Theoretical Analysis of the Commutation Frequency Range for a PWM AC - to - DC Converter with Current Hysteresis Modulation

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Abstract *- The paper deals with some new researches concerning the theoretical analysis of the commutation frequency range for a PWM AC - to - DC converter provided with hysteretic current modulation. The concepts of the line-conditioning with the PWM DC converters associated with the appropriate power electronics are briefly presented. Also, there have been investigated the advantages of the dead-beat control application in this domain. Frequency and hysteresis variation laws have been deduced supposing different sampling methods of the input ac-line voltage and the current reference signal.*

Keywords – *Line-conditioning with DC converters, Dead-beat control, Frequency and hysteresis variation laws.*

1. INTRODUCTION

It is well known that the actual PWM DC converters [12] may be used not only as unity power factor rectifiers but also as power line conditioning equipment. They can work even with no load operating as power factor correctors or active filters.

The switching devices from the converters can be controlled using any asynchronous PWM strategy. This is a very simple and robust control method but it has a major drawback: the commutation frequency is not constant. This leads to very serious electromagnetic compatibility issues.

With the purpose to reduce the frequency variation range in the case of a PWM inverter it were investigated different adaptive hysteresis current control methods [2],[3],[4]. For the PWM AC – to - DC converters provided with current controlled voltage inverters in [5] and [7] is studied the effect of a linear modulation method of the hysteresis as a function of the input current reference signal. Good results are achieved in [6] where are presented more non-linear modulation methods and their careful investigation through simulation on a MATLAB-Simulink model.

Taking into account the importance of the problem, this paper investigates an analytical approach, appropriate to the development of predictive, closed-loop hysteresis controllers.

2. THE INVESTIGATED PWM AC - TO - DC CONVERTER

The block diagram of the investigated single-phase PWM AC-to-DC converter is presented in the Figure 1.

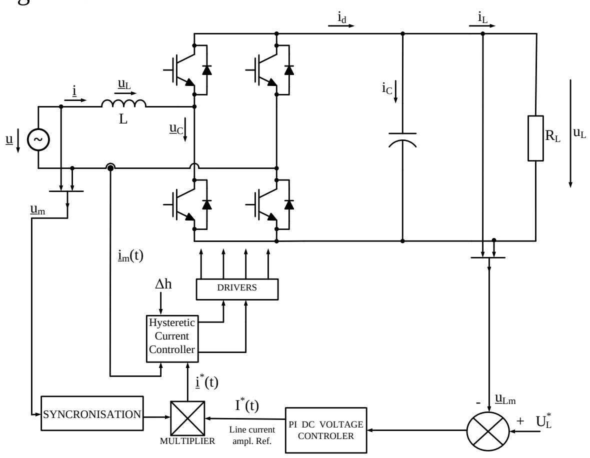

Figure 1. The block diagram of the converter (with constant hysteresis control)

The converter is based on a current controlled voltage inverter in rectifier operation mode.

Initially a current control system with a constant value of the hysteresis was investigated. This control system is also presented in the Figure 1.

Due to the drawbacks of the variable switching frequency it was considered a new improved control system that is presented in the Figure 2.

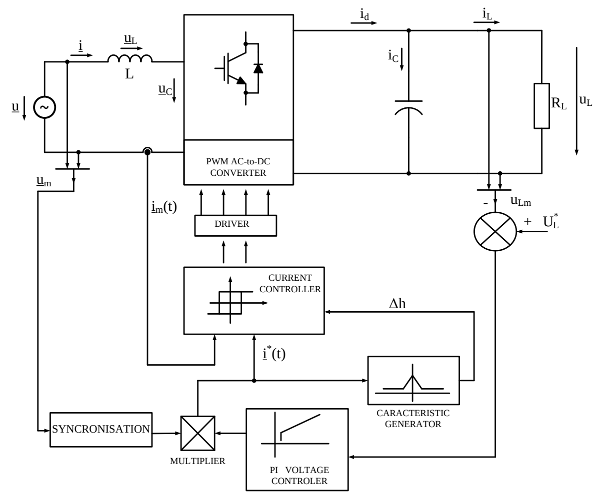

Figure 2. The block diagram of the converter controlled with hysteresis modulation

The characteristic generator modulates the hysteresis band in order to reduce the switching frequency range. The modulation methods that are controlling the operation of the characteristic generator are presented in previous papers [5], [6], [7].Moreover, the paper wants to determinate the variation law for the switching frequency and based on this to determinate a modulation method with superior performances.

