THEORETICAL CONSIDERATIONS REGARDING THE CONTROL OF STATIC CONVERTERS WITH BIDIRECTIONAL OPERATION

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The paper presents theoretical and practical aspects regarding the choice of the control angle of the thyristors of a static converter so that it can operate bidirectional, in this case, in motor and braking regime. The transition from one regime to another can be achieved only under certain conditions, which the designer must take into account, these representing the object of this paper.

Keywords: energy efficiency; static converters; motor regime; braking regime

1. Introduction

Increasing the energy efficiency of industrial solutions in the source-load structure leads more and more often to the use of bidirectional converters so that the source-load, respectively load-source energy transfers will be achieved using a single static converter working in two or four quadrants.

The result of such an approach translates into low investment costs and last but not least into an increased reliability of the application.

The practical support of this article is the industrial application presented in Fig. 1. [1]

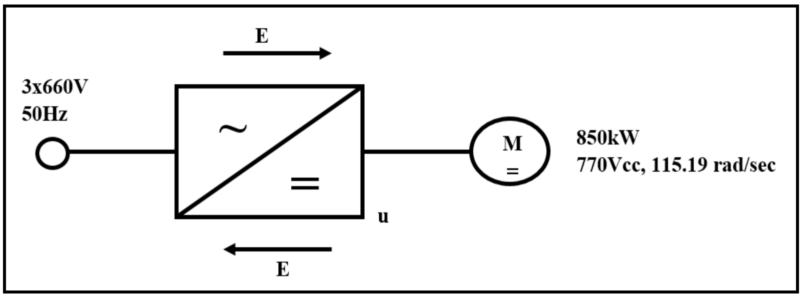

Fig. 1. DC motor drive

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In this application, the operating regimes of the direct current machine M are:

a) The motor regime in which the machine M receives energy from the power source 3x660V, 50Hz, the converter u operating in rectifier mode.

b) The braking regime in which the machine M releases energy to the energy source, the converter u operating in inverter mode.

According to the theory, in the above situation the same converter u operates in the two working modes (rectifier, respectively inverter), the control angle α of the thyristors used in its construction varying for natural switching as follows:

α € (0 ÷ 90°) for rectifier regime (theoretical range)

α € (90 ÷ 150°) for inverter regime (theoretical range)

What happens in the area α = 90°? What is the α_{max} limit for operation in rectifier mode? What is the minimum limit α_{min} for operation in inverter mode? These questions, from the point of view of energy efficiency and maximum reliability, are answered by a mathematical model developed for the optimal determination of the values of the α control angle of the thyristors, depending on the network and load parameters, model validated by the practice of this type of application. [2]

2. The maximum necessary control angle

In the case of using the same DC machine in motor and brake mode, the same AC / DC converter and the same AC connection voltage, it can be written: [3]

$$I_F = \frac{U_{d\,(\alpha max)} + C \cdot \Omega_F}{\Sigma R_{cc}} \tag{1}$$

Where:

$U_{d(\alpha max)} < 0$ - maximum inverter voltage

$$C = \frac{U_N - R_M \cdot I_N}{\Omega_N} \quad \text{- machine constant} \tag{2}$$

$$\Omega_F = \frac{2\pi}{60} n_F \quad \text{- angular speed in braking mode} \tag{3}$$

I_F - current in braking regime

I_N - nominal current of machine

U_N - nominal voltage

Ω_N - nominal angular speed of machine

$$I_M = \frac{U_{d(\alpha\ min)} - C \cdot \Omega_M}{\Sigma R_{cc}} \tag{4}$$

Where:

$U_{d(\alpha min)} > 0$ - maximum rectifier voltage

$$\Omega_M = \frac{2\pi}{60} n_M \tag{5}$$ - angular speed in motor mode

I_M - current in motor regime

In order to be able to cover both regimes with the same elements from the used solution, it results that the relation must be fulfilled: [1] [3]

$$I_M \left[U_{d0} \left(\cos \alpha_{max\ nec} - \frac{u_{sc}}{2} \cdot \frac{I_F}{I_{dN}}\right) + C \cdot \Omega_F\right] = I_F \left[U_{d0} \left(\cos \alpha_{min\ nec} - \right.\right.$$
$$\left.\left. - \frac{u_{sc}}{2} \cdot \frac{I_M}{I_{dN}}\right) + C \cdot \Omega_F\right] \tag{6}$$

