Circuit Modeling of Arbitrary Crystal Oscillator for EMC and SI Analysis

Ludovica Illiano
DEIB
Politecnico di Milano
Milan, Italy
ludovica.illiano@polimi.it

Xiaokang Liu
DEIB
Politecnico di Milano
Milan, Italy
xiaokang.liu@polimi.it

Xinglong Wu
DEIB
Politecnico di Milano
Milan, Italy
xinglong.wu@polimi.it

Flavia Grassi
DEIB
Politecnico di Milano
Milan, Italy
flavia.grassi@polimi.it

Giordano Spadacini
DEIB
Politecnico di Milano
Milan, Italy
giordano.spadacini@polimi.it

Sergio A. Pignari
DEIB
Politecnico di Milano
Milan, Italy
sergio.pignari@polimi.it

***Abstract*—Quartz crystal oscillators are fundamental components in electronic circuits with stringent time requirements; providing a proper crystal oscillator model for simulation is crucial for Electromagnetic Compatibility (EMC) and Signal Integrity (SI) analysis. This paper presents two types of behavioral models of quartz oscillators for EMC-oriented circuit simulations. These behavioral models allow the oscillator to be simulated without the need to resort to the complete oscillator circuit. The proposed models are tested in simulation of four oscillators, operating at different frequencies. These models provide a tool for early-stage analysis of EMC and SI performance in electronic systems.**

***Index Terms*—behavioral model, circuit simulation, crystal oscillators, signal integrity (SI)**

I. INTRODUCTION

Quartz crystal oscillators are electronic components essential in the design of electronic circuits featuring stringent time requirements. They are designed to generate a specific frequency signal through the mechanical resonance of a quartz crystal. This mechanical resonance is associated with the piezoelectric effect peculiar to this type of material. Thanks to the properties of the material, when subjected to an alternating voltage, the crystal oscillates at a stable frequency [1]. Oscillators, due to their constant frequency operations, are devices that warrant special attention whenever Electromagnetic Compatibility (EMC) and Signal Integrity (SI) performances need to be analyzed. As widely known, it is common practice to verify EMC performance at the early design stage in order to minimize cost and production time; additionally, the electromagnetic interference (EMI) noise caused by a clock signal, which is commonly derived from a crystal, is one of the major concerns in EMI analysis and mitigation. Accordingly, EMC simulations that reproduce as faithfully as possible the product behavior are carried out in design phase. In this context, to simulate the realistic model of an electronic board, the definition of a crystal oscillator model that provides access to its physical properties is evidently crucial. Despite the importance of modeling the crystal oscillator signal, there is a lack of general and effective models for EMC-oriented circuit simulation. Specific crystal oscillator models from several manufacturers are provided in the software libraries, yet more frequently a generic crystal oscillator model is unavailable. Therefore, the purpose of this paper is to present the behavioral circuit model of arbitrary crystal oscillators that can be integrated into EMC simulations for design-phase analysis, without resorting to full models. In Sec. II an overview of the equivalent electrical model of the crystal and of crystal oscillator basic design is presented. Sec. III provides an illustration of the circuit models suggested. Four examples of application of the models considering different oscillators are presented in Sec. IV. Finally conclusions are provided in Sec. V.

II. CRYSTAL OSCILLATORS

Crystal oscillators are among the best-performing oscillators in terms of frequency stability. Of all the different types of oscillators, crystal oscillators are the least affected by frequency drift caused by temperature variations, manufacturing tolerances, and aging [2]. The output frequency of a crystal oscillator corresponds to the fundamental crystal resonant frequency; alternatively, it is equal to a multiple of the resonant frequency, and that multiple is defined as the overtone frequency. The fundamental resonance frequency is the rate of expansion and contraction related to the piezoelectric effect and is defined by the shape, size and cut of the crystal. To tie the physical properties of the crystal to the electrical properties, the widely used electrical model of the crystal has been presented in [3] and [4] . In the following section, this model will be briefly discussed, followed by the presentation of the crystal oscillator model.

