A methodology for determining commutation quality indicators when using a PWM power source for an electric drive

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Abstract – This paper presents a methodology and structure for analyzing some important indicators of the optimal commanding of PWM power source for electric drives. In many practical situations it is necessary to have a wide range of speeds for the asynchronous motor of electric drives. In order to obtain optimal command and control of the rotor speed, frequency and amplitude modulation factors have to be carefully chosen. A complete analysis is necessary with the aid of the Fourier Transform that can be in many cases too time consuming and computational complex. The present article tries to identify and avoid these situations.

Keywords: PWM, commutation, modulation, sawtooth wave, asynchronous motor

I. INTRODUCTION

Numerous electric drives based on asynchronous AC motors with squirrel-cage rotor need speed regulation for a wide range of values. On this line, a PWM based power supply is used. Usually, such a power supply involves a carrier signal (usually, a sawtooth wave) and a modulator signal (for example „discontinuous modulating functions” realized by „bus clamping technique”) having the frequencies $f_c$, $f_m$, and modulation factors $mf$ (frequency) and $ma$ (amplitude). The inverter of the PWM based power supply in this case is fed from a DC power supply having a constant voltage $V_d$. In addition, a few constraints are imposed: the sawtooth wave carrier signal (with symmetric teeth, asymmetric left/right teeth) maintains its amplitude constant (eventually having the possibility to modify it) and also its frequency $f_c=constant$. These constraints imply that for a given $mf$ and a certain frequency respectively, a proper value for $ma$ has to be found in order to satisfy $U_{ff}=constant$ at the specified frequency. This constraint is necessary in order for the AC motor to be kept out of the magnetic saturation regime. Nowadays, numerous applications are using PWM based inverters, especially in high-efficiency, low consumption systems (renewable energy systems) [1,2,3]. Obtaining good simulation results leads to implementation with the aid of specialized hardware, like Digital Signal Processors [2], high-performance microcontrollers [4] or FPGA [5].

II. MODELING PWM POWER SUPPLY

In the same direction, optimizing PWM as a power supply for an electric drive assumes defining and utilizing modulation quality indicators. The works [6,7] assert that these indicators must refer to two specific groups: harmonic distortion factors and asymmetry factors. These are necessary in order to control the negative effects of distortions and asymmetry. The present study focuses on the first group. This is motivated by the fact that the study uses only a simulation of the PWM based electric drive with no direct physical command to semiconductor devices that constitute an inverter bridge, in consequence there is no possibility that asymmetry errors occur.

Such a simulated PWM based power supply could be structured with the aid of three subsystems, as shown in fig. 1. The three subsystems are described below:

- **A area** – represents the subsystem corresponding to the modulating signal, realized by a MATLAB Function block and can include one or multiple modulating signal types. In this final case choosing the modulating signal is made from outside the MATLAB block by a specific indicator or a Multiport switch block. Defining the carrier signal with the aid of a MATLAB Function is easier than using Simulink libraries because a complex form modulating signal (like discontinuous functions) are very hard to implement this way as opposed to writing an equivalent MATLAB Function.

- **B area** – is the subsystem that creates (forms) the carrier signal (usually as a sawtooth wave signal with symmetric saw teeth), a task easily accomplished with Simulink blocks. Some parameters, like working frequency, frequency modulating index, the amplitude of signals saw-teeth as well as the clock signal are specified from outside the subsystem.
C area – creates with the aid of „Relay” type blocks (modified in order to model the dynamic behavior) PWM signals for the three phases of the power supply.

Figure 1. Subsystems for the PWM power supply

The three areas presented form the so-called simulated PWM power supply which can be included in a single block as shown in fig. 2. Inputs to this block are distributed to internal subsystems according to fig. 1 and the outputs are actually the three phases that feed a three-phased load.

A. About commutation quality indicators

In literature [6,7] there are presented many types (V1,...,V5) of discontinuous modulating functions that can be used for an optimized commutation of the solid state components of the inverter in order to obtain a PWM signal. In addition to the five types it is possible to add a sinusoidal signal combined with the 3rd harmonic and maybe a pure sinusoid. The optimization process aims the power dissipation of the solid state components of the inverter, quantified by the power dissipation index. The most important factor in choosing a type of modulating function is constituted by the mean power factor of the given electric drive that is fed by the PWM power supply.

Harmonic distortion factors that are considered in this study can influence mainly the following parameters:

- power loss in the windings of the motor drive.
- power loss in the magnetic core of the motor.
- torque ripple (pulsation, variation) of the motor shaft.

