EMC Modelling of Radar Signal Susceptibility of Cardiac Pacemakers

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Abstract

Cardiac pacemakers are vital for many persons sufferering from heart diseases, and a malfunction of those devices can have severe consequences for their wearers. Yet, in a signal environment evermore complex, the influence of external signals interfering with the normal operation of a pacemaker is getting stronger. We present an nonlinear analytical model of a pacemaker and use it to investigte the influences of external signals on the operation. The model is able to calculate critical input voltage levels for all kinds of periodic input signals.

Introduction

Cardiac pacemakers (PMK) have been used to combat arrythmias for several decades. The PMK is connected to the heart by an electrode to read the electrocardiogram (ECG) and to stimulate the heart beat by voltage pulses if necessary. The precise detection of the ECG is essential for the error-free operation. Incident electromagnetic fields can couple into the electrode and cause a noise voltage at the PMK input. If the noise voltage level is too high, the ECG detection can be disturbed.

The critical noise voltage levels at the input of the PMK have been measured in a frequency range of 30 kHz–2.5 GHz in an extensive study [1]. An exploration of unmodulated signals can be found in [2]. The results are threshold voltages depending on the signal frequency and the type of modulation. Fig. 1 shows the critical voltages for four modulation types. U_{pp}^{max} is the maximum off-load peak-to-peak voltage that guarantees that 95% of the tested PMKs work properly. The draft standard [3] uses these results, but the values of single PMKs are weighted by their frequency of nidation. This measuring method needs a lot of time, lots of PMK samples, and expensive equipment. This work presents a method to calculate the critical voltages for any modulation type and frequency including short pulsed radar signals.

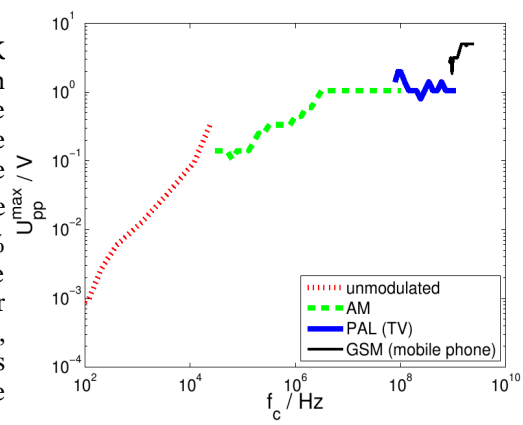

Figure 1: Measured critical voltage levels [1] [2].

2. Functionality and disturbance of PMKs

Fig. 2 shows the schematic design of the analog input circuit of a PMK. The input signal is amplified and bandpass filtered. The resulting voltage U_{out}^{BP} is compared with a defined threshold U_t . For $\left|U_{out}^{BP}\right| > U_t$ the digital output switches from “low” to “high”. This event is rated as a heart beat.

A noise signal can only have an effect if it is able to switch the digital output after passing the amplifier and the bandpass filter. A RF signal sould not be able to disturb a PMK because of the bandpass. It’s upper cut-off frequency is between 57.5–153.3 Hz, depending of the PMK model [4]. The reason for a possible disturbance is the nonlinear behavior of the amplifier. In this work it is modeled as a second order nonlinear system. This means that the output voltage depends on the input voltage and its square. Fig. 3 shows schematically the spectrum of a narrowband signal and the spectrum of its square. The output signal has additional spectral components if compared to the input signal. Important is the LF spectrum, which can pass the bandpass partially and disturb the ECG detection.

