Qualitative aspects on closed loop power switching systems control

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Abstract ***-The switching circuit control problem contains various aspects concerning the closed loop operation, the harmonically perturbation generation, the transient regime duration, the dynamic or stationary regime stability, the filtering devices costs, etc. The presented paper presents a class of control methods, based on some mathematical concepts that revel certain important advantages. In this approach there are analyzed only the aspects concerning the theoretical principles that are used and the behavior of certain types of model implementations. The numerical simulations certify the validity of the methods and enable the analysis of the functional operation. These are very useful for the future developments having a concrete and practical character.***

Keywords: **switching control, phase space**

I. INTRODUCTION

The control of the power equipment based on switching devices is dependent on the application features and its performances are determined by the active devices characteristics and the control strategy. In order to obtain a minimal dissipated power, only reactive filtering components must be used. A circuit topology based on a closed control loop is more complex, but is less sensible to different kind of perturbations or to the component parameters.

The non-ideal active devices behavior (like the parasitic inductance or capacity) alters the switching characteristics (the pulses shape). Thus is more difficult to determine the real operating parameters and to choose correctly the control strategy.

A standard closed loop configuration contains a control bloc, who achieves the comparison with the reference signal, and a switching bloc followed by a reactive low-pass filter. Both are responsible for power flux control transfer. Their dimensions are dependent on the magnitude of the transferred power and determine the main part of the equipment expenses. Despite this, the circuit model uses signals that are assigned to the current or voltage time-dependent variation.

Even for a minimal configuration, several problems may be stated, like the following:

- the limits of the switching period;
- the stability and dynamic regime characteristics;
- the output error, relative to the shape of the input reference signal;
- the delay relative to the input signal;
- the perturbation frequency spectrum.

Some of these characteristics have a contradictory character, from the optimization point of view. For example, in order to obtain better dynamical characteristics it is necessary a filter with lower time constants, having limited possibilities to reduce the perturbation spectrum. On the other hand, a more efficient filter, having a higher attenuation will produce a more important delay of the useful signal, destabilizing the control loop.

In order to obtain satisfactory characteristics, from different points of view, a unitary approach must be taken under consideration. The method presented below tries to give a good solution using an appropriate mathematical model. An important feature of the presented method, based on a phase plane representation, is the possibility to control the phase of the output signal, very important for certain applications.

II. THE PHASE PLANE REPRESENTATION

A simple switching power circuit configuration uses the two level type PWM modulation, followed by a reactive low-pass filter. The classical solution for the modulator is based on the carrier wave technique. Having the advantage of a total control for the switching frequency values, this is acceptable only when a relative high frequency may be used. If it is not the case, the output signal will be distorted and delayed, relative to the reference one. The delay is higher when is desired a good smoothness, using a high harmonic attenuation by low-pass filter. Thus, a closed loop topology is difficult to be applied, because the error and stability problem which can appear.

The purposed solution uses a closed loop configuration based on a non-linear characteristic comparator (Fig.1). In this case the switching frequency is not determined apriori, but a permanent phase control is possible, due to complete representation of the state of the circuit, using some relevant parameters. This has two parts, a non-linear one, containing the power switching devices and a linear one, represented by the reactive low-pass filter.

The transitions of the power switching circuit are determined only by the non-linear characteristic the comparator, by the instantaneous state of the circuit and by the reference signal value. The switching frequency limits may be fixed by the implementation of the control strategy.