Where:

$$U_{do} = \frac{3\sqrt{2}}{\pi} \cdot U_{ef} \tag{7}$$

$\alpha_{max\ nec}$ – maximum required control angle (inverter)
$\alpha_{min\ nec}$ – maximum required control angle (rectifier)
U_{ef} – effective value of the supply voltage

From this relation derive the restrictions regarding the limitation of α_{max}, n_{Fmax} and $U_{ef\ min}$.

For real typical conditions as:
$I_M = I_F = I_N$
$n_M = n_F = n_N$
Is obtained:

$$\alpha_{max\ nec} = \arccos\left(\cos \alpha_{min\ nec} - \frac{2 \cdot C \cdot \Omega_N}{U_{do}}\right) \tag{8}$$

Where the minimum required control angle $\alpha_{min\ nec}$ represents the control angle for which the rectified voltage in motor mode is equal to the nominal value of the induced voltage required for the motor at nominal load, taking into account the switching voltage drop. Thus, replacing cos $\alpha_{min\ nec}$, C and Ω_N and neglecting the voltage drop on the inductor, we can write: [1] [3]

$$\alpha_{max\ nec} \cong \arccos\left(\frac{u_{sc}}{2} - \frac{1}{U_{ef}^*}\right) \tag{9}$$

Where:
u_{sc} = short circuit voltage of the supply transformer

$$U_{ef}^{*} = \frac{U_{ef}}{U_{efo}} \qquad (10)$$

It was noted with U_{efo} the a.c. voltage connections (minimum) which ensures an ideal rectified voltage $U_{de\ min}$ equal to the nominal motor voltage:

$$U_{de\ min} = U_N = \frac{3\sqrt{2}}{\pi} \cdot U_{efo} \qquad (11)$$

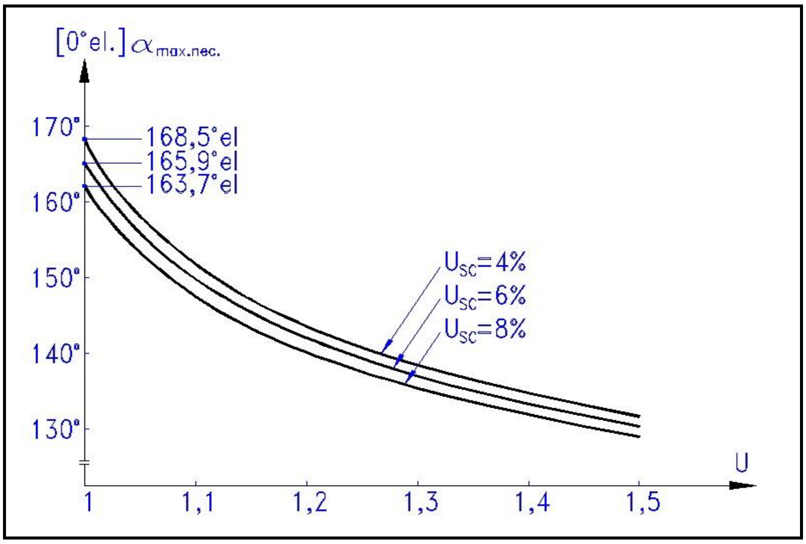

Fig. 2 - Variation of the angle $\alpha_{max\ nec}$

Fig. 2 shows the variation of the angle $\alpha_{max\ nec}$ depending on the variation of the supply voltage in relation to the nominal motor voltage for the typical conditions above. It is observed that the influence of the parameter u_{sc} is obvious in the area of the minimum allowed supply voltage. [4]

The maximum required value of the control angle in the inverter corresponds to the minimum supply voltage that ensures, at the limit, the nominal conditions in motor mode for $\alpha_{min} = 0$. [5]

So for:

$$U_N = \frac{3\sqrt{2}}{\pi} \cdot U_{ef\ min}\left(1 - \frac{u_{sc}}{2}\right) \qquad (12)$$

