Anti-electromagnetic interference analysis of equivalent circuit of ion channel based on the Hodgkin-Huxley model

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Abstract. With the continuous improvement of circuit integration and working clock frequency in the electronic system, it is increasingly easy for the system to be affected by electromagnetic waves, and electromagnetic susceptibility and vulnerability become more severe. However, living beings in nature have shown extraordinary compatibility, immunity and adaptability to the electromagnetism at the same time. In addition, the ion channel on the neuron cytomembrane is a typical representation of "bioelectrical immunity". So the Hodgkin-Huxley circuit model with one capacitor in parallel with some power supplies and resistors was adopted to simulate the ion channel on the neuron cytomembrane. Through analysis, the circuit model can be used to simulate some electrical characteristics of biological neuron cells, and then acquire a certain level of anti-electromagnetic interference ability. This method will be useful for improving the reliability, compatibility and anti-interference capability of the electronic system in the complicated electromagnetic environment.

1. Introduction
With the development of electronic technology, integrate circuits are widely used in the field of military and aerospace. At the same time, there are always all kinds of electromagnetic interference (EMI) in the application environments [1-2], such as lightning electromagnetic pulse (LEMP) and nuclear electromagnetic pulse (NEMP). Lightning electromagnetic effect consists of electrostatic induction and electromagnetic induction. Integrate circuits are especially susceptible to some short pulse disturbances aroused from electromagnetic induction of LEMP. Lightning is the result of sparks between electrical clouds and the ground. Its current reaches tens to thousands amperes. Lightning current has very high steepness of pulse edge and peak. There will be a transient electromagnetic field around it. The transient electromagnetic field will induce a big induced electromotive force to interfere with nearby electronic equipments. Furthermore, LEMP can also disturb electronic equipments in a short pulse disturbances way. Especially, circuits are especially susceptible to these short pulse disturbances whose rising edges and pulse lengths are in the range of microseconds. In the same way, NEMP will also disturb integrated circuits. Traditional electromagnetic protection measures consist of grounding, shielding and filtering etc. There are many unexpected kinds of short pulse disturbances in
the war field and the space environment. Thus relying solely on traditional protective effect is not good.

Consequently, bionic defensive way for EMI was brought forward [3-4]. The way is to imitate related biological structure and characterises to improve the anti-electromagnetic interference, fault tolerance and self-repairing ability of electronic systems further [5-6]. This paper analyses the ion channel equivalent circuit of classic Hodgkin-Huxley model to improve the anti-interference ability of circuits for short pulse disturbances.

2. **Hodgkin-Huxley mathematical and circuit model**

As shown in figure 1, this creates a simple circuit for measuring the potential difference between the intracellular space and the extracellular fluid. This potential difference is called the membrane voltage. A stimulus current (the 'input' to the cell) can be delivered through the electrode and the resulting changes in membrane voltage (the 'output' from the cell) recorded for later study.

![Figure 1. Simple electrophysiology setup for testing membrane voltage.](image1)

On the basis of such observations, we can find that the membrane voltage of cell rises and falls rapidly, as shown in figure 2. The short-lasting event is called an "action potential". It looks as if a digital pulse. The action potential can propagate over long distance without weakening, and make the neuron realize the long distance transmission of neural information. Therefore, cell membrane's transferring signal performance is better than that of the circuit.

![Figure 2. The ups and downs of an action potential of some cell membrane.](image2)
The Hodgkin-Huxley model (H-H model) is a mathematical model (a type of scientific model) that describes how action potentials in neurons are initiated and propagated. It is a set of nonlinear ordinary differential equations that approximates the electrical characteristics of excitable cells such as neurons and cardiac myocytes. Alan Lloyd Hodgkin and Andrew Huxley described the model in 1952 to explain the ionic mechanisms underlying the initiation and propagation of action potentials in the squid giant axon [7]. They received the 1963 Nobel Prize in Physiology or Medicine for this work.

