About the Design of Inverters with Turn-off Circuits

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Abstract— **It is well known the actual trend in power electronics to change power thyristors with devices which are more flexible from the point of view of commutation and control possibilities (IGBTs, MOS transistors, GTOs). For several existing applications, like DC high voltage electric power transmission for instance, where power commutation is involved, power thyristors continue to be of interest. For applications which suppose the commutation of increased powers and a lot of devices series-parallel connected, a technical-economic analysis put in evidence the possibility to use autonomous inverter with LC turn off circuits, having the advantage of the simplicity of the construction, in comparison with the schemes using turn off auxiliary thyristors. Design methodology of turn off groups for autonomous inverter with LC turn off circuit, is largely presented in literature. In the present paper are proposed expressions for designing the turn off groups, the coupling factor k_1 and the turn off coil parameters. The expressions for designing the turn off groups are calculated in the following stages: determination of the current expression $i_1(t)$ through the devices in the blocking stage and $i_2(t)$ through the devices in conduction; the calculation of the reverse polarization time, by solving a transcendental equation; the determination of the stored energy in the turn off coil and finally the expressions that result for the turn off inductivity L_S, respective for the turn off capacity C_S.**

Keywords-- reverse polarization, static commutation, turn-off group.

I. INTRODUCTION

Increasing the generation capacity of power generation systems leads to an increase in the fault current, which may exceed the maximum short-circuit currents supported by the switching equipment. Therefore, all equipment must be dimensioned so that the breaking power must be enough. Modern short-circuit current interrupting technologies use high-power static current limiters that provide a viable solution. In order to interrupt the current, static fault current limiters have to introduce very fast energy absorption devices into the circuit. Compared to mechanical circuit breakers, static circuit breakers based on high-power semiconductor devices offer some advantages in terms of switching speed and duration of use. In the case of a three-phase short-circuit, the fault duration may be limited to 100 ms, [1], [2].

During a short circuit, the use of semiconductor power devices can reduce short-circuit currents. Modern solutions using high-power semiconductors, such as the gate turn-off thyristor, are used to replace the mechanical circuits of the circuit breakers, [3], [4], [5]. The main drawback of the thyristors is that the turn-off is performed by forced commutation, by lowering the current below the maintenance current value [6], [7]. In AC networks, the natural commutation may last up to 10 ms, during which the voltage of the local network decreases strongly, leading to a power failure, so natural switching is not appropriate for the static commutation functionality. Due to its advantages, reduced power losses during the conduction process and reduced manufacturing costs, thyristors are further used in the static circuit breakers used to remove short-circuit currents [8].

II. BYPASS LIMITERS

Since a fault current limiter is series connected, it must be a low impedance device when the current is flowing under normal operating conditions. When a fault current occurs, its impedance must rise rapidly in order to limit the current flowing through the short-circuit impedance. Conceptually, all types of current limiters can be viewed as normally closed switches, having a parallel connected impedance. The type of the switch, the circuit and the impedance type may vary from one model to the other. The fault current limiter with resistance has its componence a fault current limiter and a switching device. Fig. 1 shows the configuration of a single-phase fault current limiter [9]. It consists of a bidirectional high-speed switch, built using semiconductor devices, a varistor and a snubber circuit to limit overvoltage, parallel connected to the current limiter.

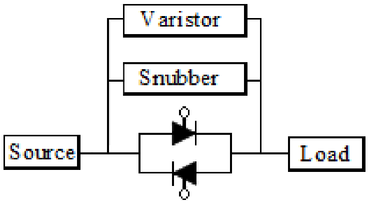

Figure 1. The fault current limiter with resistance

In normal operation conditions, the current flows constantly through the semiconductor devices and the control of the two thyristors is synchronized with the electric grid. Alternatively, the fault current limiter with resistance may be a bypass type, using an electromechanical breaker, in order to reduce conduction losses. The bypass switch is open when the fault current limiter must act. The switch is closed when the fault current reaches a preset maximal value I_{max} of the current, which must fit within the maximum currents limits that can be interrupted by the semiconductor device used. Further, the fault current will flow through the varistor.