Where: u_{sc} = short circuit voltage of the supply transformer

It is obtained:

$$\alpha_{max\,nec} = arccos\left[u_{sc} - 1 + \frac{R_M \cdot I_N}{U_N}(2 - u_{sc})\right] \cong arccos(u_{sc} - 1) \quad (13)$$

For safe operation (safe switching) in inverter mode, this required maximum control angle must not exceed a permissible limit value.

$$\alpha_{\max nec} \leq \alpha_{\max lim} \quad (14)$$

From the calculations performed for an application with direct current motor 850kW, 770Vdc, 115.19 rad/sec, the following resulted:

a) for the nominal AC supply voltage (3x660V, 50Hz) and the short circuit voltages of the source transformer of 4%, the maximum value of the ignition angle (168.5°el) resulted;

b) for the same supply voltage with the short-circuit voltage 8%, a decrease of $\alpha_{max\ nec}$. of approximately 5°el was obtained;

c) this difference of 5°el was kept even in case of increasing the supply voltage on the whole range (1 ÷ 1.5) U_N.

Where:

U_N = nominal voltage of DC motor (770Vdc)

3. Limit control angle

For a given AC connection voltage, a certain DC current and for certain parameters of the power circuit, there is a maximum real control value (limit) for a three-phase bridge with thyristors, fully controlled and with ideal current filtering: [1]

$$\alpha_{\max lim} = \pi - \beta_{min} \quad (15)$$

$$\beta_{min} = \gamma_{max} + \omega t_q \quad (16)$$

Where:

γ_{max} – overlapping angle (switching) at maximum control angle

ωt_q – safe extinction angle

Practically β_{min}, taking into account the asymmetry of the control pulses due to the dispersion of the parameters of the control device on the gate, increases to the value:

$$\beta_{min\,real} = \beta_{min} + |\varepsilon| = k_{sig} \cdot \beta_{min} \quad (17)$$

Where:

$k_{sig} > 1$ – safety factor

$|\varepsilon|$ – permissible asymmetry of the impulse generator

In practice it is very important to know exactly the value of the maximum allowed angle (limit) which under the conditions of a certain used scheme and elements becomes the date of adjustment and protection for a safe operation of the braking equipment with recovery.

An exact evaluation of the maximum control angle α_{max}, compared to the value calculated in the formula (13) is obtained if we take into account the above conditions and the fact that the switching angle is dependent on the control angle including in the point $\alpha_{max}=\alpha_{max\_lim}$. [7]

$$\alpha_{\max lim} = \pi - \beta_{\min real} = \pi - \left(\gamma_{max} + \omega t_q + |\varepsilon|\right) \tag{18}$$

According to relation (18) can be determined the characteristic γ (α, I_d^*) which for a complete three-phase bridge is:

$$\gamma = \arccos(\cos\alpha - u_{sc} \cdot I_d^* - \alpha) \tag{19}$$

Where:
γ – switching angle
α – command angle
u_{sc} – the short-circuit voltage of the a.c. source

$I_d^* = \frac{I_d}{I_{d\,N}}$ – reported rectified current (20)

The command limit angle noted with $\alpha_{max\ lim}$ is:

$$\alpha_{max\ lim} = arccos[cos(\pi - \beta_{min\ 0\ real}) + u_{sc} \cdot I_d^*] = g(I_d^* \cdot u_{sc}) \tag{21}$$

Where it was noted: $\beta_{min\ o\ real} = \omega t_q + |\varepsilon|$, the value of $\beta_{min\ real}$ for the bridge operating without load.

