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Generalized calculation expressions for the pre-commutation current in PWM control of the second kind (PWM2)

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ABSTRACT. The article presents the issue of pre-commutation current analysis in an arbitrary value of the parameter n, and under the change in load parameters and control laws of the electric drive. The evolution of pre-commutation currents needs a full clarification in terms of the design of the algorithm of control of voltage source inverters (VSI) based on the second type of pulse-width modulation (PWM2), at least in the case of wide-range adjustable frequency drives, i.e., including the traction systems. In this study, there is a special focus on the pulse-width modulation (PWM2) of the second-kind. Although PWM2 could have various benefits including; lower switching losses and better dynamic performance, PWM2 is relatively unexplored in the real world applications of engineering. The absence of universal calculating currents in PWM2 mode is one of the main obstacles on the way of its wider usage. This work attempts to bridge that gap and extend generalized formulas of calculation of pre-commutation current as a reliable tool of analysis and design to the engineers and system designers. The tools are particularly useful when viewed in the setting of sweeping changes in the power electronics and the trend towards more intelligent and adaptive control systems.

KEYWORDS:pre-commutation current, second-order pulse-width modulation (PWM2), pulse voltage converter, power switch, switching losses, simulation, analytical expressions, control algorithms, power electronics.

I.INTRODUCTION

The article offers an investigation through an analysis of the difficulty of correctly approximating pre-commutation currents in power semiconductor switches within an electrical circuit/system involving power pulse converters controlled through second-kind pulse-width modulation (PWM2). In contrast to the traditional PWM methods, PWM 2 method regulates the conductive period shifting the on -time but leaving off-time (duration of pause) unchanged. The resultant switching unique current and voltage stress conditions during the edge of commutation offer new possibilities in control of switching devices. The paper starts by describing the basic operating principles of PWM2 and considering the effect of its approach, the use of fixed-pause, variable-on-time, on current waveforms and the electrical conditions to which power switches are subjected. The behavior is quite the opposite of what is the case with traditional PWM schemes in which the duty cycle is regulated by the factors of the on and off times. Standing on this base the article proposes a generalized theoretical framework which characterizes the behavior of pre commutation currents in all converter topologies, such as buck, boost and buck-boost converters [1,2]. The expressions that have been developed are the considerations of the non- linear and transient phenomena that happen during switching providing the engineer with a handy tool to predict the magnitude and shape of currents shortly before switching events transpire. These formulas are universal so they could fit a broad variety of converter styles and it would be simpler to simulate and approximate switching loss, component stress, and electromagnetic disturbance. Due to these reasons, the suggested approach enhances superior converter design helping in proper selection of components as well as designing of control strategies to minimise the switching losses and better overall efficiency. In this area, previous work is continued on pre-commutation currents in inverter systems utilizing PWM2 control with special emphasis on the effects of switching intervals and harmonic components on current waveforms prior to commutation.

II. METHODOLOGY

The analysis will start with the description of the output of voltage waveform of the inverter that will have a number of discrete intervals (or switching elements) and these intervals will be initially numbered so that the flow of current

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during thses intervals could be analyzed in detail. In the base case of n = 1 that is usually the basic harmonic or first switching period, these intervals and timing are briefly established (see Fig. 1). This circuit can be used as a basis to perform the analysis at higher harmonics or to have more than one switching cycle (n=1). The most important is that in PWM2 modulation, the fixed pause duration is preserved and only the conduction interval changes. Consequently, the fundamental current harmonic and the voltage are present in phase, unlike in other PWM control methods where there may be phases differences. It is a simplification to the analytical model and also it influences the timing and magnitude of the peak current before switching. Considering the values of the computed pre-commutation currents on each interval it can be discovered that the largest current at n=1 will appear near the end of the third interval, at $wt=\frac{\pi}{3}+\alpha^{o}$.being the conduction angle offset. The section goes ahead to give clear formulas on the calculation of the individual current components, differentiating the fundamental current component with the high-order harmonics, since the high-order harmonic components may play a significant role in the short - circuit current as the high order harmonic components are commutated by the switching times. These are formulas in [2], modified with uniform notation and easy application. It is important to understand these existing elements to ensure creation of robust inverter controls as well as protection of power devices against excess transient current. The form of the short - circuit current with higher harmonics preconditions the assessment of the extreme and practical with respect to stress state in the switching elements and thus the choice of the devices and optimization of the control strategy.