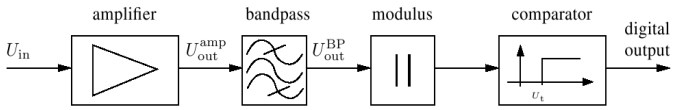

Figure 2: Input circuit block diagram

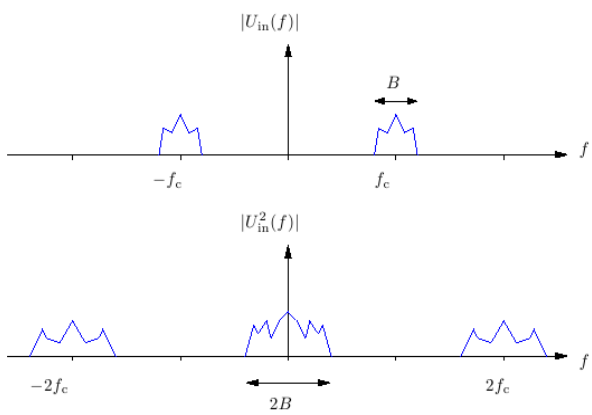

Figure 3: Top: input signal's spectrum. Bottom: square of input signal's spectrum.

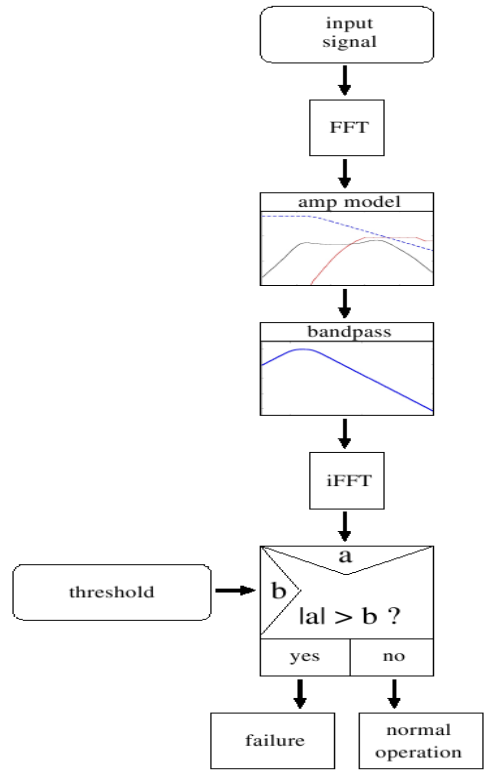

Figure 4: Immunity Model block diagramm

3. Immunity Model

To calculate the behavior of a PMK every block from Fig. 2 has been modeled. U_{out}^{amp} can be calculated by a convenient characteristic curve model [5]. This model works in frequency domain. The bandpass is described by its characteristic function easily. Finally the amplified and filtered signal U_{out}^{BP} is retransfered to time domain by the inverse Fast Fourier Transformation. The maximum amplitude is compared to a known threshold U_t . For $\left|U_{out}^{BP}\right| > U_t$ a real pacemaker would switch the digital output of the input stage to high. In other words the PMK rates the distortion signal as a heartbeat which could lead to malfunctions. Fig. 4 shows a block diagramm of the needed operations explained above.

To use the Immunity Model we need

- the characteristic curves of the amplifier,
- the characteristic function of the bandpass, and
- the critical threshold.

3.1 Amplifier Model

In [5] we presented an amplifier model. After an analytical derivation based on [6] three characteristic curves have been found which describe the weighting of the three spectral components (see Fig. 3). The spectrum at $f = f_T$ can be calculated by an iFFT of the input signal. To get the components at $f = 2f_T$ and $f \approx 0$ Hz we need the square of the input signal. It can be calculated in frequency domain by convolving the signal spectrum with itself. The spectral components have to be scaled with a factor depending of the input signal center frequency, shown in Fig. 5.

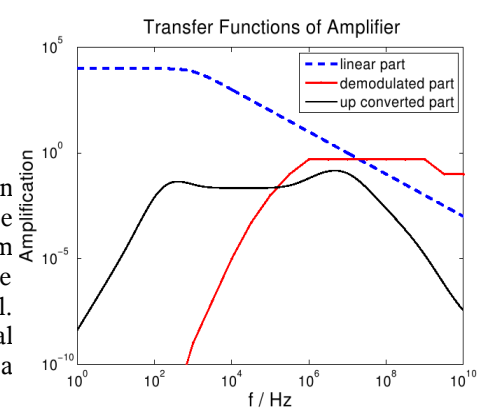

Figure 5: Transfer functions of the amplifier

3.2 Bandpass

From [4] the cut-off frequencies of different PMKs are known. In this work the lower cut-off frequency is 20 Hz, the upper 70 Hz. Fig. 6 shows the transfer function.