The components of typical Hodgkin-Huxley model are shown in the figure 3 [8]. Each component of an excitable cell has a biophysical analogy. As shown in Figure 3, we can find that the lipid bilayer membrane separating the intracellular space from the extracellular fluid is capable of storing charge and so acts as a capacitor \( C_M \). Voltage-gated ion channels are represented by nonlinear electrical sodium \( R_{Na} \) and potassium \( R_K \) resistance. This was later shown to be mediated by voltage-gated cation channel proteins, each of which has an open probability that is voltage-dependent. Leak channels are represented by linear resistance \( R_L \). The electrochemical gradients driving the flow of ions are represented by batteries \( E_L, E_{Na} \) and \( E_K \), the values of which are determined from the Nernst potential of the ionic species of interest. Finally, ion pumps are represented by stimulus current sources.

![Figure 3. The Hodgkin-Huxley equivalent circuit.](image)

In this case, the behaviour of the nonlinear resistors is described by a complex system of coupled differential equations (1), (2), (3) and (4) [8].

\[
\frac{dv}{dt} = f(v,h,m,n,i) = -120m^3h(v-45) - 36n^4(v+82) - 0.5(v+60) 
\]

\[
\frac{dh}{dt} = f(v,h) = 0.07e^{\frac{v+55}{20}}(1-h) - \frac{1.0h}{1+e^{\frac{v-14}{5}}} 
\]

\[
\frac{dm}{dt} = f(v,m) = \frac{1}{10} \frac{(v+45)(1-m)}{1-e^{\frac{v-10}{5}}} - 4.0e^{\frac{v-45}{15}}m 
\]

\[
\frac{dn}{dt} = f(v,n) = \frac{0.1 \left( \frac{1}{10} v + 6 \right)(1-n)}{1-e^{\frac{v-30}{5}}} - 0.125e^{\frac{v-40}{10}}n 
\]

The variable \( v \) corresponds to the observed membrane voltage, the variable \( i \) corresponds to the stimulus current, and the hidden variables \( h, m, n \) correspond to gating parameters of the sodium and...
potassium conductance. The equivalent circuit with H-H model can reproduce the behaviour of the modelled systems to a large degree, such as the ups and downs of action potential of the cell membrane, as shown in the figure 2.

3. The analysis of anti-electromagnetic interference ion channel circuit with Hodgkin-Huxley model

It is found that the equivalent circuits with H-H model are not sensitive to short pulse disturbances, which rising edges and pulse lengths are in the range of microseconds (10^{-6} s). This is because the capacitor $C_M$ in equivalent circuits plays a stabilizing role. It is well known that the voltage of an ideal capacitance is continuous. So capacitor’s voltage can’t spring. When a short pulse disturbance comes, the capacitor will charge and delay the cell membrane voltage $V_M$ up. If the short pulse is enough short, $V_M$ will not spring rapidly.

The LEMP and NEMP can generate many kinds of short electromagnetic pulse. The average wave first time of surge aroused from LEMP is $25 \pm 2.5 \mu s$ [9]. The average half peak time of LEMP surge is $55 \pm 15\mu s$. NEMP electric field change more quickly. It can reach a peak value in several nanoseconds ($10^9$ s) [10]. Pulse width of NEMP continues between dozens of nanoseconds and microseconds. The time of action potential of the cell membrane is milliseconds ($10^{-3}$ s). We can see that the pulse width of LEMP and NEMP is so short that the action potential of equivalent circuits will not change sharply in a short time. Accordingly, the equivalent circuits of H-H model have some degree anti-electromagnetic interference ability for short pulse disturbances like LEMP and NEMP.

4. Conclusions

According to the conclusion of “capacitor voltage can’t spring”, the equivalent circuits of H-H model can resist the short pulse disturbances aroused from LEMP and NEMP. If the design is applied to the electronic system in the war field and the space environment, it will improve the anti-electromagnetic interference ability of the circuit system.

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