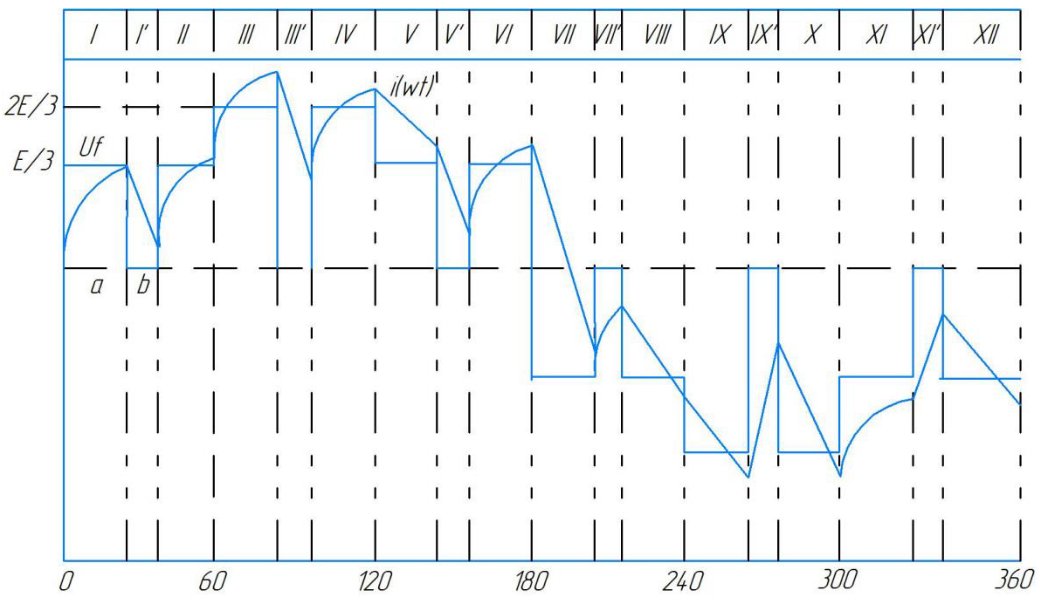

Figure1.*Waveforms of phase voltage and current for a voltage source inverter (VSI) using second-kind pulse-width modulation (PWM2) at n=1*

One pulse/half cycle scheme A Voltage Source Inverter (VSI) with Second-Kind PWM (PWM2) at n = 1 generates one pulse per half cycle of the reference sine wave. This produces a two step phase voltage wave form that switches between +Udc/2 and -Udc/2. The phase voltage is not sine shaped, but the average value is sine-shaped. With the inductive load, the phase current is smoother and more sinusoidal and it usually lags behind the voltage.

$$I_{scE}=A\frac{(1-c)(2+c+cd-c^2d-c^2d^2-2c^3d^2)}{1+c^3d^3} \quad ,(1)$$

The equation describing the output current I_{scE} (formula (1)) is a nonlinear consequence of two parameters c and d, which are multiplied by constant A. The numerator reflects non-simple products (and third-order terms) between c and d as well as the denominator places the result into a cubic term so that it may reflect a non-linear control or saturating effect.