The fault current limiter with series resonant circuit is designed with LC series circuits tuned to the fundamental frequency of the electric system. The fault current limiter series with resonant circuit and controlled thyristors limits the fault current by introducing a coil series connected in the power circuit. During normal permanent operation mode, when the frequency is close to the fundamental frequency, the resonant circuit has a very low impedance, and a very high one in fault conditions. This type of circuit is shown in Fig. 2 [9].

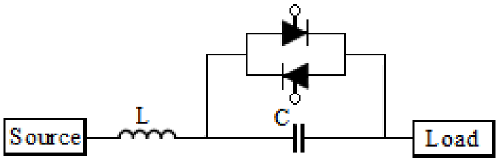

Figure 2. Fault current limiter with series resonant circuit and controlled thyristors

Since the fault current limiter is tuned to the supply voltage, the impedance in normal operating mode will be infinite.

III. THEORETIC CONSIDERATIONS

As mentioned earlier, the main issue of a continuous voltage system is the switching problem. Compared to natural switching, which is performed by the network or the load voltage, forced commutation is characterized by the necessary extinguishing energy, stored in capacities or soft-extinguished semiconductor devices such gate turn-off thyristors GTO's or insulated gate bipolar transistors IGBT's.

It is worth mentioning that in the circuits with constant voltage sources, the turned-on thyristors cannot be controlled to be turned-off, thus so-called extinguishing circuits are needed [10]. In designing the extinguishing groups of a thyristor by-pass circuit, it is necessary to consider the expression of self-induced voltage on the thyristor which is turned off and the coupling factor between the extinguishing coils.

Figure 3 shows a bypass circuit with L-C extinguishing circuit where T_1, T_2, T_3, T_4 - the main thyristors, L_1, L_2, L_3, L_4 - are the extinguishing coils C_1 , C_2, C_3, C_4 – the extinguishing capacitors, D_1, D_2, D_3, D_4 – the reverse current diodes and Z_r the load of the H bridge circuit. The load inductance is represented by impedance of the resonant circuit determined by the inductance L_S and the capacitors C_S. In the first stage the thyristors T_1 and T_2 are turned on, and until the current is canceled through the thyristor T_2, the differential equations characterizing the operation of the extinguishing circuit are:

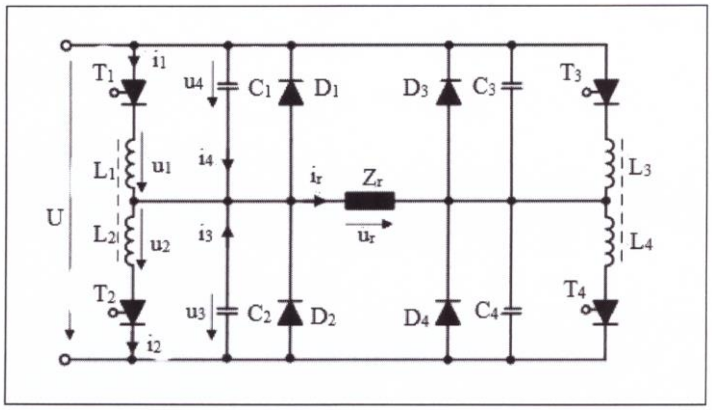

Figure 3. Bypass circuit with L-C extinguishing circuit

$$i_1 - i_2 + i_3 + i_4 - i_r = 0 \tag{1}$$

$$u_1 = U - u_2 = u_4 = L_s \frac{di_1}{dt} + M_s \frac{di_2}{dt}\ ;\ u_2 = u_3 = L_s \frac{di_2}{dt} + M_s \frac{di_1}{dt}\ ;\ u_3 + u_4 = U \tag{2}$$

where:

U – is the voltage in the continuous voltage circuit;

L_s – represents the self-inductance of the extinguishing circuit;

M_s – represents the mutual inductance of the extinguishing circuit.