3. COMMUTATION FREQUENCY RANGE ANALYSIS IN THE CASE OF THE UNIFORM SAMPLING OF THE INPUT VOLTAGE

In the reference [1] the variation law of the switching frequency for DC/DC converters was determined. The intention was to generalize it for AC/DC converters and based on this, to develop an automatic frequency control system, with superior commutation performances.

Therefore, a real time computation of the frequency could be done. Depending on it we will compute the hysteresis value so that the frequency is always maintained near a desired point. Figure 3, illustrates the commutation process supposing the natural physical time-variable voltage and current.

We begin our computation considering the general voltage written at the input equation of the converter:

$$L \cdot \frac{di(t)}{dt} = u(t) - u_c(t) - R \cdot i(t) \tag{1}$$

where, $u(t) = U\sin(\omega t)$ represents the mains voltage;

$i(t) = I\sin(\omega t)$ represents the input current of the converter;

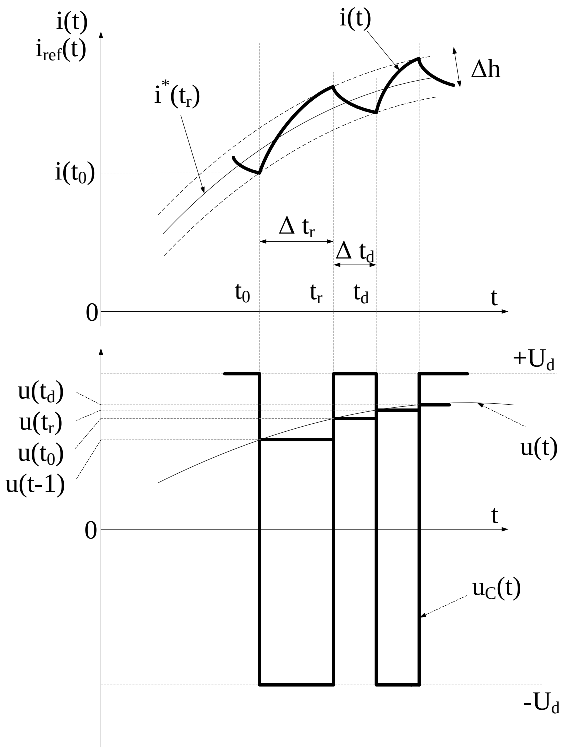

Figure 3. Uniform sampling of the input voltage and of the reference current

$u_c(t)$ represents the input voltage of the converter. It takes both the positive values and the negative ones, according with (2).

$$u_c = \begin{cases} -Ud, & \Delta i(t) \geq \dfrac{\Delta h}{2} \\ +Ud, & \Delta i \leq -\dfrac{\Delta h}{2} \end{cases} \tag{2}$$

where, U_d represents the output rectified voltage.

$\Delta i = i^*(t) - i(t)$, represents the deviation of the input current in respect to the reference current

Δh represents the hysteresis value.

The equation (1) describes the operation of the power electronics in every voltage pulse interval.

Solving equation (1) with the sampled value $u(t_0) = U_0$ we obtain:

$$i(t) = \frac{u(t) - u_c(t)}{R} \cdot (1 - e^{\frac{-(t-t_0)}{\tau}}) + i(t_0) \cdot e^{\frac{-(t-t_0)}{\tau}} \tag{3}$$

In order to obtain the variation of the frequency equation (3) must be solved, with the time as unknown variable. Considering the time variable we obtain the required frequency using f = 1/T.

However, we do notice that the line voltage and the reference current have a sinusoidal variation in time. Therefore, we cannot solve the equation in the same manner as in [1]. We have to make an approximately computation with an estimated sampled reference current and mains voltage.

Accepting that the reference current, respective the mains voltage varies very little between two successive commutations, we can agree that these are constant. We will do a uniform sampling of the current and the mains voltage.

Also, taken into account that the reference current, respective the mains voltage varies very little for short periods of time (e.g. the period between two commutations), we can simplify equation (3) by assuming that they remain constant during a considered period of time.