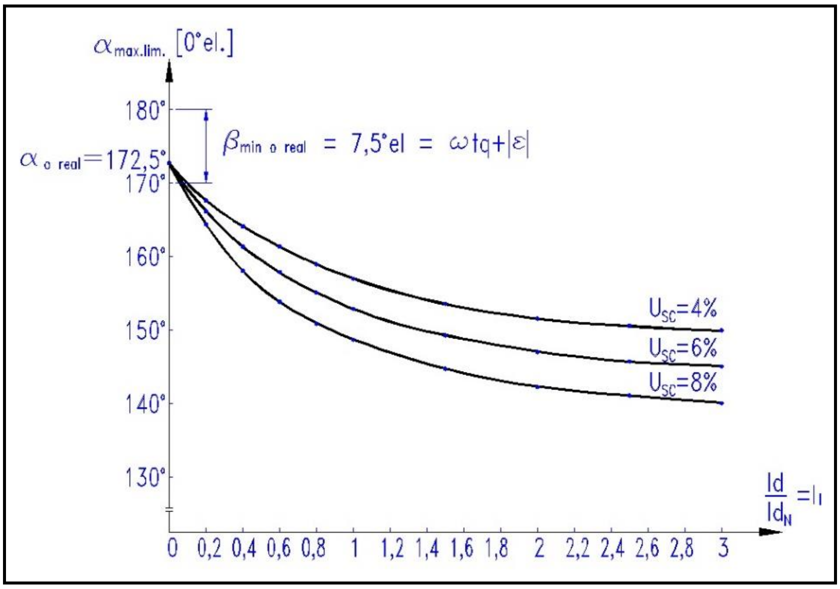

Fig. 3 – The characteristic $\alpha_{max\ lim}$ (I_{dr}) for a fully controlled three-phase bridge

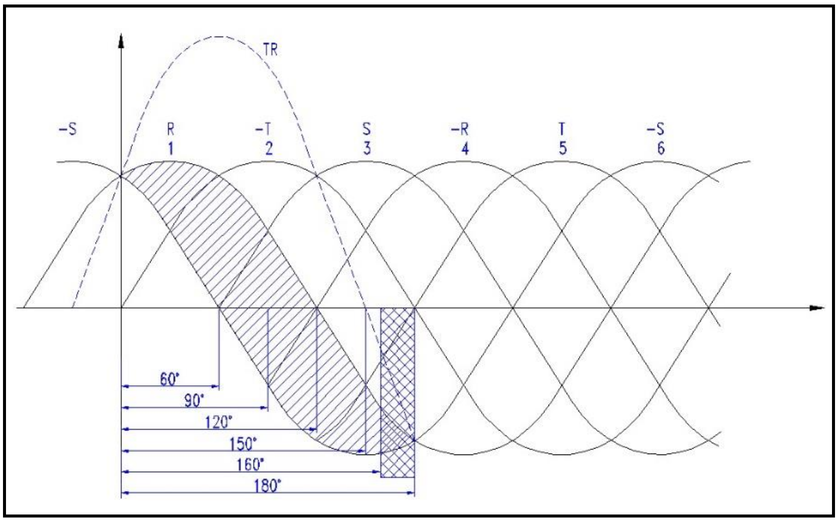

Fig. 4 – Voltage system

The characteristic $\alpha_{max\ lim}$ (I_d^*) having u_{sc} as parameter, for a fully controlled three-phase bridge and for a certain type of thyristor and control device on the gate, has the bearing from Fig. 3.

It is observed that, the higher the short-circuit voltage of the source, the control angle must be limited to lower values even below 150°el. The reference point in the setting is the point α = 150°el which represents for the voltage system in Fig. 4 the position of the control pulse for the thyristor R +, in the zero-crossing point of the line voltage TR. [8]

Depending on the data of the elements from Fig. 1 (AC supply, AC / DC converter and used motor), it is verified that the required control angle $\alpha_{max\ nec}$ does not exceed the limit value $\alpha_{max\ lim}$.

In case of non-fulfillment of this condition, either the braking speed in the sense of increase or the minimum allowed limit of the supply voltage in the sense of decrease is limited.

In order to determine the limit control angle by calculation, we took into account the following conditions:

a) The short circuit voltage of the source;

b) The charge (load) of the DC motor armature.

It is observed that for idle operation (zero load current), the calculations show that $\alpha_{max\ lim}$ = 172.5°el for any source with different short circuit voltage.

Instead, as the load current increases, a difference is observed between the $\alpha_{max\ lim}$ values in the sense of decreasing these values with the increase of the short-circuit voltage, the differences at the nominal current being 5°el.