By setting the conditions $i_1(0) = i_r$ and $u_3(0) = U$, from equations (1) and (2), the following expressions of currents and voltages result:

$$i_1(t) = i_r - \frac{U}{2(L_S - M_S)\omega_3}\sin(\omega_3 t) + \frac{U}{2(L_S + M_S)}t\ ;\ i_2(t) = \frac{U}{2(L_S - M_S)\omega_3}\sin(\omega_3 t) + \frac{U}{2(L_S + M_S)}t \tag{3}$$

$$u_3(t) = 0.5U\left(1 + \cos(\omega_3 t)\right) \tag{4}$$

where ω_3 represents the angular frequency, given by the relationship: $\omega_3 = \sqrt{\dfrac{1}{C_S(L_S - M_S)}}$

If the expression of the $\sin(\omega_3 t)$ is developed in a Taylor series expansion and neglecting the upper order terms, eqns. (3) and (4) become:

$$i_1(t) = i_r - \frac{U}{L_s}\cdot\frac{k_1}{1-k_1^2}t\ ;\ i_2(t) = \frac{U}{L_s}\cdot\frac{1}{1-k_1^2}t \tag{5}$$

where

- k_1 - represents the coupling factor between the extinguishing coils;
- t_1 - is the time during which the current flowing through the thyristor is canceled.

The expression of t_1 is given by the relation (6):

$$t_1 = \frac{i_r}{U}\cdot L_s \cdot \frac{1-k_1^2}{k_1} \tag{6}$$

IV. The Dependence of the Extinguishing Groups Versus the Coupling Factor

To increase the commutation speed, time t_1 must be as small as possible, thus the coupling factor as close to the unit. If time t_1 is zero, the slope of current through the thyristor T_2 would be infinite, therefore limiting the value of the coupling factor to not exceed the allowable value of the current slope through the thyristor. Fig. 2 shows the dependence of time t_1 versus the coupling factor.

The initial conditions for the calculation of the extinguishing groups are determined in the hypothesis of a unitary coupling factor.

$$\begin{cases} i_2(t) = i_r \\ u_3(t_1) = U \\ \sin(\alpha_1 - \omega_4 t_q) = 1/2\sin\alpha_1 \end{cases} \tag{7}$$

With these initial conditions, the voltage across capacitor C_2 becomes:

$$u_3(t) = U\frac{\sin(\alpha_1 - \omega_4 t)}{\sin\alpha_1} \tag{8}$$

At the moment $t = t_2$, when the voltage across the capacitor C_2 becomes negative, the diodes D_2 and D_4 turn in conduction. In order to obtain a higher power factor, the conduction time of the reverse current diodes must be as small as possible. This means that at the moment t_2, the energy accumulated in the coil L_2 must be minimal. The time interval in which the thyristor T'_1 will be in conduction automatically determines a larger conduction interval for the diode D2 conduction, during the commutation. From the relation (8) the value of the time interval t_2 is:

$$t_2 = \frac{\alpha_1}{\omega_4} \tag{9}$$

At the moment $t = t_2$, the energy stored in the coil L_2 is:

$$W_{L_2}\left(t_2\right) = \frac{U \cdot i_r \cdot t_q \left(2 - \cos\alpha_1\right)^2}{4 \sin\alpha_1 \cos\alpha_1 \left(\alpha_1 - \arcsin\frac{\sin\alpha_1}{2}\right)} \tag{10}$$

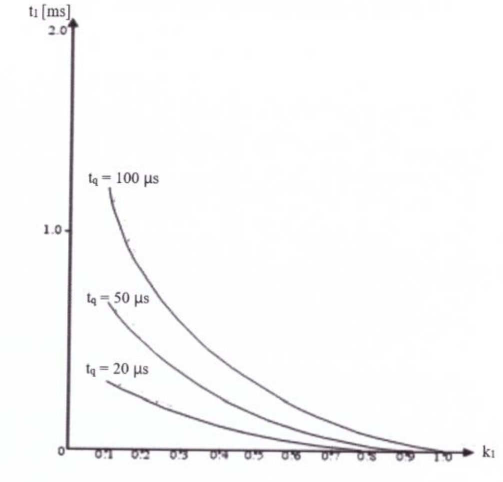

Figure 4. The dependence of the current cancellation time through the thyristor T_1 (front) versus the coupling factor k_1

