonant thyristor inverters if the duality theory is applied.

The following variables are introduced for the convenience of the analysis. The load coefficient of the transistor inverter (Fig.1.), which dually corresponds to the load coefficient of the thyristor parallel current - fed inverter (Fig.2), given in [5], can be expressed by

(1)
$$B=\frac{\sqrt{1+\omega^2C^2R^2}}{\omega^2LC}$$

and the load power factor, corresponding to the thyristor inverter load power factor, given in [5], can be expressed by

(2)
$$\cos\varphi=\frac{1}{\sqrt{1+tg^2\varphi}}=\frac{\omega CR}{\sqrt{1+\omega^2C^2R^2}}$$

where $\omega=2\pi f$ is the controlling frequency. Then the following correlations for the serial diagonal inverter circuit (Fig.1) can be written down

(3)
$$\delta=\frac{R}{2L}=\frac{\omega B\cos\varphi}{2}$$

(4)
$$\frac{1}{LC}=\omega^2 B\sin\varphi$$

For the critically - aperiodical mode of operation of the inverter

(5) $$\delta^2 = \frac{1}{LC}$$

and hence

(6) $$B = B_{cr} = \frac{4\sin\varphi}{\cos^2\varphi} = \frac{\sqrt{1-\cos^2\varphi}}{\cos^2\varphi} = f(\cos\varphi)$$

The function $f(\cos\varphi)$ is given in a tabular form in Table 1, column 2.

If

(7) $$\delta^2 > \frac{1}{LC}$$

and

(8) $$B > B_{cr} = f(\cos\varphi)$$

the inverter is working in periodical mode

If

(9) $$\delta^2 < \frac{1}{LC}$$

and

(10) $$B < B_{cr} = f(\cos\varphi)$$

the inverter is working in resonant mode.

When the diagonal serial RLC circuit is a resonant one ((9) and (10) are satisfied) then some of the main inverter parameters can be expressed in the following manner:

(11) $$\frac{\omega_o}{\omega} = \sqrt{B\sin\varphi - \frac{B^2\cos^2\varphi}{4}}$$

and

(12) $$\theta_2 = \pi\frac{\omega_0}{\omega} = \pi\sqrt{B\sin\varphi - \frac{B^2\cos^2\varphi}{4}}$$

where ω_0 is the resonant frequency of the inverter circuit.

When

(13) $$\frac{\omega_0}{\omega} = 1$$

and

(14) $$\theta_2 = \pi$$

which means that the following quadratic equation is satisfied

(15) $$\frac{\cos^2\varphi}{4}B^2 - \sin\varphi . B + 1 = 0$$

then the serial resonant RLC circuit in Fig.1 is in resonance. This mode is characteristic for resonant inverters without free - wheeling diodes. The dual inverter in Fig.2. is not fit for operation because there is no time left for turning off the thyristors.

The roots of the quadratic equation (15) are

(16) $$B_1 = \frac{2\sin\varphi}{\cos^2\varphi} + \frac{2\sqrt{\sin^2\varphi - \cos^2\varphi}}{\cos^2\varphi} = f_1(\cos\varphi)$$

and

(17) $$B_2 = \frac{2\sin\varphi}{\cos^2\varphi} - \frac{2\sqrt{\sin^2\varphi - \cos^2\varphi}}{\cos^2\varphi} = f_2(\cos\varphi)$$

The functions $f_1(\cos\varphi)$ and $f_2(\cos\varphi)$ are given also in a tabular form in Table 1, columns 3 and 4.

When

(18) $$\frac{\omega_0}{\omega} < 1$$

and

(19) $$\theta_2 < \pi$$

which is true if

(20) $$B > B_1$$

or

(21) $$B < B_2$$

the serial resonant RLC inverter circuit has an inductive reaction. This is typical for the transistor inverter (Fig.1). Then the diagonal parallel RLC circuit of the corresponding dual thyristor parallel current - fed inverter has a capacitive reaction and the inverter is in principle fit for operation if the other restricting requirements are satisfied. The thyristor turn - off time for $B > B_1$ or $B < B_2$ can be derived from the parameter θ_1 and is