A. *Quartz crystal equivalent electric model*

Quartz crystal (XTAL) is the oscillator resonating unit. The XTAL equivalent electrical model is illustrated in Fig. 1; it

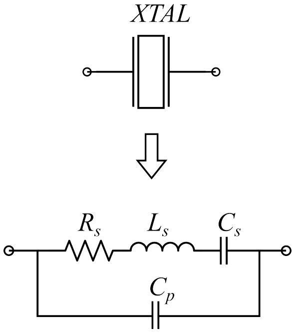

Fig. 1: Crystal equivalent electrical model.

includes an RLC series, constitued by L_s, C_s, R_s, representing the vibrational mechanics of the crystal, in parallel with a capacitor C_p, representing the parasitics of the electrical connection. The circuit thus described resonates at two specific frequencies, f_s and f_p. The first is related to the RLC series and the second is due to the parallel interaction of the capacitance. They are hence defined as follows [3]:

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}} \tag{1}$$

$$f_p = \frac{1}{2\pi\sqrt{L_s(\frac{C_s C_p}{C_s + C_p})}}. \tag{2}$$

The two frequencies are related to the operating frequency of the crystal f_{osc} as (with Δf indicating the relative frequency tolerance in parts per million (ppm), as is generally available from the crystal datasheet):

$$f_s = f_{osc} * (1 - \Delta f \times 10^{-6}) \tag{3}$$

$$f_p = f_{osc} * (1 + \Delta f \times 10^{-6}) \tag{4}$$

To determine the XTAL equivalent circuit parameter values, information is retrieved from the crystal data-sheet. Specific indications of series equivalent resistance R_s and shunt capacitance C_p values are usually provided by the manufacturer. L_s and C_s are then derived from the combination of (1) to (4), yielding:

$$C_s = C_p(\frac{f_p^2}{f_s^2} - 1) \tag{5}$$

$$L_s = \frac{(C_s + C_p)}{C_s C_p} \frac{1}{(2\pi f_p)^2} \tag{6}$$

B. Basic scheme

A crystal oscillator operates by exploiting the natural resonant frequency of the crystal itself. The basic scheme consists of two parts, as shown in Fig. 2: a filter stage, which includes the crystal and determines the operating frequency of the oscillator, and an amplification stage [5]. The two sections are connected in positive feedback, so that any noise v_i in the oscillator loop will trigger the oscillation. The positive feedback signal v_f will self-reinforce the oscillation. The oscillator should be designed so that the feedback signal v_f is phase-shifted by 2π with respect to v_i. When v_f is phase-shifted by 2π from v_i, it is ensured that v_f is in phase with v_i and thus positive feedback does not cause uncontrolled oscillation or instability. A closed-loop gain equal to or greater than one is necessary to ensure steady-state oscillation stability, according to the Barkhausen stability criterion [6]. Usually the amplification section is integrated within a microprocessor μP (see Fig. 3). To further tune the oscillation frequency, the use of two capacitors, C_{L1} and C_{L2}, connected in series to ground is suggested, determined by the load capacitance C_L specified by the crystal manufacturer [5]. Indeed, the oscillator circuit has to exhibit the same load capacitance as the one it was tuned for to maintain frequency stability.

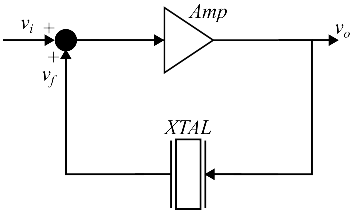

Fig. 2: Crystal oscillator principle scheme.

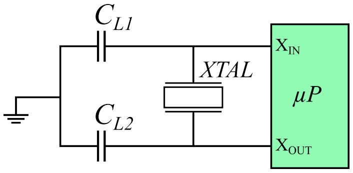

Fig. 3: Crystal resonator connected to μP pins.

III. PROPOSED CRYSTAL OSCILLATOR CIRCUIT MODELS

The basic circuit model presented in Sec. II effectively summarizes the operation of crystal oscillators. As previously explained, in many applications the amplification section is integrated into μP. Several guidelines are available which, based on μP, describe the amplification stage scheme and outline the crystal resonator specifications [7]–[9]. The possibility to connect an oscillator that satisfies frequency tolerance criteria to the pins designated for the crystal is frequently mentioned in μP specifications. Likewise extensive documentation on the design of crystal oscillators is available, e.g., as shown in [10]–[12]. However, in the literature, the simulation models of crystal oscillators are usually full models including nonlinear components (e.g., thyristors). This work proposes models that can be employed in integrated systems simulations without resorting to the full model of the oscillator and allow the properties of the real oscillation to be considered. As discussed previously, such a simulation model may contribute to the

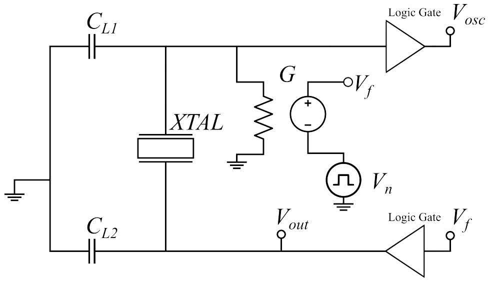

Fig. 4: Passive circuit model.