All the aforementioned effects are based on the equivalent scheme of the asynchronous AC motor and finally the next quality indexes are established:

\[
IC_2 = \sum_{k=2}^{\infty} \frac{U(k)^2}{k^{3/2}} \frac{U(1)^2}{U(1)^2}
\]

\[
IC_3 = \sum_{k=2}^{\infty} \frac{U(k)^2}{k} \frac{U(1)^2}{U(1)^2}
\]

where:

- \(IC_k\) is the quality index of order \(k\).
- \(U(k)\) is the effective value or the amplitude of the \(k^{th}\) harmonic of the voltage (phase voltage of the motor).
- \(k\) is the order of the voltage harmonic.

Relations (1), as stated in [6,7] can be utilized in the evaluation of the quality of the modulation signals of different types used by the PWM source as well as other parameters. Aforementioned relations take into account an infinite number of harmonics, but in practice it is recommended [6,7] to consider harmonics at most 6 kHz or above 20 kHz in order to avoid the domain of audio frequency. For example, considering a working frequency of 40Hz, a maximum number \(mf\) =147 would result, because \(f_c=40\cdot mf=40\cdot 147=5880Hz \leq 6kHz\). In addition, the amplitude of the fundamental will have a value of 311\(\cdot\)40/50=248.8V, where the value 311=220\(\sqrt{2}\) represents the amplitude of the DC source that feeds the PWM inverter.

If \(mf \in N\) than it is the case of a synchronous modulation, as opposed to \(mf \in R\) when the modulation is called asynchronous. On the other hand, if the modulation index is divided by 3 (147/3=49), than during the modulation process, the 3rd upper harmonic and its multiples are strongly reduced.

The PWM pulse train produced by the PWM power supply on each output is non-sinusoidal but has a periodicity that allow to decompose it by Fourier series that will provide its fundamental and a series of upper harmonics. In practice, a FFT (Fast Fourier Transform) analysis take into account a number of 25-30 upper harmonics. The precision of a FFT analysis is
proportional to the number of harmonics considered, although a big number of harmonics implies a great computational effort that can be overwhelming.[8]

B. A model for adjusting $ma$ and computing quality indicators

From the ideas presented hitherto, it is clear that a relevant study of the commutation quality indicators (as the one in (1)) takes into account a number of constraints that can be fulfilled only by a specific value for the modulation coefficient $ma$, value that it is not known beforehand (not even approximately). Such a study presumes a well-defined methodology and respectively an optimal working strategy in order not to waste precious computing time (because usually many simulations are necessary).

Such a structure is presented in fig. 3. This structure permits simultaneous adjustment to be made to the amplitude modulation factor $ma$ and selection of the quality indicators. The structure presented is divided in specific areas that are discussed next:

- **section A** – represents a MATLAB Function that models a PWM signal, providing multiple modulating functions: pure sinusoid, sinusoid with 3rd harmonic added, type 3 of modulating function (from V1...V5 types), type 5 of modulating function (from V1...V5 types).

- **section B** – implements FFT analysis that considers 50 upper harmonics of the fundamental (its frequency is given in section J) and computes the quality indicators $IC_1$, $IC_3$, and $IC_5$, the amplitude of the fundamental, DC component (Direct Current) and THD (Total Harmonic Distortion).

- **section C** – permits the selection of the modulating factor $ma$. A smaller initial value for $ma$ with respect to its final value can lead to a smaller computing time. MS1 block (Manual Switch) set on its upper position permits using an already known value of the amplitude modulation factor $ma$ in order to determine quality indicators.

- **section D** – displays permanently $ma$ value, after the simulation ends, its final value can be extracted.

- **section E** – displays permanently the values of the quality indicators $IC_2$, $IC_3$, $IC_5$, its final value can be extracted also after the simulation ends.

- **section F** – displays permanently the values of the DC component and THD, again its final values can be extracted after the simulation ends.

- **section G** – continuously displays intermediary values for the fundamental in proportion to the incrementing value of $ma$ as well as its computed value (a precision of 0.02[V] has been imposed), the two values being displayed nearby for a better comparison.

- **section H** – is responsible for stopping the simulation when the condition below is fulfilled:

$$|f_{calc} - f_{det}| \leq 0.02,$$  \hspace{1cm} (2)

with the ascertation that the value 0.02 [V] can be modified (increased or decreased) taking into account the incrementing step for $ma$.

- **section I** – records through the Scope block the signal for a single phase that is produced by the PWM block during the entire simulation; the Scope block is configured for recording its input signal in “workspace” for an ulterior FFT analysis using “powergui” block. Such an analysis has to be careful made because all the signal evolution is recorded, including the transient time.

- **section J** – assigns the input values for the PWM block A.