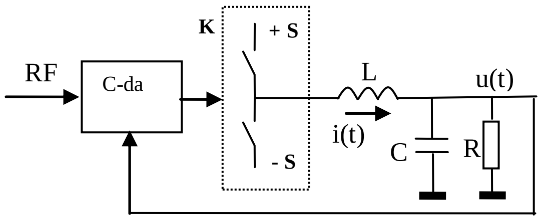

Fig.1.The functional scheme

It is important to emphases that the two configurations, both are based on a comparison process, the operating mechanisms and the model representations are very different.
When the carrier wave method is used in a closed control loop configuration, regularly, the circuit model is analyzed in the frequency domain representation by the Laplace transform formalism. But this technique is rigorous valid only for linear systems. In this case, the harmonic components of the output signal must be linear functions of those of the input signal. Obvious, the PWM modulator is not a linear circuit because it generates harmonics that are inexistent in the input signal. Although, for some conditions, the carrier wave system may be seen as a linear one, if the modulator-filter group is considered as one bloc with quasi-linear characteristics. In this case, the perturbation rejection must be very efficient for the whole operating domain, that usually, it is not an optimal situation. The main advantage of the frequency domain representation is the possibility to apply the stability compensation methods, specified by the regulator theory. But, in this context is impossible to take under consideration, in a unitary and simultaneous manner the problems concerning the stability, transient regime optimization, phase error and instantaneous output error.
The purposed solution uses a phase plane representation. This uses as coordinates a parameter value and its derivative. These magnitudes describe the state of a dynamical system, when its model concerns a second order differential equation. For a closed loop system, as representative parameter, is chosen an error signal or the output signal value.
The phase plane representation has several important advantages: the state of the system is completely described at any time moment, the optimization and stabilizing criteria may be defined and represented in a clear manner, the possibility to improve the dynamical transient regime and the phase error. In addition there are eliminated the considerations concerning the linear approximation and spectral analysis, that are difficult to be correctly defined, in general, for a PWM configuration obeyed to transient regimes.
It is important that the phase plane analysis eliminates the choice of a certain type of modulation, the switching control depending only on the system evolution. In this case the signal delay compensation is included in the control procedure, because this uses complete information on the system state.

From the theoretical point of view, the operation of systems based on the two above representations is different. The first concerns a control error process and the second a pursuit process for a certain reference signal.
In the phase plane, the possible evolution of a two level PWM filtered system is represented by two families of traces, corresponding to the states of the power switch. The effective trace is determined, by continuity, during the evolution, starting with the initial conditions. The switching control strategy is determined if there is defined a, so called, switching curve. If the evolution trace from one family intersects this curve, the future evolution of the system will follow a trace from the other family. For a certain stated conditions, the switching curve may be determined such the system evolution goes to the origin of the phases plane. When this is fixed, it represents a static equilibrium point. When the origin is modified, step by step, together with the instantaneous value of the reference signal, it can be obtained a pursuit process by witch the output system parameter follow a given reference input signal. Thus the state of the system remains close to a dynamical equilibrium point.
There are to situations, which ensure the system evolution to the equilibrium point. The first appears when there exist traces that pass through the origin of the phase plane. Then, it can be determined, by analytical computation, a switching curve passing through the origin and their two segments represent solutions of the differential equation that describe the physical system. For an ideal case, in absence of numerical approximations, the evolution trace will follow the switching curve, after the first intersection, going to the origin. But, because the inherent numerical approximations, the evolution goes close to the switching curve, approximating the origin in a cyclical manner by curve segments, on the to sites of the origin point. In a time domain representation, the corresponding signal has a damped oscillating evolution.
The second situation appears when the traces passing through the origin can't be finding. In this case may be determined a switching curve (or straight line) containing the origin. Now, the evolution takes place, going to the origin, by short distance segments, oriented in zigzag, intersecting the switching curve from its two sides, in a so called sliding mode. This working mode may be used when, instead of determining of a switching curve by analytical calculus, a straight line approximates this, defined corresponding certain criteria.

III. CASES STUDIES

For this there are chosen three representative cases. The analysis is based on numerical simulations. In this context, no importance was paid to aspects concerning the technical configuration or to the range of variation of the parameters. The physical magnitudes are considered scaled relative to unimportant value, so the unit system is also unimportant. In the graphical diagrams the parameters are used with conventional denotations specific to the vector representation specific to the used simulation program (Mathcad). The main purpose is to analyze the evolution process for parameters corresponding to a mathematical model characteristic to a certain physical system. Here there are given information about the explicit schemes or mathematical models.