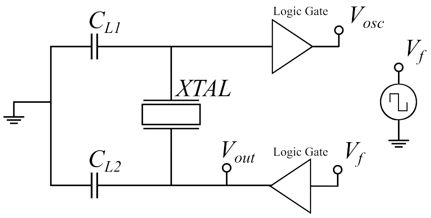

Fig. 5: Active circuit model.

identification of system unexpected behaviors at an early stage that may result in EMC and SI problems.

In this work, two crystal oscillator models, i.e., a passive model and an active model, are proposed, and will be discussed in the following sections. Here, the term passive or active indicates the presence or not of a working *clock* source in the circuit. The selection of the model to be used depends on the system to be simulated as will be explained later. Like the basic oscillator model, both models consist of a filter unit and a feedback unit The filter section simulates the crystal's natural frequency and coincides with the definition provided in Sec. II-A. The second part related to pulse generation is essential for generating the clock signal. This part changes according to the model (active or passive) that will be employed.

A. Passive model

The passive model is represented in Fig. 4 and is based on the physical operation of the crystal oscillator described in II-B. Through the combination of a voltage-controlled voltage source (VCVS, represented as circuit component G in Fig. 4) with a pulse source (V_n in Fig. 4), a feedback signal is introduced into the circuit through the driver output. The pulse initiates the oscillation; after a given settling time, this oscillation will reach a steady state.

To function properly, the pulse period T_{pulse} is selected to match the oscillation frequency f_{osc}, and the noise impulse magnitude V_n should be selected with enough energy, so as to guarantee the oscillation to start. The gain G introduced by the VCVS is set negative to produce a phase shift of π. The residual π phase shift is induced by the combined effect of $XTAL$, C_{L1} and C_{L2}, and by the time delay T_d inputted through the VCVS. The VCVS gain, G, should also be picked to ensure proper fitting of the logic gates voltage level.

TABLE I: Oscillators specifics and Crystal equivalent electric circuit parameters

	Oscillator Specifics			Circuit parameters	
f_{osc} [MHz]	$R_s[\Omega]$	C_p [pF]	Δf [ppm]	L_s [mH]	C_s [pF]
15	30	5.0	50	98.80	0.0011
25	40	7.0	50	28.95	0.0014
27	40	5.7	50	30.50	0.0011
30	20	3.0	50	46.90	0.0006

TABLE II: Passive model: time parameters

f_{osc} [MHz]	T_d [ns]	T_{pulse} [ns]
15	21.0	33.34
25	8.0	20.00
27	6.5	18.50
30	4.8	16.67

B. Active model

The passive model just introduced can be employed in the simulation of electronic systems. In simulation of complex electronic systems, integrated circuit components, as μPs, are usually represented by Scattering or, more often, by IBIS models, which are behavioral models of components and do not reveal any information about circuit design. It has been empirically verified that in simulation the use of inaccurate models compromise clock stability, especially when a model is partially extracted from real measurements and is therefore ill-defined due to numerical errors, in which case there is often the extinction of oscillation. In this case a single pulse is not enough to sustain the oscillation. To ensure that the clock does not extinguish regardless of the interface, the amplification stage is modified by introducing a stable clock source in place of the pulse generator, as illustrated in Fig. 5. Maximum and minimum voltages, V_{min} and V_{max}, and frequency f_{clock} of the clock source are defined based on the requirements of μP.

IV. CIRCUIT MODELS APPLICATIONS

The proposed models permit the generation of signals with no recourse to the design of the complete oscillator circuit, while incorporating all the fundamental oscillator parameters. To illustrate the correct operation in simulation of these models, four applications are presented: four oscillators are considered, operating at 15, 25, 27 and 30 MHz, respectively. The specifications of these oscillators are given in Table I.