III. RESULTS OBTAINED THROUGH SIMULATION

Because of the nonlinear character of the process, it can be observed that:
• optimum values for the quality indicators increase at higher values of \( m_f \), as the working frequency decreases.

• \( m_a \) decreases in the same manner along with the working frequency, such that the condition \( U/f=\text{constant} \) is met.

An important aspect can be underlined, that the variation of \( m_f \) does not imply important modifications of the fundamental frequency. From the definition of the modulation factor, it can be stated that:

\[
f_p = m_f \cdot f_m
\]

and considering the structure presented in fig. 3 for calculating the quality indicators with the modulating function type 3 and a decrementing step of 5 Hz (50-30 Hz domain), the results presented in Table 1 have been obtained.

Table 1 presents the optimum results with „opt” marking and close to optimum results with grey zone („gz”) marking. From the table results that the mean value of the carrier frequency is 5438.25Hz, so a rounded value \( f_p=5500 \) Hz can be admitted (it fulfills the constraint \( < 6 \) kHz) for the entire domain of working frequencies. In a more general case, a weighting function can be used that considers the specific working frequency in order to determine the final carrier frequency. This value will reside at least in the grey zone of every working frequency, an important result of this type of FFT analysis.

Once a carrier frequency is established for the entire working frequency domain, modulation factor \( m_a \) has to be determined such that \( U/f=\text{constant} \) constraint is fulfilled (the condition of normal working regime, applicable to the entire working frequency range). A series of functions \( F(m_f)=m_a \) can be defined for the full working frequency range that will allow an automatic control for the PWM system when an extended working frequency range will be necessary.

But more important is to establish a relation for computing \( m_a \) as a function of the working frequency subject to a fixed carrier frequency (for example \( f_p=5500\) Hz and respectively \( m_f=5500/f_{\text{work}} \)). Fig. 4 presents the graph for \( m_a=f(f_{\text{work}}) \) described by a 4th order polynomial having very small residuals. Such an approximation assures for a working frequency of 32.5 Hz an amplitude modulating factor \( m_a=0.561 \), provided that for an \( f_{\text{work}}=30\) Hz corresponds a factor \( m_a=0.519 \) and a fundamental amplitude of 187.3V.

The values for the optimum quality commutation indicators will not have their calculated values listed in Table 1, but adjacent values that will assure good conditions for a working asynchronous AC motor controlled by a PWM based electric drive and a type 3 modulating function as presented before.

<table>
<thead>
<tr>
<th>Working frequency [Hz]</th>
<th>Carrier frequencies [Hz]</th>
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<tbody>
<tr>
<td>50</td>
<td>5500 Hz</td>
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<tr>
<td>45</td>
<td>5495 Hz</td>
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<tr>
<td>40</td>
<td>5400 Hz</td>
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<td>35</td>
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<td>5580 Hz</td>
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<td></td>
<td>5590 Hz</td>
</tr>
</tbody>
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An extended set of modulating functions can be tested having a structure and analysis methodology as the one in fig. 3, for example with the addition of 3rd harmonic for which the next statements can be made:

• the gray zone („gz”) - extends on the whole analyzed working frequency interval, such that any value for \( m_f \) can be considered as a working value, because all the analyzed parameters are practically identical (situation not encountered before);

• quality indicators \( IC_2, IC_3, IC_5 \) in this case are superior to the previous case (a more precise setting had to be used for the simulation: max step = 0.000015 and relative tolerance = 1e-4 having a longer running time)

• in general, it can be concluded that the case of using a modulating function with the addition of the 3rd harmonic is better than the case presented before, mainly because it doesn't necessitates a precise modulating factor \( m_f \) for a working frequency in order to obtain optimum quality indicators.

![Graph of mar=f(work) and its polynomial approximation](image)

**IV. CONCLUSIONS**

Many electric drives based on squirrel-cage rotor AC asynchronous motors need speed control for extended ranges that presupposes modifying supply voltage frequency also for an extended range. This situation implies the use of an inverter with a PWM power supply for which some constraints regarding the
modulating and carrier functions (or signals) characterized by their frequency modulating \((mf)\) and amplitude modulating factors \((ma)\) are imposed.

Choosing a certain type of modulating function presupposes that the mean power factor for the electric drive is known and also that an analysis of some quality commutation indicators of the inverter is made. The system has a pronounced non-linear character such that the analysis mentioned before need a certain methodology with regard to the simulation time especially that a great number of simulations have to be made in order to have adequate results. The study presented analyses the most important aspects of this approach and suggests some solutions concerning the computation and the analysis of quality commutation indicators in optimal conditions. The solutions are opened to improvement as a working methodology and also as simulating workspace, taking into account the importance of such studies.

REFERENCES