Initial values of the extinguishing groups are given by the equation (11):

$$L_s = \frac{U \cdot t_q}{i_r \cdot k_2}\,;\; C_s = \frac{i_r \cdot t_q}{U \cdot k_3} \tag{11}$$

where k_2 and k_3 are constants.

Fig. 5 shows the variation of the magnetic energy stored in the coil L_S.

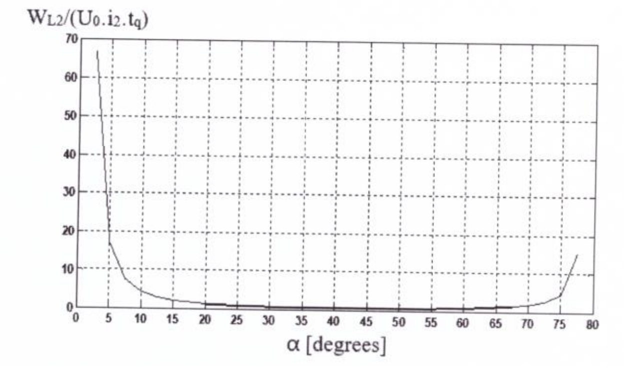

Figure 5. The variation of the magnetic energy stored in the extinguishing coil

V. CONCLUSIONS

For calculating the coefficients k_2 and k_3 an iterative calculation method is used. Starting from the initial conditions, the new values of the coefficients k_2 and k_3 can be determined for each coupling factor value between 0.6 and 1, with an increment $\Delta K_1 = 0.01$. The procedure is resumed until values of the coefficients k_2 and k_3 are obtained with an error lower than 0.01.

Starting from a minimum coupling factor $k_1 = 0.06$, the angle α_1 for which the function $f(\alpha_1, k_1)$ is minimal is determined, respectively the energy stored in the coil L_2 at the moment t_2, has the minimum value. With this value of the angle α_1, the new values of the coefficients k_2 and k_3 are calculated using the previously stored values. Iterations continue until between two consecutive values of k_2 and k_3, the error is less than the imposed value.

Fig. 6 shows the dependence of the coefficients with respect to the coupling factor.

$$k_2 = \frac{(1+k_1)\left(\alpha_1 - \arcsin\left(\frac{\sin\alpha_1}{(1+k_1)\beta}\right)\right)}{\frac{k_{1\beta}}{tg\alpha_1}},\quad k_3 = \frac{\beta\left(\alpha_1 - \arcsin\left(\frac{\sin\alpha_1}{(1+k_1)\beta}\right)\right)}{\frac{(1+k_1)tg\alpha_1}{2k_1}}. \tag{12}$$

Following the H-bridge by-pass circuits simulations, one can assert that both thyristor and IGBT’s circuits, limit the short-circuit current. The by-pass H-bridge circuits with thyristors has been analyzed and implemented because their control is simpler compared to IGBTs and the voltage used for these devices parallel-connected may be 220 kV or 440 kV.