We have three sampling procedures:

1) the mains voltage and the reference current are constant between two successive commutations (uniform – asymmetrical sampling of the ac – voltage and reference current);

2) the mains voltage and the reference current are constant between three successive commutations (uniform – sampling of the ac – voltage and reference current);

3) the mains voltage is constant between two successive commutations and the reference current remains constant between three successive commutations (uniform asymmetrical sampling of the ac – voltage and uniform sampling of the reference current).

4. COMMUTATION FREQUENCY RANGE ESTIMATION SUPPOSING UNIFORM-ASYMMETRICAL SAMPLING OF THE INPUT AC-VOLTAGE AND REFERENCE CURRENT

We have Δt_r – rising time – the interval of time in which the current grows inside the hysteresis band and Δt_d – decreasing time – the interval of time in which the current decreases.

i(t) – the input current of the converter;
$i_{ref}(t)$ – the reference current;
u(t) – the mains voltage;
U_d – the output rectified voltage;

The period between two successive commutations is $T = \Delta t_r + \Delta t_d$.

Now the equation (3) can be solved. We can compute the lapses of time Δt_r and Δt_d and then determine the commutation period T, and the corresponding frequency:

$$f = \frac{1}{T};$$

For illustration we will compute the period of time (Figure 4),

$$T = t_1 - t_0 = \Delta t_r + \Delta t_d .$$

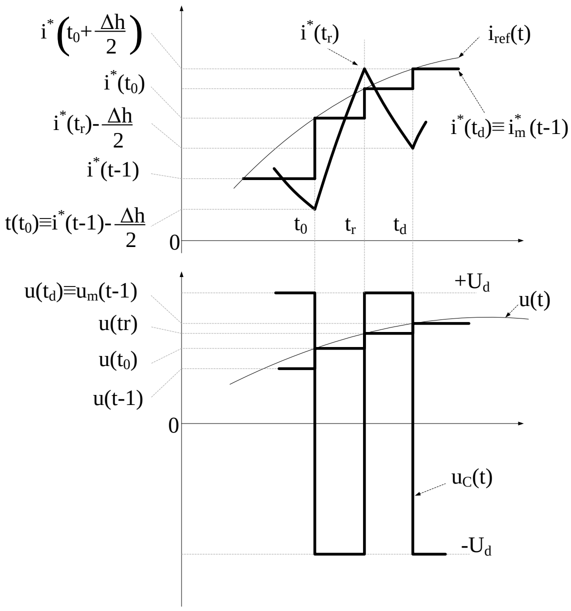

Figure 4. Uniform-asymmetrical sampling of the input ac-voltage and of the reference current.

At the beginning of every computation cycle, we have to determine the values of the reference current and mains voltage at the initial moment of time, t_0. These values can be easily deduced observing Figure 4.

$$i(t_0) = i^*(t_{-1}) - \frac{\Delta h}{2} = ct \tag{4}$$

$$i(t) = \frac{u(t_0)+U_d}{R}\cdot(1-e^{\frac{t-t_0}{2}}) + \left[i^*(t_{-1}) - \frac{\Delta h}{2}\right]\cdot e^{-\frac{(t-t_0)}{2}} \tag{5}$$

In order to determine Δt_r we have to write the equation (5) for the moment of time t_r.

$$i(t_r) = \frac{u(t_0)+U_d}{R}\cdot(1-e^{-\frac{\Delta t_r}{\tau}}) + \left[i^*(t_{-1}) - \frac{\Delta h}{2}\right]\cdot e^{-\frac{\Delta t_r}{\tau}} \tag{6}$$

where $i(t_r)$ is (according with Figure 4):

$$i(t_r) = i^*(t_0) + \frac{\Delta h}{2} = ct \tag{7}$$

Solving equation (6) with Δt_r as unknown variable we obtain:

$$\Delta t_r = \tau\cdot\ln\frac{i^*(t_{-1}) - \frac{\Delta h}{2} - \frac{u(t_0)+U_d}{R}}{i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_0)+U_d}{R}} \tag{8}$$

For the Δt_d computation we have the initial conditions:

$$i(t_r) = i^*(t_0) + \frac{\Delta h}{2} = ct$$

$$u(t_r) = U\sin(\omega \cdot t_r) = ct \tag{9}$$

$$u_c(t_r) = +U_d$$

As a result, we have obtained:

$$i(t) = \frac{u(t_r) - U_d}{R} \cdot (1 - e^{-\frac{t-t_r}{2}}) + \left[i^*(t_0) + \frac{\Delta h}{2} \right] \cdot e^{-\frac{(t-t_r)}{2}} \tag{10}$$