All the cases correspond to a closed loop controlled system, based on a two level bipolar switching bloc. The first configuration is an idealized one, using for filtering purposes a two level integrator circuit. The last two examples uses as reactive low-pass filtering circuit a Γ type, LC structure. For the three cases it is studied the evolution of the system parameter, relative to a given reference signal. The following analysis tries to determine the characteristics and the quality of the time dependent approximation process that can be defined. The system behavior is useful in order to derive conclusions concerning the features of the purposed methods and their implementation.

In the first case it is used a quadric type of reference signal. This enable an analytical determination of the switching curve and a behavior study for a large variation range. In addition, it is possible to choose, as phase plane coordinates, the error signal and its derivative. This equals the difference between the output and reference signal. In this context, the evolution of the trace to the origin, near the switching curve, represents the error signal minimization (Fig.2). In Fig.3 it can be seen the variation of the switching function, and implicitly the set of switching time moments, during the approximation process. In order to emphasis the efficiency of the method, during the transient regimes, starting far from the equilibrium point, a large value for the initial condition was chosen.

The second case represents the approximation process for a reference signal with a constant unitary value (Fig.4). In this example, it is used for the switching curve a linear approximation (a straight line). Thus, it is not necessary to use an analytical method, which lead to complex computation. For some type of problems, it is sufficient to use a straight line, passing through the origin, depending on a single one parameter (the angle corresponding to the slope of the line). This can be determined experimentally, by numerical simulations.

In this example, based on a reactive LC filter, the phase plane is substituted by a state variable plane, where the coordinates are the inductive current and the capacitor voltage, equaling the output parameter of the circuit. The origin of the coordinate system is translated on the abscissa, reaching the value of the reference signal.

For the given initial conditions, the evolution trace contains three zones. The first is a curve segment, starting from the initial point and ending at the first intersection with the switching line. The second contains a set of short length line segments, characterizing for the sliding mode, that continue until the vicinity of the coordinate system origin.

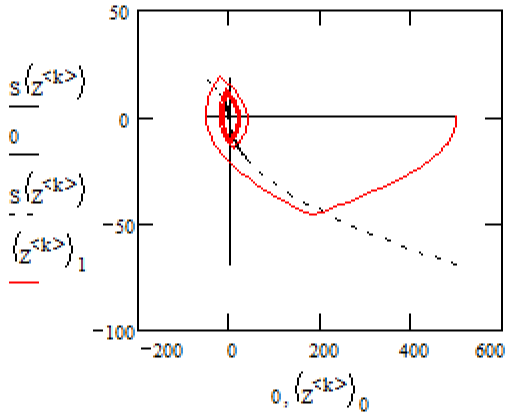

Fig.2.The phase plane trace and the switching curve approximation process

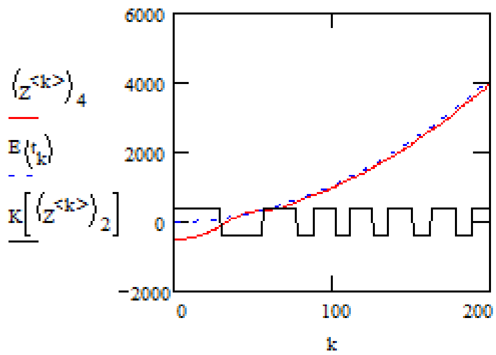

Fig.3.The switching function and the approximation process

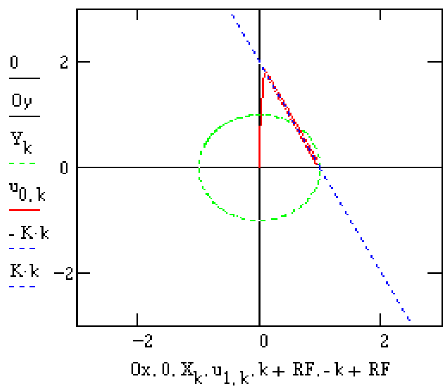

Fig.4.The phase plane trace (constant reference)