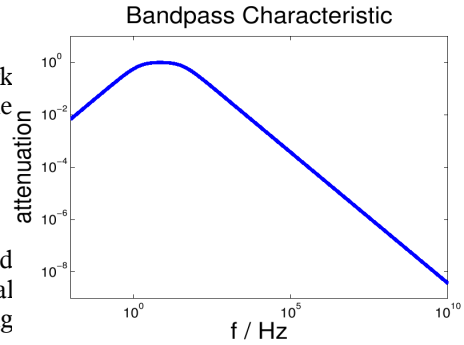

Figure 6: Transfer functions of the bandpass

3.3 Critical Threshold

U_t can be calculated with the help of the known values from [1]. A defined test signal with its critical voltage amplitude can be used as the input signal U_{in}. As we know, this input almost causes a malfunction. Thus the resulting output voltage U_{out}^{BP} equals the threshold voltage U_t of the simulated PMK.

4. Results

4.1 Known Test Signals

The presented Immunity Model was validated by test signals from [1] with known critical voltages. Fig. 7 shows the results of the presented model and the measured critical voltage levels from [1] and [2]. They are very high correlated.

4.2 Radar Signals

While using the Immunity Model for pulsed signals it is noticeable that the critical voltage level is eqaul for a wide range of puls widths, but becomes higher with decreasing pulse time below a special border. This phenomenon is explained in the following. Radar signals are at such high frequencies that the spectral components at $f \approx f_c$ and $f \approx 2f_c$ can be neglected, because they can't get through the bandpass. As Fig. 5 shows the demodulated part dominates the amplifier's output anyway. Fig. 8 shows the demodulated part (signal at $f \approx 0$) of U_{out}^{BP} for pulsed input signals with varying pulse widths. The envelope of the linear part (signal at f_c) of U_{out}^{amp} in time domain is on the left for a better orientation. For $T_{on} < 5$ ms the bandpass output amplitude becomes smaller. This border can be explained by the step responce of the bandpass. As Fig. 9 shows it reaches its maximum after 5 ms. Longer input pulses will not lead to a higher output voltage. But for shorter input pulses the output voltage doesn't reach its possible maximum. Fig. 10 shows the critical voltage levels of pulsed signals at $f_c = 1$ GHz.

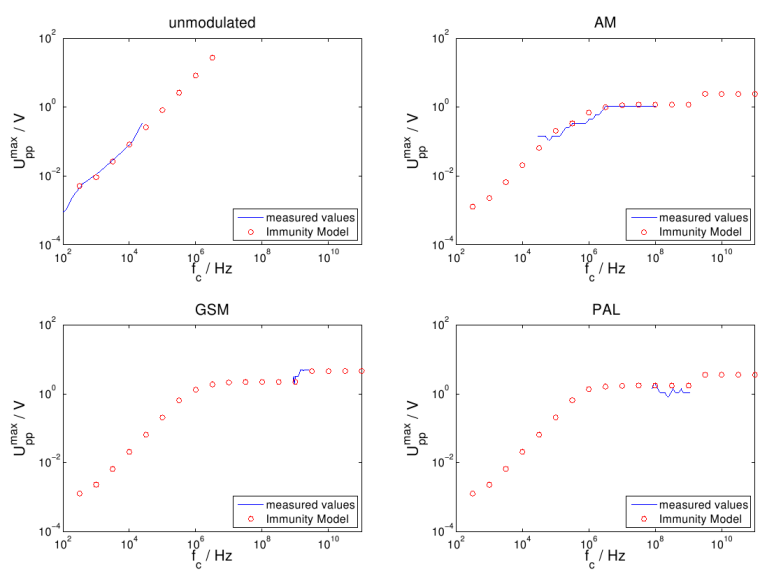

Figure 7: Immunity voltages calculated by the Imunity Model and critical levels from [1] and [2].