In order to determine Δt_d we have to write equation (5) for the moment of time t_d.

$$i(t_d) = \frac{u(t_r) - U_d}{R} \cdot (1 - e^{-\frac{\Delta t_d}{\tau}}) + \left[i^*(t_0) + \frac{\Delta h}{2} \right] \cdot e^{-\frac{\Delta t_d}{\tau}} \tag{11}$$

Considering $i(t_d) = i^*(t_r) - \frac{\Delta h}{2}$ we find Δt_d:

$$\Delta t_d = \tau \ln \cdot \frac{i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R}}{i^*(t_r) - \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R}} \tag{12}$$

$$T = \frac{1}{f} = \Delta t_r + \Delta t_d$$

Because of:

$$T = \tau \cdot \ln \cdot \frac{\left[i^*(t_r - \frac{\Delta h}{2} - \frac{u(t_0) + U_d}{R} \right] \cdot \left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R} \right]}{\left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_0) + U_d}{R} \right] \cdot \left[i^*(t_r) - \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R} \right]} \tag{13}$$

and

$$e^{\frac{1}{\tau \cdot f}} = \frac{\left[i(t_{-1)} - \frac{\Delta h}{2} - \frac{u(t_0) + U_d}{R} \right] \cdot \left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R} \right]}{\left[i(t_0) + \frac{\Delta h}{2} - \frac{u(t_0) + U_d}{R} \right] \cdot \left[i^*(t_{-1}) - \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R} \right]} \tag{14}$$

The frequency is obtained easily: $f = \frac{1}{T}$

Due to this algorithm we can compute the frequency in real time. Depending on the frequency value, we compute the hysteresis value so that the frequency is always maintained inside of a desired domain.

The necessary value of hysteresis is computed at the end of each period T.

We have to solve the equation (14), with Δh as unknown variable. For simplicity we make the following notations:

$$\frac{\Delta h}{2} = x \tag{15}$$

$$i(t_{-1}) - \frac{u(t_0) - U_d}{R} = a \tag{16}$$

$$i(t_0) - \frac{u(t_0) + U_d}{R} = b \tag{17}$$

$$i(t_0) - \frac{u(t_0) - U_d}{R} = c \tag{18}$$

$$e^{\frac{1}{\tau \cdot f}} = d \tag{19}$$

$$i^*(t_r) - \frac{u(t_r) - U_d}{R} = k \tag{20}$$

We can consider that d is approximately 1. Equation (14) becomes:

$$1 = \frac{(a - x)(c + x)}{(b + x)(k - x)} \tag{21}$$

Therefore the estimated value for the hysteresis of the controller becomes:

$$x = \frac{b \cdot k - a \cdot c}{a - c + b - k} \tag{22}$$

The equation (22) is not difficult to implement in practice.

5. COMMUTATION FREQUENCY RANGE ESTIMATION SUPPOSING UNIFORM-SYMMETRICAL SAMPLING OF THE INPUT AC-VOLTAGE AND OF THE REFERENCE CURRENT

In order to find the most practical and, at the same time, accurate method to compute the switching frequency we will make an uniform – symmetrical sampling of the input ac – voltage and reference current. Figure 5 presents currents and voltages in the case of this method.

According to the Figure 5, the initial conditions are the following:

$$i(t_0) = i^*(t_{-1}) - \frac{\Delta h}{2} = ct$$

$$u(t_0) = U\sin(\omega \cdot t_0) = ct \tag{23}$$

$$u_c(t_0) = -U_d$$

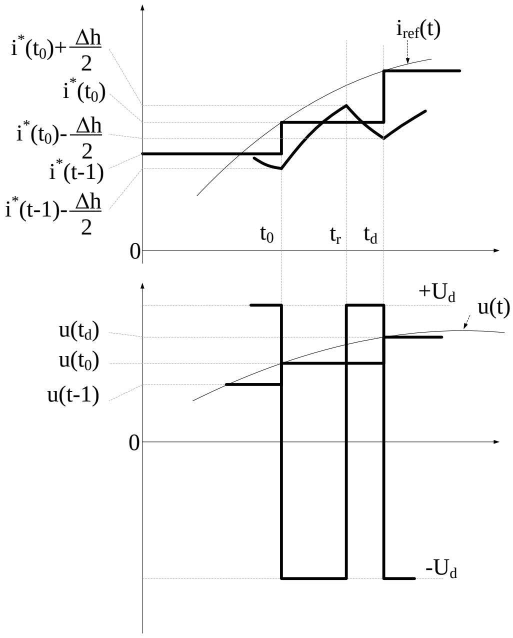

Figure 5. Uniform-symmetrical sampling of the input ac-voltage and of the reference current