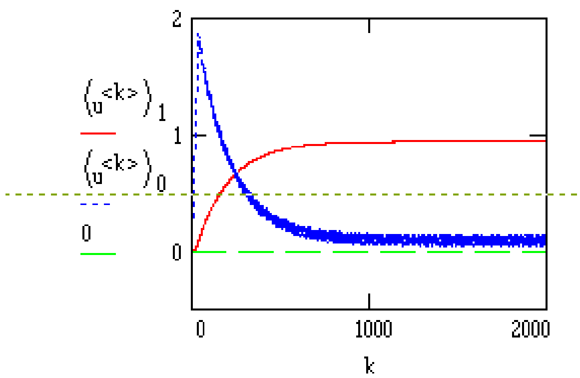

Fig.5.Time domain approximation (constant reference)

The third zone includes an infinitely oscillating approximating process of the reference value, in the vicinity of the origin, with alternative moving directions. In Fig.5 it is shown the time-dependent evolution for the two system parameters, whose samples are components of vector variables. The component (0) corresponds to the inductive current and component (1) corresponds capacitor voltage (output voltage).
The current approximation oscillation, higher comparing to the voltage one, is conform to a filtering process, when an input perturbation is present, in this case, due to numerical computation. The zero initial condition corresponds with the starting condition of the system.
The third case is a generalization for the preceding situation, when a variable reference signal, of sinusoidal shape, is taken under consideration. The initial values are chosen outside from the range of the sinusoidal function, in order to analyze the behavior during the transient regime.
The state variable plane representation (Fig.6) shows two phenomena, a transient one and a stationary one. The first, concerning the matching transient regime to the variation mode of the reference signal, is represented by curved trace segments. In time domain (Fig.7), this are linked with important exceeding of signal, which need a very short transient regime, close to an optimal one. The exceeding of the output signal is inherent, taking in consideration the short duration of the transient regime and the time constants specific to the LC circuit.
The second phenomenon, concerning the steady-state regime corresponding to the following of the reference signal is represented by a turbulent elliptic shaped zone. This contains a lot of curved micro-segments, which results after each approximation step, corresponding to the variation of the reference signal variations. Although the output signal is smooth, as we can see in the time domain, the state variable plane turbulence is present because the current parameter which has larger variations.

III. CONCLUSIONS

The content of the paper presented, from a qualitative point of view, the characteristics of a method useful for PWM modulation, for a closed loop configuration. The operating mode, described above, although contain an interesting mathematical background, for some particular situation, may be easy implemented, both in an analogical manner or in digital one, using functional blocs witch realize simple arithmetical operations. From the global scheme point of view, for the same functionality, we can say that the implementation of the presented method is simpler that the classical implementation, based on the carrier wave technique.

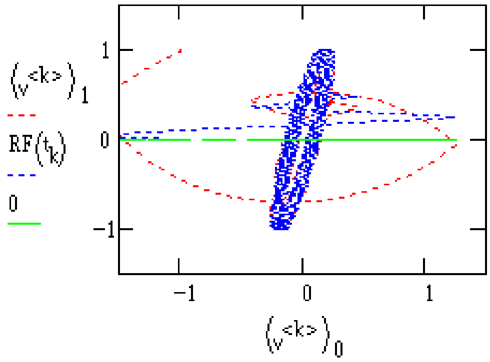

Fig.6.The phase plane trace (variable reference)

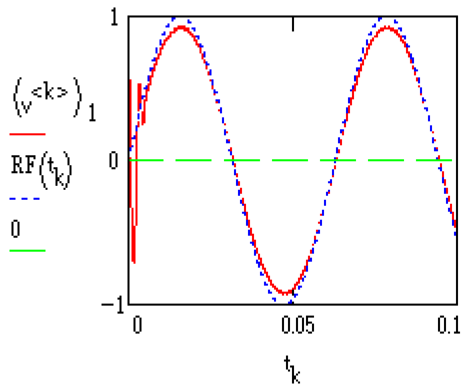

Fig.7.Time domain approximation (constant reference)

The presented method is powerful when is needed a phase synchronism between the output and input signals and when short transient regime are requested. The numerical simulations were proved by the last two case studies. Also a simple circuit was used, these methods may be generalized for more complex structure, obvious for a non-important different shape of reference signal. In addition, it can show that the method is unitary, from the point of view of the purposes followed by the design process, concerning the optimal criteria concerning the error level, the stability limits and transient regime duration.

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