(22) $$t_{q.c.} = \frac{\theta_1[rad]}{\omega_0}$$

When

(23) $$\frac{\omega_0}{\omega} > 1$$

and

(24) $$\theta_2 > \pi$$

which is true if

(25) $$B_2 < B < B_1$$

the serial resonant RLC inverter circuit has a capacitive reaction. Then the inverter (Fig.1) may be implemented with thyristors instead of transistors. In this case the turn - off time given to the thyristors for their recovery can be determined from the parameters θ_1 and θ_2 in the following manner

(26) $$t_{q.c.} = \frac{(\theta_2 - \theta_1)[rad]}{\omega_0}$$

But the corresponding dual thyristor parallel current - fed inverter is not fit for operation because its diagonal parallel circuit has an inductive reaction and there is no time left for turning - off the devices. Hence the functions $B_1 = f_1(\cos\varphi)$ and $B_2 = f_2(\cos\varphi)$ principally restrict the operational area of the thyristor parallel current - fed inverter from the thyristor turn - off time point of view.

Let us now consider the case when (23), (24) and (25) are fulfilled and only the resonant thyristor (or transistor) inverter with free - wheeling diodes is fit for operation with capacitive reaction of its diagonal RLC circuit. If

(27) $$\frac{\omega_0}{\omega} \leq 2$$

the inverter current i is continuous. That is true if

(28) $$B > B_3$$

or

(29) $$B < B_4$$

where B_3 and B_4 are the roots of the quadratic equation (30) derived from (27), taking into account (11)

(30) $$\frac{\cos^2\varphi}{4} B^2 - \sin\varphi . B + 4 = 0$$

If

(31) $$\frac{\omega_0}{\omega} > 2$$

or therefore

(32) $$B_4 < B < B_3$$

the inverter current is discontinuous. The expressions for B_3 and B_4 are

(33) $$B_3 = \frac{2\sin\varphi}{\cos^2\varphi} + \frac{2\sqrt{\sin^2\varphi - 4\cos^2\varphi}}{\cos^2\varphi} = f_3(\cos\varphi)$$

(34) $$B_4 = \frac{2\sin\varphi}{\cos^2\varphi} - \frac{2\sqrt{\sin^2\varphi - 4\cos^2\varphi}}{\cos^2\varphi} = f_4(\cos\varphi)$$

The functions $B_3 = f_3(\cos\varphi)$ and $B_4 = f_4(\cos\varphi)$ are given in a tabular form in Table 1, columns 5 and 6.

If the transistor voltage - fed inverter with RL load is taken into consideration, then its circuit diagram corresponds to Fig.1 with shunted C

(35) $$C = \infty$$

The load coefficient is

(36) $$B = \frac{R}{\omega L}$$

and the load power factor is

(37) $$\cos\varphi = 1$$

The transistor voltage - fed inverter always operates in aperiodical mode. The dual counterpart of the transistor voltage - fed inverter is the thyristor parallel current - fed inverter with purely active load (Fig.2 with missing L).

The functions (6), (16), (17), (33) and (34) are drawn together in Fig.3. If the main parameters of the inverter circuit, namely the load coefficient B and the load power factor $cos\varphi$ are known the mode of operation of the inverter can be easily determined from the generalized diagram obtained. This diagram allows the classification of inverter circuits in accordance with their mode of operation.

Table 1

$\cos\varphi$	$B_{cr}=f(\cos\varphi)$	$B_1=f_1(\cos\varphi)$	$B_2=f_2(\cos\varphi)$	$B_3=f_3(\cos\varphi)$	$B_4=f_4(\cos\varphi)$
0.05	1598	1597	1.0025	1594	4.0151
0.1	398	397	1.0081	394	4.0621
0.2	98	97	1.0317	93.7	4.2686
0.3	42.4	41.3	1.0756	37.68	4.7182
0.35	30.59	29.48	1.1076	25.46	5.1306
0.4	22.9	21.76	1.1487	17.05	5.8633
0.44721	17.9	16.69	1.1987	3.9443	3.9443
0.5	13.86	12.58	1.2714		
0.6	8.89	7.38	1.5047		
0.65	7.19	5.46	1.7336		
0.7	5.83	3.49	2.3376		
0.70711	5.66	2.8284	2.8284		
0.8	3.75				
0.9	2.15				
0.95	1.384				
1.0	0.0				