Replacing these values in equation (3) we obtain:

$$i(t)=\frac{u(t_0)-U_d}{R}\cdot(1-e^{-\frac{t-t_0}{2}})+\left[i^*(t_{-1})-\frac{\Delta h}{2}\right]\cdot e^{-\frac{(t-t_0)}{2}} \quad (24)$$

and considering $i(t_r)=i^*(t_0)+\dfrac{\Delta h}{2}$, we can determine:

$$\Delta t_r=\tau\cdot\ln\frac{i(t_{-1})-\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}}{i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}} \quad (25)$$

$$i(t_d)=i^*(t_0)-\frac{\Delta h}{2} \quad (26)$$

$$\Delta t_d=\tau\ln\cdot\frac{i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}}{i^*(t_0)-\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}} \quad (27)$$

The period of commutation $T=t_2-t_0$ is equal to the sum between Δt_r and Δt_d, as can be observed in Figure 5. With the help of (25) and (27) it results:

$$T=\Delta t_r+\Delta t_d=\tau\cdot\ln\cdot\frac{\left[i(t_{-1})-\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}\right]\cdot\left[i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}\right]}{\left[i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}\right]\cdot\left[i^*(t_0)-\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}\right]} \quad (28)$$

The frequency is now easily to be obtained:

$$f=\frac{1}{T} \quad (29)$$

Considering the commutation period T, we can now compute the necessary value of the hysteresis. Taking into account the relation (29) we write the equation (27) as follows:

$$\frac{1}{\tau\cdot f}=\ln\frac{\left[i(t_{-1})-\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}\right]\cdot\left[i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}\right]}{\left[i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}\right]\cdot\left[i^*(t_0)-\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}\right]} \quad (30)$$

Or, in the exponential form:

$$e^{\frac{1}{\tau\cdot f}}=\frac{\left[i(t_{-1})-\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}\right]\cdot\left[i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}\right]}{\left[i^*(t_0)+\dfrac{\Delta h}{2}-\dfrac{u(t_0)+U_d}{R}\right]\cdot\left[i^*(t_0)-\dfrac{\Delta h}{2}-\dfrac{u(t_0)-U_d}{R}\right]} \quad (31)$$

We have to solve the equation (30), with Δh as unknown variable. For simplicity we make the following notations:

$$\frac{\Delta h}{2}=x \quad (31)$$

$$i(t_{-1})-\frac{u(t_0)+U_d}{R}=a \quad (32)$$

$$i(t_0)-\frac{u(t_0)+U_d}{R}=b \quad (33)$$

$$i(t_0)-\frac{u(t_r)-U_d}{R}=c \quad (34)$$

$$i(t_1)-\frac{u(t_r)-U_d}{R}=k \quad (35)$$

$$e^{\frac{1}{\tau\cdot f}}=d \quad (36)$$

We can consider that d is approximatively 1.
Based on the above introduced abbreviations, the equation (30) becomes:

$$1=\frac{(a-x)(c+x)}{(b+x)(k-x)} \quad (37)$$

As a result, the appropriate hysteresis value is possible to be determined easily in the case of this sampling procedure too:

$$x = \frac{ac - bk}{b + c - a + k} \tag{38}$$

6. COMMUTATION FREQUENCY RANGE ESTIMATION SUPPOSING UNIFORM-ASYMMETRICAL SAMPLING OF THE INPUT AC-VOLTAGE AND UNIFORM SAMPLING OF THE REFERENCE CURRENT

The sampling of the ac – voltage remains the same as in section 4, that is, uniform asymmetrical sampling but for the reference current we will do a uniform sampling. We consider that this method is more accurate than the one presented in section 5, as the value of the input ac-voltage is computed more frequently, at every commutation. Figure 6 presents this method based on the specific electric parameters.