Where $d = exp(-\frac{\frac{\pi}{3}-\alpha^{o}}{tg\varphi_{1sc}})$

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$c = exp(-\frac{\alpha^o}{tg\varphi_{1sc}})$.

c –Control parameter/Modulating parameter.
d – Duty cycle or other system variable made normalized.
The short-circuit current component caused by the fundamental harmonic of the phase voltage is just like the equation

$$i_{Isc}(wt) = A\frac{36\alpha^o cos\varphi_{1кз}}{\pi^2}sin(wt-\varphi_{1sc})(2)$$

The component of the pre-commutation current given by higher-order harmonics assumes the following expression [3]:

$$I(0)_B=A\{\frac{(1-c)(2+c+cd-c^2d-c^2d^2-2c^3d^2)}{1+c^3d^3}-\frac{36\alpha^o cos\varphi_{1sc}}{\pi^2}sin(\frac{\pi}{3}+\alpha^o-\varphi_{1sc})\},(3)$$

Formula (3) gives the output or base current $I(0)_B$in a power electronic system in terms of control parameters c, d, firing angle 0 and load φ_{1sc}. It takes a sinusoidal term, phase-dependent, which describes power factor and timing losses, out of the idealized nonlinear current model to give a more accurate/realistic current value at a certain set of operating conditions.
Where A–Scaling constant or amplitude (system-Dependent).
α^o– Firing angle or phase-control angle
The complete pre-commutation current is obtained:

$$I(0)_I=\frac{E}{3R_Э}\cdot\frac{36cos\varphi_1}{\pi^2}sin(\frac{\pi}{3}+\alpha^o-\varphi_1)(4)$$

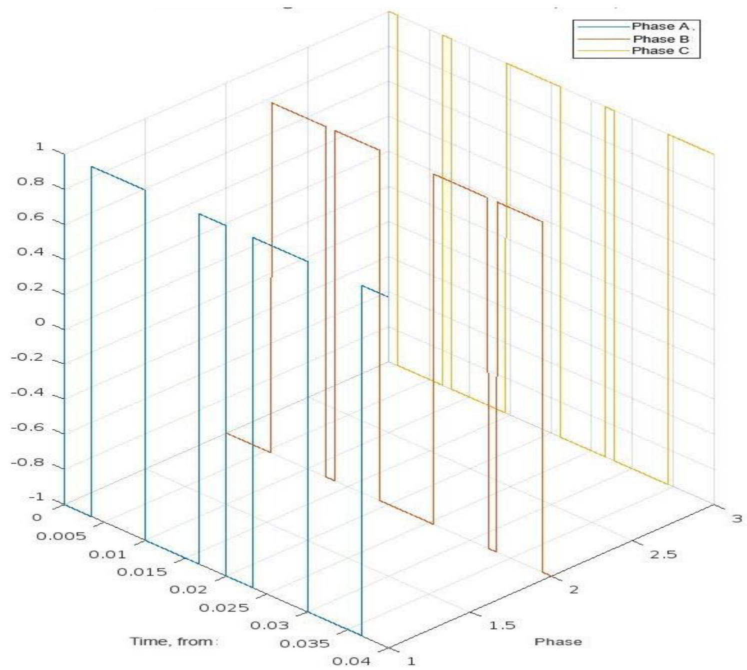

Figure2. ***Waveforms of phase voltage for a voltage source inverter (VSI) using second-kind pulse-width modulation (PWM2) at n=1 (MATLAB)***

Figure 2illustrates: The approximations of PWM2 with n = 1 to the sine functions with very few switchings. The output voltage shape under the influence of the low-frequency modulation. This PWM technique has very simple and efficient nature, but with larger harmonic content.