In practice, validated experience, a difference $\Delta\alpha = \alpha_{max\ nec} - \alpha_{max\ lim}$ of at least two electrical degrees is used to have a maximum safety of the “separation” of the two rectifier / inverter operating regimes of the AC / DC converter associated with the DC motor. [8] [9]

4. Mathematical model

For example, we considered the following:

a) the power supply source has the following characteristics:

- rated supply voltage: U_N (660V_{ef});
- short circuit voltage u_{sc} (6%);

b) CA/CC converter SINAMICS – SIEMENS type, with the allowed asymmetry of the impulse generator |ε| (3%).

c) MCF 850 DC motor with the following characteristics:

- Nominal rotor voltage: U_{dN}=770V_{cc}.
- Nominal rotor current: I_{dN} = 1160A.

4.1 Calculation of $\alpha_{max\ nec}$ at nominal rotor voltage equal to 800VDC

According to relation (13) we have the following:

$$\alpha_{\max nec} = \arccos(u_{sc} - 1) = \arccos(\frac{6}{100} - 1) = \arccos(-0.94) = = 160°el \tag{22}$$

In accordance with Fig. 2, for $u = \frac{U_r}{U_{rn}} = \frac{800Vcc}{770Vcc} = 1.039 \cong 1.04,$ it is observed on the characteristic u_{sc}=6%, tha value of $\alpha_{max\ nec}$ equal to 160°el.

4.2 Calculation of $\alpha_{max\ lim}$ at nominal rotor voltage equal to 800VDC and $I_d = 0.6\ I_{dN}$

According to the graph in Fig. 3, for $I_d^* = \frac{I_d}{I_{dN}} = 0.6$ and u_{sc} = 6%, results a value for $\alpha_{max\ lim}$ equal to 158°el.

From relation (13) results the value $\alpha_{max\ lim}$, namely:

$$\alpha_{\max lim} = \arccos\left[\cos\left(\pi - \beta_{\min 0\ real}\right) + u_{sc} \cdot I_d^*\right] \tag{23}$$

$$\beta_{min\ 0\ real} = \omega t_q + |\varepsilon|, \tag{24}$$

Where:

ωt_q = command angle for safe extinction of the thyristor bridge

$|\varepsilon|$ = the allowed asymmetry of the impulse generator from the grid control device of the six thyristors from the fully controlled three-phase bridge.

From the theory but also from the practice of using three-phase bridge converters with fully controlled thyristors, it is known as:

ωt_q has the value of 12° for safe extinction of the thyristor bridge for an inductive load;

$|\varepsilon|$ has the value of about 3° (asymmetry of the impulse generator)

Replacing in relation (13) results:

$$\beta_{\min 0\ real} = \omega t_q + |\varepsilon| = 15° \tag{25}$$

$$\alpha_{max\ lim} = arccos[cos(\pi - 15°) + 0.06 \cdot 0.6] = arccos(cos165° + 0.036) = arccos(-0.965 + 0.036) = arccos(-0.929) \cong 158° \tag{26}$$

This difference $\Delta = \alpha_{\max nec} - \alpha_{\max lim} = 160° - 158° = 2°\ el,$ represents a sufficient value that ensures the total safety in the net differentiation between the rectifier and the inverter regime for the control in the bidirectional operation of the static converters with natural commutation. [5]

5. Conclusions

In the design and achievement of energy efficient solutions using static power converters and electric motors, it is possible to use braking with recovery.

Switching from one mode to another (engine-brake and vice-versa) is a challenge for any designer in terms of ensuring operational safety.

In practice, choosing the limits αmax, αmin is made by repeated tests, often with material losses, mainly safety fuses. The solution that is the object of the present paper is original, validated by practice.

The mathematical model developed in the paper is not found in any material from the specialized technical literature, being the result of equipment research, design and execution activities that works in marine and terrestrial drilling, in the operation of drilling solutions.

The influence of the variation of the connection voltage of AC on the maximum control angle required to control the braking current is highlighted and evaluated in the paper.

The paper presents an exact evaluation of the maximum control limit angle in the inverter, taking into account the particularities of the used scheme, the elements of the scheme, the dispersion of the parameters of these elements and the value of the load.

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