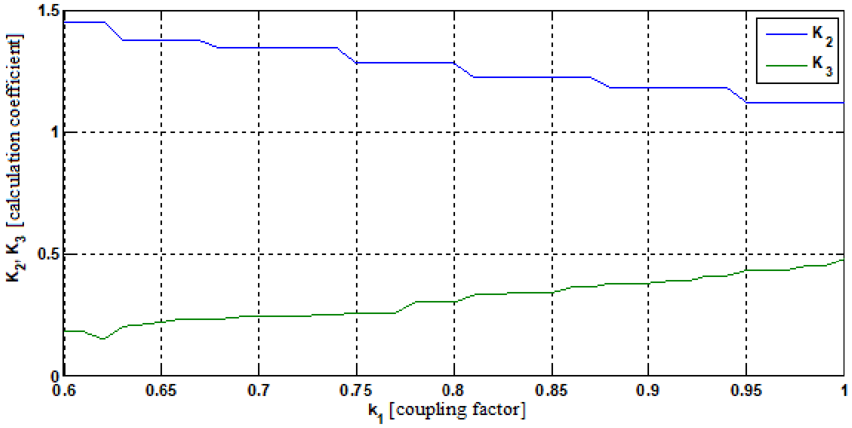

Figure 6. Calculation coefficients according to coupling factor.

REFERENCES

[1] Varodi, T., Balan, H., Pop, A.A., Buzdugan, M., “Diagnosis of short circuit and the earthing of a transformer station”, 12th International Conference on Applied and Theoretical Electricity, ICATE 2014; Craiova; Romania; 23 October 2014, through 25 October 2014; Category number CFP1499S-ART; Code 109581, Article number 6972613, ISBN: 978-147994161-2, DOI: 10.1109/ICATE.2014.6972613, Document Type: Conference Paper, Publisher: Institute of Electrical and Electronics Engineers Inc.

[2] Buzdugan, M., Bălan, H., Laslo, H., “Electromagnetic Compatibility Issues during Faults in Electric Power Systems”, Renewable Energy and Power Quality Journal (RE&PQJ), ISSN 2172-038 X, No.16, April 2018.

[3] Balan H., Buzdugan M., Sasu G., Munteanu A.R., Duță M., Iacob A., “Testing variable speed Driving Systems for conducted interference”, Proceedings CNAE 2010, Craiova, Romania, October 6-8, 2010, Section SAM-Acquisition Systems and Monitoring, ISSN 1842-4805.

[4] Balan H., Botezan A., Buzdugan M., Stefan Elena, Pîrv G., Karaissas P., “The off-line diagnose of automatic circuit breakers by the time domain and frequency vibration analysis”, Proceedings ICATE 2010, Craiova, Romania, October 8-9, section R2-Electrical Equipment and Technologies, paper ID 2.7., on CD.

[5] Stefan Elena, Balan H., Buzdugan M., Karaissas P., “Study of the DC voltage circuit breakers commutation with EMTPWorks software simulation” Proceedings ICATE 2010, Craiova, Romania, October 8-9, section R2-Applied Informatics in Electrical Engineering, on CD.

[6] Bălan, H., Botezan, A., Stefan, Elena, Cozorici, I., Chiorean, Cristina, Karaissas, P., “Commutation losses in HVDC systems converters” The National Symposium of Theoretical Electrotechnics, SNET’10, Bucharest, 3 – 4 December 2010, Proceedings Paper, (in Romanian).

[7] Balan H., Stefan E., Cozorici I., Botezan A., Karaissas P., “Converters used in HVDC systems. The study of switching” 3rd International Conference on Clean Electrical Power: Renewable Energy Resources Impact, ICCEP 2011, art. No. 6036318, pp. 600-603, ISBN: 978-142448928-2, DOI: 10.1109/ICCEP.2011.6036318, Document Type: Conference Paper.

[8] Buzdugan M.I., Balan H., Munteanu R., Munteanu R.A., “A Practical Procedure in Assessing Power Quality in Power Converters”, Book: Management of Technological Changes, ISBN:978-960-99486-2-3, Pages: 481-484, 7th International Conference on Management of Technological Changes, Alexandroupolis, GREECE, SEP 01-03, 2011, Publisher: Democritus Univ. Thrace, Document Type: Proceedings Paper.

[9] CIGRE WG 13.10, “Functional Specification for a Fault Current Limiter”, ELECTRA, 2001, no. 194, pp. 22-29, http://www.cigre.org.

[10] Kelemen, A., Imecs, M., “Power Electronics”, Didactic and Pedagogic Publishing House, Bucharest, 1983 (in Romanian).