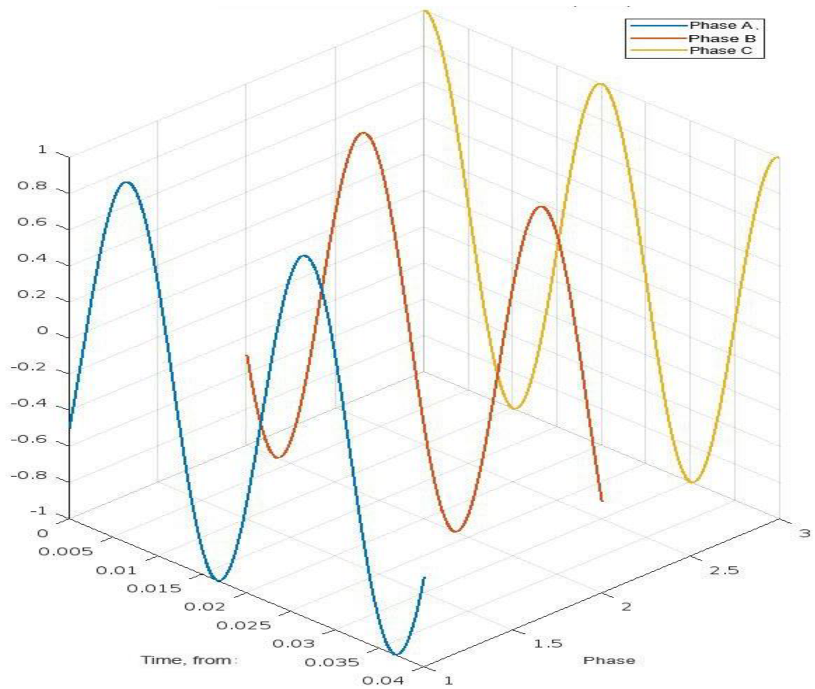

Figure.3. ***Waveforms of phase current for a voltage source inverter (VSI) using second-kind pulse-width modulation (PWM2) at n=1 (MATLAB)***

In this plot, the low switching frequency PWM (n = 1) is demonstrated to be sufficient, even when switching frequency is low: The load inductance is what allows the output current to be of the sinusoidal nature. The current waveform filters out the harmonics in voltage. It shows that even the PWM2 with a low switching can manage to produce a good enough quality of current to suit most applications.

The calculation formula for the pre-commutation current at n=2 is given by:

$$I(0)_B=A\left[\frac{(1-c)(2+2c+2cd+c^2d+c^2d^2+c^3d^2+c^3d^3-c^4d^3-c^4d^4-c^5d^4-c^5d^5-2c^6d^5)}{1+c^6d^6}-\frac{72\alpha^o\cos\varphi_{1sc}}{\pi^2}\sin\left(\frac{\pi}{2}+\alpha^o-\varphi_{1sc}\right)\right],(5)$$

For n=3

$$I(0)_B=A\cdot\left[\frac{(1-c)(2+2c+2cd+c^2d+c^2d^2+c^3d^2+c^3d^3+c^4d^3+c^4d^4+c^5d^4+c^5d^5-c^6d^5-c^6d^6-c^7d^6-c^7d^7-c^8d^7-c^8d^8-2c^9d^8)}{1+c^9d^9}-\frac{108\alpha^o\cos\varphi_{1sc}}{\pi^2}\sin\left(\frac{5\pi}{9}+\alpha^o-\varphi_{1sc}\right)\right],(6)$$

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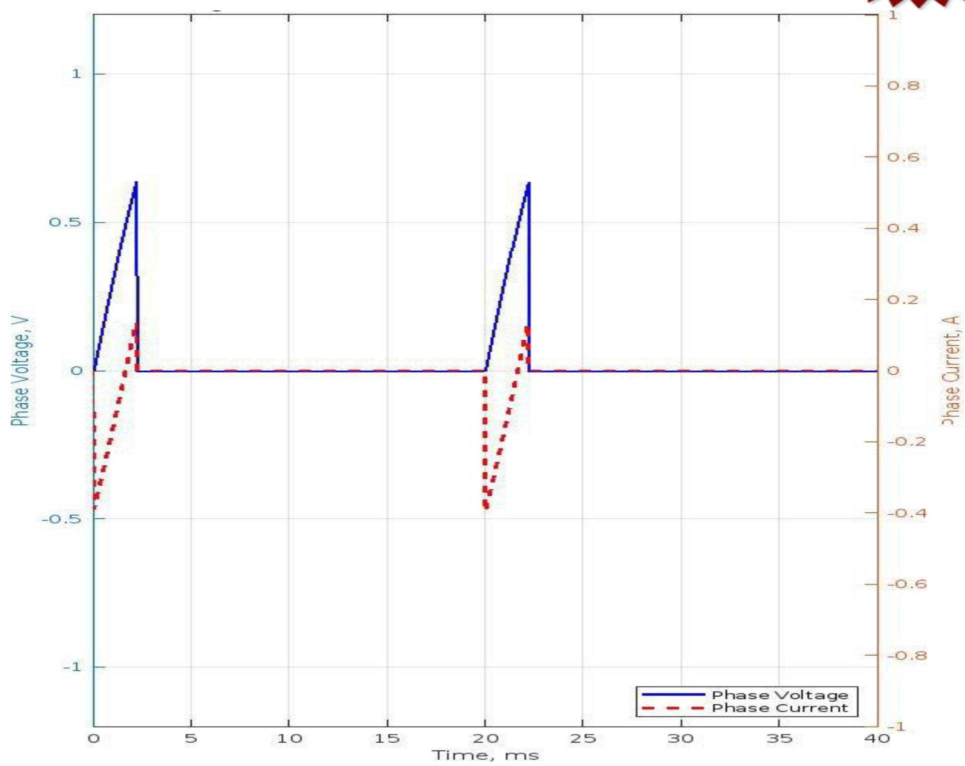