From the values given in the specifications, it is possible to derive the equivalent electrical circuits of each crystal by means of the equations (5) and (6). C_{L1} and C_{L2} are selected equal to 10 pF in all the proposed examples. Computation results are given in Table I. Once the electrical equivalent of the crystal has been defined, 1) the μP crystal logic gates and 2) the parameters of the source circuits defined in the previous paragraph must be specified. In the cases examined, the interface logic gate is the low voltage transistor-transistor logic (LVTTL). Since all oscillators are connected to LVTTL μP gates, it is possible to use the same magnitude values for all passive models and active models. Therefore, considering

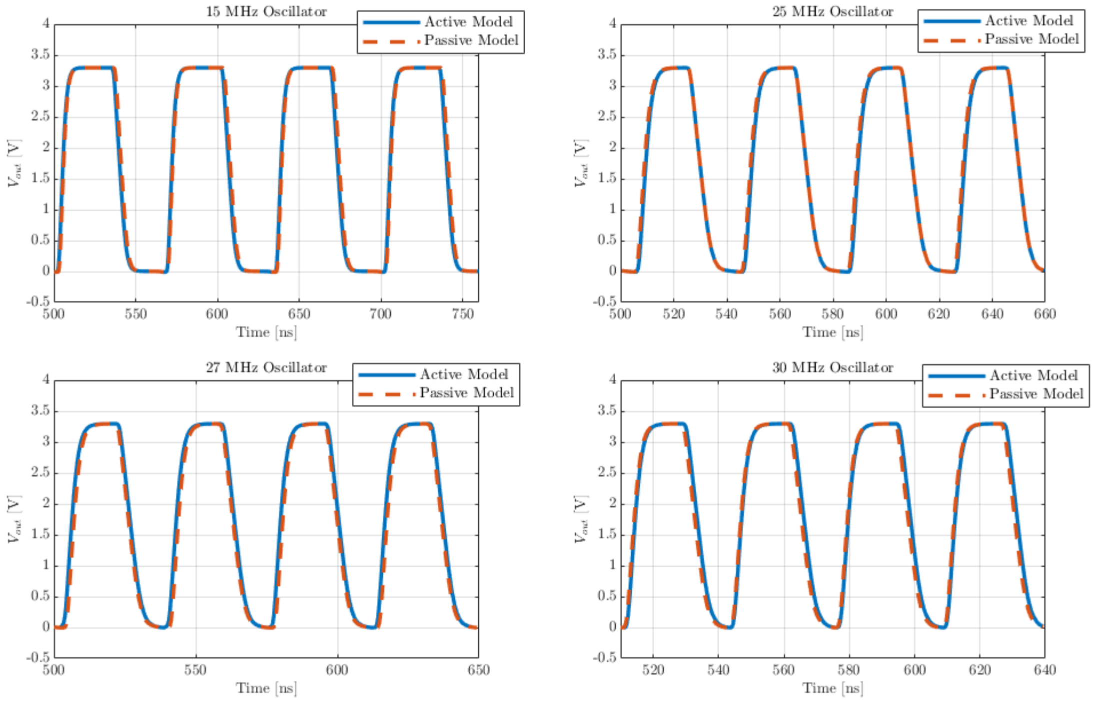

Fig. 6: Performance of proposed circuit models with oscillators operating at (a) 15 MHz, (b) 25 MHz, (c) 27 MHz, and (d) 30 MHz.

the requirements described in the previous section, V_n is set equal to -30 V and G is set equal to -50 for all the passive models; V_{min} is 0 V and V_{max} is 3.3 V for the active model. Regarding the selection of time quantities, in the active model f_{clock} is set equal to f_{osc}. More attention should be paid to the choice of T_d and T_{pulse} in the passive model; Table II shows the parameters values that ensure oscillation stability.

As application examples, Fig. 6(a)-6(d) show the performance of V_{out} for the different operating frequencies; in all cases there is good agreement between the two models. The rise and fall transients are affected by the IBIS model of the interface implemented in the study. Use of the passive model allows more flexibility. However, if the quality of the μP model in use in simulation is not satisfactory (e.g., if the circuit fails to oscillate in connection with a complex external network), the use of the active model is suggested.

V. CONCLUSIONS

Two behavioral models of crystal oscillator were presented in this paper, providing a simple modeling procedure considering the properties of the real oscillation. The passive model allows the characteristics of the feedback loop to be pointedly defined. The active model ensures a more robust oscillation. The models were applied to the analysis of complex systems: the results show that the proposed schemes, combined with other non-ideal signals in the system, work properly. The models can be used in EMC and SI simulations at the design stage and for troubleshooting purposes.

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