5. Conclusion

An analytical model for the calculation of the critical input signal voltages of cardiac pacemakers (PMKs) was presented. The input circuit was analyzed and tranformed into an algebraic description. It is now possible to calculate the reaction of the PMK to any periodic disturbance signal. The model was tested against several known test signals. The correlation between results and measurements was very good.

Thus the model was found suitable for determining threshold amplitudes of periodic disturbance signals that could interfere with a PMK's operation.

6. Acknowledgment

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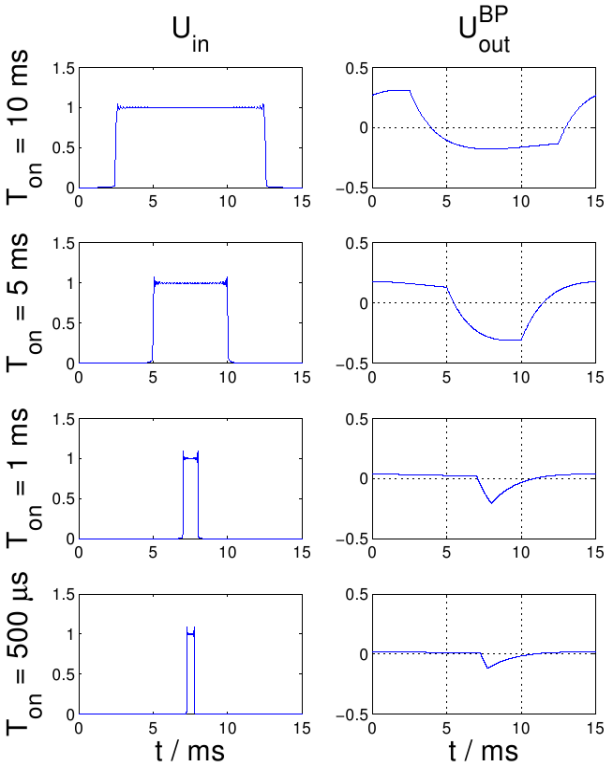

Figure 8: Demodulated and bandpass filtered output signal of short pulses.

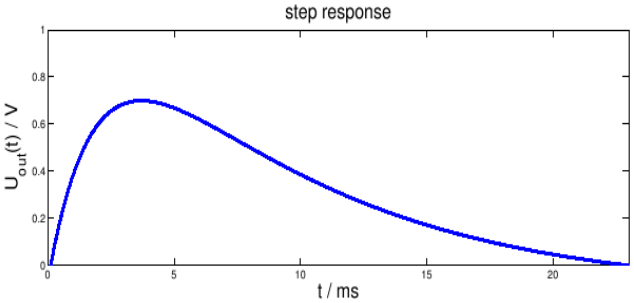

Figure 9: Step response of the bandpass

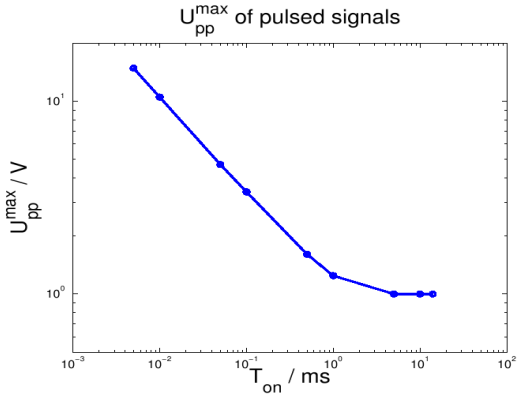

Figure 10: Critical voltage levels of pulsed signals at f_c = 1 GHz