Figure. 4.*Waveforms of phase voltage and current for a voltage source inverter (VSI) using second-kind pulse-width modulation (PWM2) at n=2*

Figure 4 shows the output voltage waveform of the inverter and the phase current for the voltage source inverter (VSI) with PWM2 at n=2. It should be noted that the maximum value of the pre-commutation current at n=2 corresponds to the angle $wt=\frac{2\pi}{3}-(\alpha^o+\beta^o)$,, which is the same as for n=1 (see Figure 1). However, unlike the case for n=1, this angle here refers to the end of the pulse with a duration of 2α∘[4,5].

To draw some general lines we do an appraisal of these expressions. We set standard notations. In the case of PWM2, the relationship between the angles has the following character:

$$2\alpha^o+\beta^o=\frac{\pi}{3n},$$

$$\overset{\circ}{\alpha}_{max}=\frac{\pi}{6n};\ \gamma=\frac{\alpha^o}{\overset{\circ}{\alpha}_{max}};\ \alpha^o=\frac{\gamma\pi}{6n}.,(7)$$

Based on equation (7), the relationships for the coefficients c and d can be written as

$$c=exp(-\frac{\gamma\pi}{6ntg\varphi_{1sc}}),(8)$$

$$d=exp(-\frac{(2-\gamma)\pi}{6ntg\varphi_{1sc}}),(9)$$

Pre-commutation component of the current that is generated by said higher-order harmonics will be the following generalized answer:

$$I(0)_B=A\{(1\text{-}c)(\frac{\sum_{i=0}^{n-1}2c^id^i+\sum_{i=0}^{n-2}2c^{i+1}d^i+\sum_{i=0}^{2n-1}c^id^i+\sum_{i=2n}^{2n-2}c^{i+1}d^i}{1+c^{3n}}--\frac{\sum_{i=2n}^{3n-1}c^id^i+\sum_{i=2n-1}^{3n-2}c^{i+1}d^i-2c^{3n}d^{3n-1}}{1+c^{3n}})-\frac{6\square cos\varphi_{1sc}}{\pi}sin[\frac{(4n-2+\square)\pi}{6n}-\varphi_{1sc}]\},\quad(10)$$

Note that, for n=1n = 1n=1, the second summation term vanishes

$$\sum_{i=0}^{n-2}2c^{i+1}d^i=0$$

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This is because, as it was mentioned before, the angle values associated with the maximum value of the pre-commutation current, when using n = 1 and n > 1 are not the same.The pre-commutation current component that is caused by the fundamental harmonic can be represented as follows:

$$I(0)_1=\frac{E}{3R\text{э}} \cdot \frac{6?\cos\varphi_1}{\pi}\sin[\frac{(4n-2+?)\pi}{6n} - \varphi_1], \quad (11)$$

III. RESULTS AND DISCUSSIONS

Although the expressions of the pre-commutation current are consciously simple that are well adapted to implementation through computer aids. The generalized expressions allow the calculations of pre-commutation currents with any amount of pulses in the modulated inverter output voltage waveform. Other motor control strategies are also able to be taken into consideration with the help of these formulas [6]. The parameters of the motor$\varphi_{1sc}$and R_{sc} affect the portion of the pre-commutation current due to higher-order harmonics and phi1 and R_e the portion due to fundamental harmonic.