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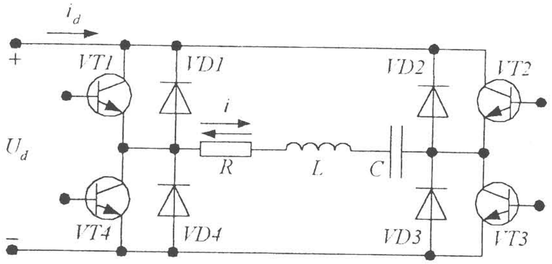

Fig.1

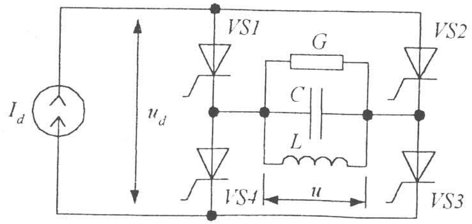

Fig.2

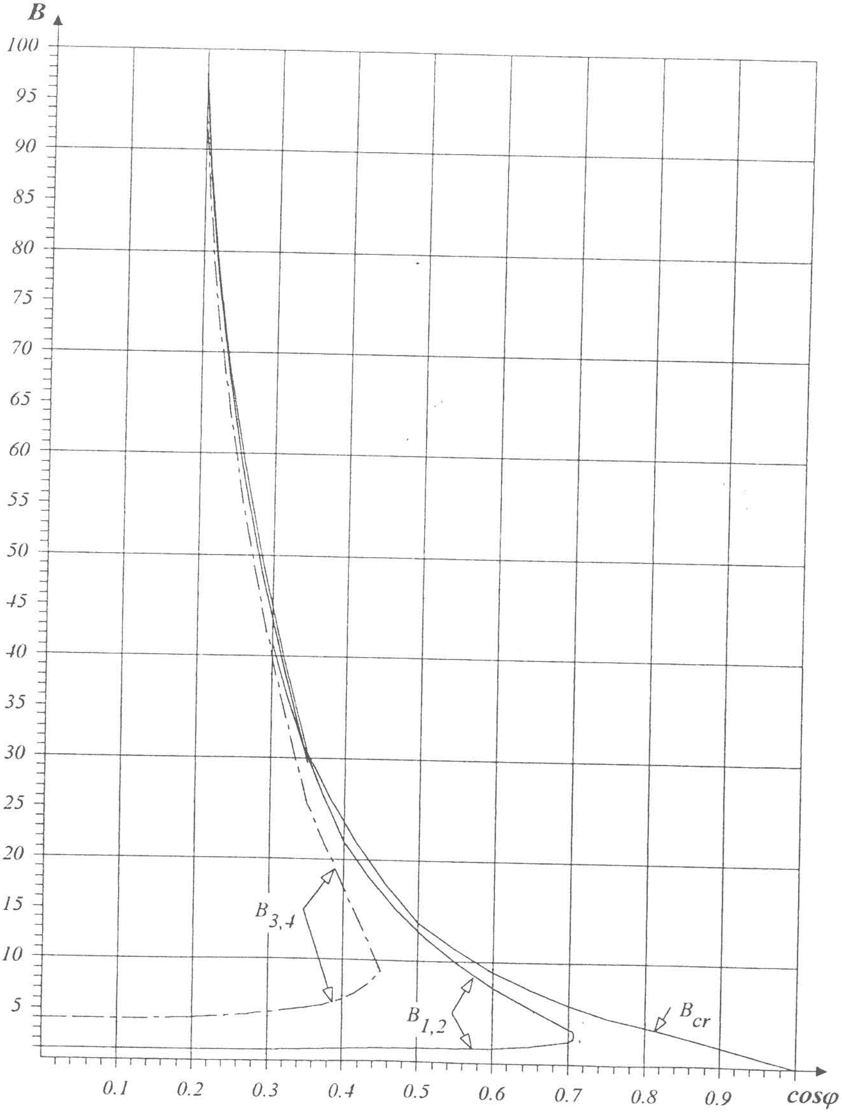
B
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
cosφ
B3,4
B1,2
Bcr

Fig.3