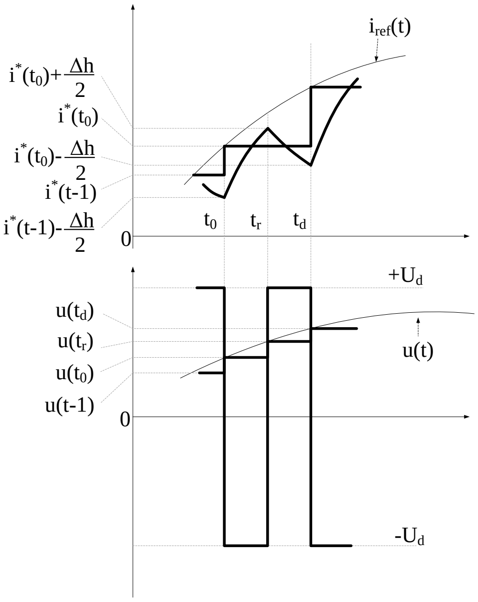

Figure 6. Uniform-asymmetrical sampling of the input ac-voltage and uniform sampling of the reference current**.**

The computation is very similar to the one presented in the previous sections. The obtained solutions for the rising time, respective the decreasing time are:

$$\Delta t_r = \tau \cdot \ln \frac{i(t_{-1}) - \frac{\Delta h}{2} - \frac{u(t_0) + U_d}{R}}{i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_0) + U_d}{R}} \tag{39}$$

$$\Delta t_d = \tau \cdot \ln \cdot \frac{i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R}}{i^*(t_0) - \frac{\Delta h}{2} - \frac{u(t_r) - U_d}{R}} \tag{40}$$

The commutation period is $T = \Delta t_r + \Delta t_d$

Finally we obtain the following two equations:

$$T = \frac{1}{f} = \tau \cdot \ln \cdot \frac{\left[i(t_{-1}) - \frac{\Delta h}{2} - \frac{u(t_0)+U_d}{R}\right] \cdot \left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_r)-U_d}{R}\right]}{\left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_0)+U_d}{R}\right] \cdot \left[i^*(t_0) - \frac{\Delta h}{2} - \frac{u(t_r)-U_d}{R}\right]} \tag{41}$$

$$e^{\frac{1}{\tau \cdot f}} = \frac{\left[i(t_{-1}) - \frac{\Delta h}{2} - \frac{u(t_0)+U_d}{R}\right] \cdot \left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_r)-U_d}{R}\right]}{\left[i^*(t_0) + \frac{\Delta h}{2} - \frac{u(t_0)+U_d}{R}\right] \cdot \left[i^*(t_0) - \frac{\Delta h}{2} - \frac{u(t_r)-U_d}{R}\right]} \tag{42}$$

In order to find the necessary value of the hysteresis, we make the similar notations:

$$\frac{\Delta h}{2} = x \tag{43}$$

$$i(t_{-1}) - \frac{u(t_0) + U_d}{R} = a \tag{44}$$

$$i^*(t_0) - \frac{u(t_r) - U_d}{R} = b \tag{45}$$

$$e^{\frac{1}{\tau \cdot f}} = d \tag{46}$$

Therefore equation (145) can be written as follows:

$$d = \frac{(a - x) \cdot (b + x)}{(a + x) \cdot (b - x)} \tag{47}$$

We can consider that $d \approx 1$ equation (47) becomes:

$$(a - b) \cdot x - (a - b) \cdot x = 0 \, , \forall \; x > 0 \tag{48}$$

7. CONCLUSIONS AND OUTLOOKS

We developed an algorithm that computes the switching frequency or the appropriate value for the hysteresis in real time. Based on this algorithm, we have developed a new control system for the commutation frequency, with the help of hysteretic modulation. This control system will be investigated in other, new papers.

It is indicate to resume here the proposed hysteresis control possibilities. On the one hand, based on the equations (13), (30) or (41) it can be computed the actual operation frequency of the converter. Then, with the help of a slow frequency controller, characterized by a large stationary deviation becomes possible to determinate the hysteresis for the next PWM cycle. On the other hand, the equations (14), (31) or (42) allow the prediction of the hysteresis for the next PWM cycle, according to the operation frequency and the hysteresis computed for the actual cycle.

The next step of our researches is to implement in a MCU system the algorithm which computes the actual value of the frequency or the actual hysteresis value with the help of the switching frequency analysis. Finally we would test our control system as a practical experiment on a laboratory model.

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