General analytical forms have been derived in this research to compute the pre-commutation currents in power semiconductor switches that have been running under the second-kind pulse-width modulation (PWM2). These equations take into consideration the control design where only the off-time is at fixed points and on-time varies, to enable the proper analysis of the existing behavior of the several converter topologies such as buck and boost pentodes as well as detention types. Among the important findings lies the fact that the PWM2 technique also allows a sinusoidal-like current output current waveform to be generated even using low switching frequency (n = 1) as it was demonstrated in the simulation. Although the phase voltage is a stepped waveform, the inductive characteristic of the load has the beneficial effect of filtering higher-order harmonic content so that the phase current is smooth (Figure 3). This shows that low frequency PWM2 is viable in applications in which the switching loss is to be kept low without the output current quality seriously being affected. Equations (1), (3), (5), (6) and others proposed as the analytical expressions of current components of pre-commutation state of the currents have relatively high sensitivity to control parameters c and d which are functions of the firing $\alpha^{o}$and power factor $\varphi_{1\,sc}$. These expressions have value in describing the nonlinear dynamics as well as the transient effects that happen around the switching moments. Specifically, eq.(10) obtained has given a generalized formula to calculate the pre-commutation currents in any value of n in the circuit and hence it is applicable in systems with different complexities of modulation.

The results of the calculations using analytical methods and MATLAB-simulations are in good agreements and the variances are also maintained within the engineering limits of tolerance. In applicative purposes, the relative error did not amount to more than 5,7 percent in most instances, which proves the goalfulness of the modeling technique. The peak current positions predicted correctly are also confirmed in the waveform comparisons, e.g., at 2 and 4, ωt=π/3+α∘ (n = 1), ωt= π/3-(α^{o}+ β^{o})(n = 2). The other aspect of interest is the occurrence of higher-order harmonics in the pre-commutation current, especially of n > 1. These materials have a greater effect of the stress that affects the switching devices especially in commutation. The models deal with it by making the distinction between the lower harmonic contribution (eq.(11)) and the high frequencies. The split assists in improving the choices of the semiconductor devices and in enhancing the measures of protecting against overcurrent conditions. On the whole, the findings reinforce the idea that PWM2 is less studied in practice, but it holds huge potential in enhancing the efficiency, controllability, and reliability of power electronic converters. The analytical circuit proposed in this work is an easy to use, and scale analysis tool that engineers can use to interpret the analysis of switching behavior approach, converter design method and maximize the converter performance with minimal energy losses in a large to the applications.

IV. CONCLUSION AND FUTURE WORK

Also in this research, a detailed description of pre-commutation currents is done on power converter second kind pulse-width modulation (PWM2), and more so in inverter topologies. Studying the impacts of fixed-pause and variable-on-time fixed-pause variable control delay characteristic of PWM2, the research points out the characteristic features of current when switching devices are approaching commutation process. This has been accomplished by anchoring analytical modeling, generalized expression derivation and numerical verification in order to create a robust framework that remains able to predict pre-commutation current components accurately at a fundamental and higher-order harmonic level. The derivation results in highly-flexible formulas that may be used on most types of converters and most types of control schemes, enhancing the accuracy of both simulation and design. In practical terms, they give the designer useful tools to shape switching behavior, minimize power losses and help to ensure that semiconductor

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devices are reliable in transient events. It has been found that the overall strategy will help to develop more efficient, predictable and reliable power electronic systems supporting development of modern converter design and control.

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