Chapter 6

Study on the Development of Synapse Model: Integrate-and-Fire Based Model
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Over past few years, excellent models were proposed to simulate post synaptic neuron both for excitatory and inhibitory states. In this chapter a study on the development of synapse model based on Integrate-and-Fire based concept has been carried out. Simulation of the model yields an output representing the overall membrane potential of the postsynaptic region. The description of the model and its simulation results have been presented and compared with the results obtained by the previous researchers.

6.1 Introduction:

As explained in chapter 4, referring to the electrical mechanism of synapse (Fig. 4(a), (b), (c)), when an impulse from the presynaptic neuron arrives at postsynaptic neuron, neurotransmitters are released from the presynaptic neuron. Because of which Sodium ions flow into the cell of the postsynaptic membrane resulting into positive current in case of excitatory synapse and the membrane depolarizes. If the postsynaptic membrane depolarizes sufficiently, then the postsynaptic membrane initiates an action potential. In the case of inhibitory synapse, Chloride ions move into the cell, making the postsynaptic membrane hyperpolarize, resulting into negative current. If the hyperpolarization of the postsynaptic membrane is sufficiently large then the postsynaptic membrane will be able to initiate an action potential, but in negative direction. Fig. 4.1(c) of chapter 4 shows the electrical equivalent circuit of a synapse which consists of a presynaptic neuron, synaptic cleft and postsynaptic neuron. Rewriting the equation 4.2:
I = C(dV_m/dt) + g_n(e(V_m - E_o) - g_{na}(V_m - E_{na}) + g_{cl}(V_m - E_{cl}) + g_{k}(V_m - E_{k}) (6.1)

The expression of total current is composed of capacitive current and ionic current. The basic circuit which can be used to simulate the action of synapse is shown in as Fig. 5.1 in chapter 5 [1]-[3].

In the model developed, each presynaptic neuron has one or more inputs and produces an output; each input having a weighting factor, which modifies the value entering the synapse. The synapse mathematically compares the integrated inputs with a threshold limit, and if the integrated input value is greater than the threshold limit then synapse outputs the result or more precisely an action potential is generated. In the case of excitatory synapse, the synapse mathematically compares the integrated inputs with a threshold limit, and though in this case the integrated input value is less than the threshold limit then also an action potential is generated in positive direction. In the case of inhibitory synapse, the synapse mathematically compares the integrated inputs with a threshold limit, and if the integrated input value is greater than the threshold limit, an action potential is generated but in negative direction.

6.2 A Simple Integrate-and-Fire Based Circuit Model for Excitatory and Inhibitory Synapse:

The membrane of post synaptic neuron has two types of ion channels - excitatory and inhibitory, whereas these channels are ion specific. Sodium ions specific channels are excitatory in nature and Chloride ions specific channels are inhibitory in nature. And the diffusion of Sodium ions into the cell causes a membrane potential in positive direction which is known as excitatory postsynaptic membrane potential (EPSP) whereas the flow of Chloride ions
causes a membrane potential in negative direction which is known as inhibitory postsynaptic membrane potential (IPSP).

When an action potential from the presynaptic neuron arrives at its terminals connecting the cleft, neurotransmitters are released into the cleft which diffuse through the cleft and bind with the receptor sites of the postsynaptic membrane. This binding mechanism opens the ion channels situated at the membrane surface and ions move into or out of the membrane. If the synapse is excitatory, Sodium ions flow into the cell resulting into positive current. As a result the membrane depolarizes. If sufficient number of Sodium channels open, then membrane potential will be greater than the action potential threshold $V_T$ of the neuron and initiates an action potential. If the synapse is inhibitory, Chloride ions move into the cell, resulting into negative current. As a result the membrane hyperpolarizes. If the number of Chloride channels are sufficiently large then membrane potential will be able to initiate an action potential in negative direction.

Here, excitatory and inhibitory synapses based on integrate-and-fire models are developed. The circuit model for the excitatory synapse is shown in Fig. 6.1. The different component values used in the model is given in Table 6.1.
Fig. 6.1. Electrical circuit model of excitatory synapse
The circuit model for the inhibitory synapse is shown in Fig. 6.2. The different component values used in the model is given in Table 6.2.

**TABLE 6.1
DIFFERENT COMPONENTS USED IN THE PROPOSED MODEL OF NEURON OF FIG. 6.1**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Component Name</th>
<th>Component Details</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>V1</td>
<td>A.C. Voltage Source(Pulse)</td>
<td>Volt</td>
<td>5mV</td>
</tr>
<tr>
<td>02</td>
<td>V2</td>
<td>A.C. Voltage Source(Pulse)</td>
<td>Volt</td>
<td>5mV</td>
</tr>
<tr>
<td>03</td>
<td>V3</td>
<td>A.C. Voltage Source(Pulse)</td>
<td>Volt</td>
<td>40mV</td>
</tr>
<tr>
<td>04</td>
<td>R1</td>
<td>Resistor</td>
<td>Ohms</td>
<td>33.33K</td>
</tr>
<tr>
<td>05</td>
<td>R2</td>
<td>Resistor</td>
<td>Ohms</td>
<td>20K</td>
</tr>
<tr>
<td>06</td>
<td>R3</td>
<td>Resistor</td>
<td>Ohms</td>
<td>0.1K</td>
</tr>
<tr>
<td>07</td>
<td>R4</td>
<td>Resistor</td>
<td>Ohms</td>
<td>2K</td>
</tr>
<tr>
<td>08</td>
<td>R5</td>
<td>Resistor</td>
<td>Ohms</td>
<td>2.34K</td>
</tr>
<tr>
<td>09</td>
<td>U1</td>
<td>Op-Amp (μ741)</td>
<td>Volt</td>
<td>60mV</td>
</tr>
</tbody>
</table>

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Fig. 6.2: Electrical circuit model of inhibitory synapse
5.2.1 Results:

The simulation output for excitatory synapse is shown in Fig. 6.3, which illustrates an EPSP with sufficient amplitude for triggering an action potential.
Fig. 6.3: The output profile of excitatory synapse

The simulation output for inhibitory synapse is shown in Fig. 6.4, which illustrates an IPSP with sufficient amplitude for triggering an action potential in negative direction.
Fig. 6.4: The output profile of Inhibitory synapse.

The results obtained from simulation are compared with those reported by previous researchers and are given in Table 6.3.
In the conclusion of this work, it can be summarized that, simple electrical models both for excitatory and inhibitory synapses have been developed by considering a synapse to be made of presynaptic terminals, cleft and postsynaptic membrane. The overall effect of all presynaptic terminals is integrated and then reduced to a single point. The single point value is compared with threshold to produce an output. Models demonstrate the basic mechanism of neuron namely the effects of excitation and inhibition.

### 6.3 References:


