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(72) **Inventeur/Inventor:**
SAEEDFAR, AMIN, CA

(73) **Propriétaire/Owner:**
HUSKY OIL OPERATIONS LIMITED, CA

(74) **Agent:** MLT AIKINS LLP

(54) **Titre :** PROCEDE DE FRACTURATION DE GISEMENT SUBSURFACE A L'AIDE D'IMPULSIONS ELECTROMAGNETIQUES

(54) **Title:** METHOD OF SUBSURFACE RESERVOIR FRACTURING USING ELECTROMAGNETIC PULSE ENERGY

(57) **Abrégé/Abstract:**

A method for initiating and/or propagating fractures in a hydrocarbon reservoir, to improve fluid-flow permeability and hydrocarbon production. The method comprises the use of at least one electromagnetic energy pulse to both heat the reservoir rock and water within, causing thermal pressurization, and initiate electrokinetic pressurization.

Abstract

A method for initiating and/or propagating fractures in a hydrocarbon reservoir, to improve fluid-flow permeability and hydrocarbon production. The method comprises the use of at least one electromagnetic energy pulse to both heat the reservoir rock and water within, causing thermal pressurization, and initiate electrokinetic pressurization.

METHOD OF SUBSURFACE RESERVOIR FRACTURING USING ELECTROMAGNETIC PULSE ENERGY

Field of the Invention

The present invention relates to methods to enhance hydrocarbon reservoir permeability and hydrocarbon production, and specifically to methods for fracturing a hydrocarbon reservoir.

Background of the Invention

The availability of an efficient fracturing method for separating constituents of a rock is of interest for recovering useful materials such as hydrocarbons. Common to all subsurface formation fracturing techniques is the creation of mechanical stresses that exceed the fracture stress of a given formation rock. This leads to generation of micro-cracks in the rock, which consequently results in a significant loss of strength in the formation rock and its fracturing.

Hydraulic fracturing is one form of fracturing that is commonly applied for hydrocarbon reservoir stimulation, especially for tight reservoirs and/or interbedding shale. By creating and/or extending a fracture from a borehole into the reservoir formations, target hydrocarbons such as oil and gas can be produced from the formation towards the borehole with much less flow resistance. Conventionally, in hydraulic fracturing a pressurized fluid used to create and/or widen the fracture is provided with a special type of material such as proppant, which proppant remains in the fracture after injection of the fluid to keep the fracture flow-conductive after relieving fluid pressure.

Other types of fracturing are known in the art. For example, US. Patent Application Publication No. 2012/0061081 Al to Sultenfuss et al. teaches a method of applying steady-state radiofrequency (RF) heating to fracture a reservoir for a steam-assisted gravity drainage (SAGD) application. Notwithstanding the exploration of alternative fracturing methods and techniques, hydraulic fracturing remains a standard and ubiquitous reservoir stimulation method.

However, it is known that hydraulic fracturing techniques have been subject to criticism on environmental grounds, and they can also be undesirably expensive to implement.

What is needed, therefore, is a method for fracturing reservoir rock that can reduce the environmental impact and the associated costs.

Summary of the Invention

The present invention therefore seeks to provide a method for applying electromagnetic energy to a reservoir in such a way that it fractures the reservoir, opening up permeability and enhancing production, while reducing or eliminating the need for conventional hydraulic fracturing techniques.

According to a first broad aspect of the present invention, there is provided a method for initiating and propagating fractures in a hydrocarbon reservoir, the method comprising the steps of:

a. applying at least one electromagnetic energy pulse to a portion of the reservoir;

b. allowing application of the at least one electromagnetic energy pulse to expand pore fluids within the portion of the reservoir;

c. allowing the expansion of the pore fluids to increase pore pressure; and

d. allowing the increased pore pressure to create mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, initiating and propagating fractures in the reservoir.

According to a second broad aspect of the present invention, there is provided a method for improving permeability in a hydrocarbon reservoir, the method comprising the steps of:

a. applying at least one electromagnetic energy pulse to a portion of the reservoir;

b. allowing application of the at least one electromagnetic energy pulse to expand pore fluids within the portion of the reservoir;

c. allowing the expansion of the pore fluids to increase pore pressure; and

d. allowing the increased pore pressure to create mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, fracturing the portion of the reservoir to improve the permeability.

According to a third broad aspect of the present invention, there is provided a method for improving production of hydrocarbon from a reservoir, the method comprising the steps of:

a. applying at least one electromagnetic energy pulse to a portion of the reservoir;

b. allowing application of the at least one electromagnetic energy pulse to expand pore fluids within the portion of the reservoir;

c. allowing the expansion of the pore fluids to increase pore pressure;

d. allowing the increased pore pressure to create mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, initiating and propagating fractures in the reservoir; and

e. producing the hydrocarbon through the fractures.

According to a fourth broad aspect of the present invention, there is provided a method of hydrocarbon reservoir stimulation, the method comprising the steps of:

a. applying at least one electromagnetic energy pulse to a portion of a reservoir;

b. allowing application of the at least one electromagnetic energy pulse to expand pore fluids within the portion of the reservoir;

c. allowing the expansion of the pore fluids to increase pore pressure;

d. allowing the increased pore pressure to create mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, initiating and propagating fractures in the reservoir; and

e. producing hydrocarbon through the fractures.

In some exemplary embodiments of the above aspects, a series of the electromagnetic energy pulses are applied to the portion of the reservoir, or a plurality of the electromagnetic energy pulses are applied to the portion of the reservoir, or the electromagnetic energy pulses are periodically applied to the portion of the reservoir. The preferred methods further comprise the step before step a of determining a suitable pulse strength for the at least one electromagnetic energy pulse. The at least one electromagnetic energy pulse is preferably applied by radiating the at least one electromagnetic energy pulse so as to propagate the at least one electromagnetic energy pulse at least partially through the portion of the reservoir.

The expansion of the pore fluids may result from thermal pressurization and electrokinetic pressurization. The expansion of the pore fluids can result at least partially from vaporization of connate water in the portion of the reservoir. The fractures may comprise micro-cracks, such that the micro-cracks reduce strength of the portion of the reservoir, enabling propagation of the fractures. The mechanical stresses reduce shear strength of the portion of the reservoir, and cause tensile failure of the portion of the reservoir, causing the fracturing.

A detailed description of exemplary embodiments of the present invention is given in the following. It is to be understood, however, that the invention is not to be construed as being limited to these embodiments.

Brief Description of the Drawings

In the accompanying drawings, which illustrate exemplary embodiments of the present invention:

Figure 1 is an illustration of an electric double layer in a fluid-saturated porous medium;

Figure 2 is a simplified view of an electromagnetic (EM) pulse generator in a wellbore, according to an exemplary embodiment of the present invention;

Figure 3 is a chart illustrating real and imaginary parts of the impedance of a reservoir formation;

Figure 4 is a simplified circuit model of a reservoir formation;

Figure 5 is a chart illustrating a single EM energy pulse;

Figure 6 is an illustration of a periodic pulse wave with a smaller frequency than the cosine wave; and

Figure 7 is an illustration of a periodic pulse wave with a frequency equal to the cosine wave.

Exemplary embodiments of the present invention will now be described with reference to the accompanying drawings.

Detailed Description of Exemplary Embodiments

Throughout the following description specific details are set forth in order to provide a more thorough understanding to persons skilled in the art. However, well known elements may not have been shown or described in detail to avoid unnecessarily obscuring the disclosure. The following description of examples of the invention is not intended to be exhaustive or to limit the invention to the precise forms of any exemplary embodiment. Accordingly, the description and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

Unlike conventional hydraulic fracturing, the electromagnetic pulse energy (EMPE) method disclosed herein involves a process of fracture initiation and propagation by a joint thermal-electrokinetic pressurization mechanism that preferably occurs in a relatively short period of time, which results in thermal-pressure shock. Such rapid pressurization may generate multiple fractures, which can be beneficial to reservoir stimulation, particularly in relatively tight formations.

According to some embodiments of the present invention, for general applications and processes (for example, thermal recoveries, CHOPS, conventional recoveries, carbonate reservoirs, clastics reservoirs, shale oil/gas reservoirs, heavy oil reservoirs, etc.), near-instantaneous thermal and pressure stress in the reservoir rock can be introduced through:

1) rapid electromagnetic heating and thermal pressurization of the rock and the water contained within it, and

2) electrokinetic pressurization by means of one or more electromagnetic pulses using high power signals.

In those areas of a target reservoir formation having low permeability, the pore pressure resulting from the electro-thermal expansion of pore fluids and the electrokinetic mechanism may not be balanced with the fluid flow and the fluid volume increment resulting from pore-space dilation. If the pore pressure is created in a relatively short period of time through exerting a pulsed power, particularly an electromagnetic pulse, the described mechanism will be more rapid and dramatic, which can lead to shear or tensile failure of formation rock and creation of desirable micro-cracks and fractures.

<u>EM rapid heating</u>: EM heating can be generally divided into two main categories based on the frequency of the electrical current used by the source, (i) direct (DC)/low frequency currents, and (ii) high frequency (radio frequency (RF), microwave) currents, which may be employed depending on reservoir fluid properties (e.g., resistivity, dielectric permittivity) and other formation characteristics. Two different electromagnetic mechanisms underlie the electromagnetic heating using different kinds of EM sources. When a DC or a low frequency current source is applied, the joule heating based on the electric conduction in materials, is dominant. In this low frequency mechanism, charged particles in an electric circuit are accelerated by an electric field but give up some of their kinetic energy each time they collide with a particle. The increase in the kinetic energy of these particles manifests itself as heat and a rise in the temperature of the conducting material. With a higher frequency electromagnetic source, the dielectric heating prevails in which dipoles formed by the molecules tend to align themselves with the electric field (called dielectric polarization) with a velocity proportional to the frequency of the field's alternation. This molecular movement can result in significant heating, as seen in commercial microwave ovens. The key requirement for dielectric polarization is that the frequency range of the external oscillating field should enable adequate inter-particle interaction. The larger the masses involved, the slower the response upon applying or removing of the external EM field. As the frequency goes higher, the slower polarization mechanisms for heavier particles fail to follow. From the dependency of characteristic relaxation

frequency and particle mass, it can be deduced that at higher frequencies, heating is achieved mostly by polarization mechanisms and local oscillation of charged particles. In contrast, as the frequency decreases, free charge/ionic conduction plays a dominant role in the heating process. Back to the reservoir scale, through the relatively rapid heating, the internal pore pressure of the reservoir rock (for example, interbedding shale) increases, thereby causing the fracturing. When an electromagnetic pulse is utilized (as opposed to steady-state RF heating), rapid heating occurs even faster and the fracturing process is more efficient. Also, an instantaneous input power with greater amplitude can be applied during the EMPE process, which introduces a greater heat rate to the reservoir and further improves the fracturing performance, yet maintains energy efficiency when compared to steady-state radio frequency (RF) heating, which will be described below. Fracturing is achieved by rapid heating through the radiation of electromagnetic high-power pulse signals and consequent near-instantaneous vaporization of the connate water trapped in the reservoir rock, which introduces thermal pressurization and mechanical fracture as a result. While vaporization will take place depending on the heat introduced at a particular point in the reservoir (which depends on distance from the antenna or the location of the electromagnetic beam), vaporization per se does not necessarily have to occur, as dilation pressure can occur due simply to differential thermal expansion coefficients between the pore matrix and the pore space components. In other words, thermal pressurization is overpressure of the pore fluids caused by thermal expansion, which either quickly dissipates in high permeability formations or accumulates in low permeability areas. Thermal pressurization occurs when the thermal expansion of pore fluids exceeds that of the pore space. In this case, the pore-space stiffness acts against the expansion of the pore-fluid volume and compresses the fluid by increasing pore pressure to minimize its increase in volume, which results in a reduction of the effective stress. This reduces the shear strength of the formation rock which may lead to fracturing. This pore pressurization may also induce tensile failure.

Electrokinetic mechanism: The electrokinetic mechanism is based on the fact that mechanical (acoustic pressure) and electromagnetic energies are generally coupled in wetted porous rocks. In a subsurface formation, electrokinetic phenomena arise from the bound charges on a solid surface in contact with an electrically conductive fluid. As a result the electric charges within the fluid separate into an electric double layer (EDL), as is illustrated in Figure 1. The inner layer consists of ions absorbed onto the solid surface, while the outer layer is formed by ions under the combined influence of ordering electrical and disordering thermal forces. A low frequency electromagnetic wave that propagates through such a fluid-saturated porous medium will produce an electric current (called the streaming current) by applying electromagnetic forces on outer layer ions of the EDL. This creates a mechanical disturbance in the fluid and therefore a pressure gradient. By taking this effect into account, the pressure response resulting from low frequency electromagnetic (EM) energy can contribute to the fluid pressurization in a porous media and consequently the fracturing process.

An illustration of an exemplary process is shown in Figure 2, where an EM pulse generator (generating a periodic pulse wave of any shape) located on the surface is connected to an EM applicator in a wellbore (which wellbore may be single/multiple, vertical or horizontal, as would be known to those skilled in the art) through an appropriate transmission line. An EM field is thus propagating through the formation, but its amplitude is attenuating due to the electrical properties and skin depth effect of the reservoir formation; therefore, a single pulse is likely not adequate to create the necessary pressure in some cases for fracturing purposes, and multiple or periodic pulse waves are therefore recommended for consideration. It is possible to combine this aspect of the present invention with various EM sources, such as induction coils as a low frequency EM source or an antennae array as a radio frequency EM source, to focus the beam of the electromagnetic pulse on the area that is to be fractured, in a known manner. It is also possible to use acoustic pulses simultaneously to expedite the fracturing process, again in a manner that would be clear to those skilled in the art.

To illustrate the potential utility of embodiments of the present invention, it is important to note that the soils, unconsolidated sediments, and rocks of the crust of the Earth are principally composed of silicate minerals, which are electrical insulators. Their electrical resistivities are typically greater than 1010 Ohm-m and they carry no current. However, at high temperatures these minerals begin to dissociate and current can be carried by their ions in the pore solutions.

For most rocks and soils where current is carried by ions in the pore fluid, the resistivity depends on the rock properties such as porosity, pore fluid resistivity/salinity, temperature, pore fluid saturation, and pressure. Electrical resistivity or the apparent resistivity is also a function of the frequency of the applied current called electrical impedance, which is a complex number, i.e., the measured voltage has a component in phase with the current and a component 90 degrees out of phase (in quadrature) with the current. The real and imaginary components of V/I (proportional to the resistivity) have the form illustrated in Figure 3.

It has also been observed in field measurements employing a switched DC current that the voltage across the measuring electrodes decayed slowly after the current was shut off. This suggests an energy storage mechanism in the subsurface material. Qualitatively, the transient and frequency domain observations for the resistivity are compatible with the response of the resistor-capacitor circuit analog illustrated in Figure 4.

At DC the capacitor is an open circuit and all the current passes through the sum of R1 and R2, developing a voltage V = I × (R1 + R2). As the frequency increases, current can flow through the capacitor, which decreases the overall resistance. Finally, at high frequency the current is effectively short circuited by the capacitor and the voltage developed is simply V = I × R1. Between the DC and high frequency limits the voltage across the capacitor is phase shifted 90° from the current and so adds an imaginary component to the total voltage measured across the circuit, which peaks midway between the low and high frequency asymptotes. Thus it can be seen that the illustrated circuit reproduces the key features observed in measurements. The electric circuit representation of subsurface formation rock is a simplified model of the rock electrical behaviour. While more complicated circuit representations could be developed based on other electrical mechanisms in rocks, the basic model in Figure 4 is employed for simplicity. However, the proposed methodology can be employed for other types of electric circuit representations.

To begin, the impedance of the circuit model at given angular frequency, $\omega = 2\pi f$, is written as

$$\frac{V}{I} = Z = |Z(\omega)|e^{j\varphi(\omega)} = R_1 + \frac{1}{\frac{1}{R_2} + j\omega C} = \frac{R_1 + R_2 + j\omega C R_1 R_2}{1 + j\omega C R_2} \qquad (1)$$

where $j = \sqrt[2]{-1}$. If the applied voltage is a single frequency cosine wave (steady-state source), then the time-averaged power being consumed by the electric circuit (turned to heat in the rock) is given by

$$\langle p_s \rangle = \frac{1}{2} Re\{V_0 I^*\} = \frac{1}{2} Re\left\{\frac{V_0^2}{Z^*}\right\} = \frac{V_0^2}{2}\frac{1}{k_1}\frac{k_2 + \omega^2 C R_2}{k_2^2 + \omega^2} \tag{2}$$

where

$$k_1 = C R_1 R_2 \,, \qquad k_2 = \frac{R_1 + R_2}{C R_1 R_2} \tag{3}$$

as the time domain input voltage is defined as

$$v_s(t) = V_0 \cos(\omega_0 t) \tag{4}$$

and the instantaneous power delivered to the circuit can be written as follows

$$\begin{aligned} p_s(t) = v_s(t) i_s(t) &= \frac{V_0^2}{|Z(\omega_0)|}\cos(\omega_0 t)\cos\big(\omega_0 t - \varphi(\omega_0)\big) \\ &= \frac{1}{2}\frac{V_0^2}{|Z(\omega_0)|}\big[\cos\big(2\omega_0 t - \varphi(\omega_0)\big) + \cos\big(\varphi(\omega_0)\big)\big] \end{aligned} \tag{5}$$

Therefore the maximum instantaneous power is given by

$$\max_t p_s(t) = \frac{1}{2}\frac{V_0^2}{|Z(\omega_0)|}\big[1 + \cos\big(\varphi(\omega_0)\big)\big] \tag{6}$$

In the case of a single pulse (for example, a rectangular pulse as illustrated in Figure 5), the frequency spectrum is wide band and continuous. In this case, the instantaneous power could be greater than the single frequency time harmonic wave, but for the EMPE fracturing to be more effective the source has to emit multiple pulses, which lead to a periodic pulse emission from the EM applicator.

In the case of a general periodic pulse voltage, Fourier expansion is required to calculate the maximum and average power to the load. The frequency of the periodic pulse wave is selected in the same way that it is done for the single frequency time harmonic wave, which is based on electrical properties, electromagnetic loss tangent and skin depth of the reservoir formation. However, it is recommended that the frequency of the periodic pulse wave be less than (as in Figure 6) or equal to (as in Figure 7) the reference frequency of the time harmonic wave. This will adjust the frequency contents of the periodic pulse wave source so that it can contribute in both low frequency electrokinetic and wide range frequency thermal mechanisms in reservoir formations.

The time-domain representation of a generic periodic pulse is given by

$$v_T(t) = \sum_{n=-\infty}^{+\infty} a_n \, e^{jn\omega_0 t} \tag{7}$$

and its Fourier spectrum is then given by

$$V_T(\omega) = \sum_{n=-\infty}^{+\infty} 2\pi a_n \, \delta(\omega - n\omega_0) \tag{8}$$

where $\delta(\omega)$ is the Dirac-delta function. As it is seen from (8), unlike the single frequency cosine wave, a generic periodic pulse voltage has an infinite number of frequency components. As such, higher frequency components can contribute to dielectric heating and lower frequency components can contribute to both resistive heating and the electrokinetic process. As described above, all these mechanisms may be beneficial for the thermal and hydro pressurization of a fluid saturated porous medium to create fractures.

Now, using Parseval's theorem, it can be easily shown that the time-average power consumed by the load for a generic periodic pulse is calculated by

$$\langle p_T \rangle = \frac{|a_0|^2}{Z(0)} + 2\sum_{n=0}^{+\infty} \frac{|a_n|^2}{|Z(n\omega_0)|} Re\{Z(n\omega_0)\} \tag{9}$$

In the following workflow, from an energy transport perspective, it will be shown why EM pulse energy is more effective than steady-state single frequency EM wave for rapid heating purposes. To create a pulse voltage that can provide greater heat (and consequently thermal pressurization) than a single frequency cosine wave at a given frequency, the periodic pulse with a given shape can be designed so that time-average power consumed by the load is the same for the periodic pulse wave and single frequency cosine wave but the instantaneous power delivered to the load by the periodic pulse wave is greater than that of the single frequency cosine wave, i.e.,

$$\begin{cases} \langle p_T \rangle = \langle p_s \rangle \\ \max_t p_T(t) \gg \max_t p_s(t) \end{cases} \tag{10}$$

By imposing the conditions in (10), the total input energy provided by both types of source of voltages are the same but the instantaneous power which provides thermal shock and kinetic pressurization is greater for the periodic pulse wave than single frequency cosine wave. Here, this process is described for the rectangular pulse and cosine wave shown in Figure 6 or 7. However, the same procedure can be done for any type of periodic pulse wave and time-harmonic single frequency wave form.

To then obtain the time-average power delivered to the circuit shown in Figure 4 from a periodic pulse voltage source as show in Figures 6 and 7, one will first calculate the electric current from a voltage source as shown in Figure 5, which is one single pulse from the periodic waveform.

Using the fundamentals of electric circuits theory, one can show that the electric current is obtained by

$$i(t) = V_m\left[\frac{1}{R_1+R_2}+\left(\frac{1}{R_1}-\frac{1}{R_1+R_2}\right)e^{-k_2 t}\right]u(t)$$
$$-V_m\left[\frac{1}{R_1+R_2}+\left(\frac{1}{R_1}-\frac{1}{R_1+R_2}\right)e^{-k_2(t-\tau)}\right]u(t-\tau)$$

(11)

where $u(t)$ is the Heaviside step function. Using the theory of a linear time-invariant system, it can be shown then that the electrical current as the response of periodic pulse is given by

$$i_T(t) = \sum_{n=-\infty}^{+\infty} i(t+nT)$$

(12)

Therefore, the time-average power delivered to the circuit is given by

$$\langle p_T\rangle = \frac{1}{T}\int_T v_T(t)\, i_T(t)dt$$
$$= \frac{{V_m}^2}{T}\left[\frac{\tau}{R_1+R_2}+\frac{1}{k_2}\frac{1-e^{-k_2\tau}}{1-e^{-k_2T}}\left(\frac{1}{R_1}-\frac{1}{R_1+R_2}\right)\right.$$
$$\left.-\frac{1}{k_2}\frac{1-e^{-k_2\tau}}{1-e^{-k_2T}}\left(\frac{1}{R_1}-\frac{1}{R_1+R_2}\right)e^{-k_2(T-\tau)}\right]$$

(13)

For a sufficiently large amplification coefficient, G, the following selection is made so that the instantaneous power delivered by periodic pulse waveform becomes greater than single frequency cosine wave (steady-state source)

$$V_m = \sqrt{G(R_1+R_2)\max_t p_s(t)} = \sqrt{\frac{G(R_1+R_2)}{2}\frac{{V_0}^2}{|Z(\omega_0)|}\left[1+\cos(\varphi(\omega_0))\right]}$$

(14)

Now, for this value of V_m, the following nonlinear algebraic equation has to be solved for τ ($\tau < T$) to find the appropriate duty cycle for the periodic pulse wave so the time-average power from both voltage sources become equal.

$$\frac{V_m^2}{T}\left[\frac{\tau}{R_1+R_2}+\frac{1}{k_2}\frac{1-e^{-k_2\tau}}{1-e^{-k_2T}}\left(\frac{1}{R_1}-\frac{1}{R_1+R_2}\right)-\frac{1}{k_2}\frac{1-e^{-k_2\tau}}{1-e^{-k_2T}}\left(\frac{1}{R_1}-\frac{1}{R_1+R_2}\right)e^{-k_2(T-\tau)}\right] = \frac{V_0^2}{2}\frac{1}{k_1}\frac{k_2+\omega^2CR_2}{k_2^2+\omega^2} \tag{15}$$

Thus, a periodic pulse wave can be designed by a skilled person based on this teaching which can provide greater instantaneous power to the load compared to a single frequency time harmonic wave for a given frequency and yet, maintain an equal total input power.

Similarly, a system can be designed so that the maximum instantaneous power delivered by a periodic pulse wave and a single frequency time harmonic wave are equal but the time-average power delivered by the periodic pulse wave becomes much less than that of single frequency time harmonic wave, i.e.,

$$\begin{cases} \langle p_T \rangle \ll \langle p_s \rangle \\ \max\limits_t p_T(t) = \max\limits_t p_s(t) \end{cases} \tag{16}$$

The potential benefit of using a periodic pulse wave over a single frequency time harmonic wave is also demonstrated, where less input power from a periodic pulse wave source gives the same maximum instantaneous dissipated power that can be transformed to equal thermal shock for fracturing purposes.

This proposed technique is potentially both more environmentally friendly than conventional hydraulic fracturing and less expensive. However, this invention can potentially be combined with standard hydraulic fracturing techniques to improve the process. The performance can be evaluated and dynamically tracked through a micro-seismic monitoring system installed nearby.

As will be clear from the above, those skilled in the art would be readily able to determine obvious variants capable of providing the described functionality, and all such variants and functional equivalents are intended to fall within the scope of the present invention.

Specific examples have been described herein for purposes of illustration. These are only examples. The technology provided herein can be applied to contexts other than the exemplary contexts described above. Many alterations, modifications, additions, omissions and permutations are possible within the practice of this invention. This invention includes variations on described embodiments that would be apparent to the skilled person, including variations obtained by: replacing features, elements and/or acts with equivalent features, elements and/or acts; mixing and matching of features, elements and/or acts from different embodiments; combining features, elements and/or acts from embodiments as described herein with features, elements and/or acts of other technology; and/or omitting combining features, elements and/or acts from described embodiments.

The foregoing is considered as illustrative only of the principles of the invention. The scope of the claims should not be limited by the exemplary embodiments set forth in the foregoing, but should be given the broadest interpretation consistent with the specification as a whole.

Claims

1. A method for initiating and propagating fractures in a hydrocarbon reservoir, the method comprising the steps of:

   a) applying at least one radiofrequency electromagnetic energy pulse to a portion of the reservoir;

   b) expanding pore fluids within the portion of the reservoir via the at least one radiofrequency electromagnetic energy pulse;

   c) increasing pore pressure via the expansion of the pore fluids; and

   d) creating mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, thereby initiating and propagating fractures in the reservoir;

   wherein the initiating and propagating of the fractures in the reservoir is caused by a joint thermal-electrokinetic process via the application of the at least one radiofrequency electromagnetic energy pulse to the portion of the reservoir.

2. The method of claim 1 wherein a series of the radiofrequency electromagnetic energy pulses are applied to the portion of the reservoir.

3. The method of claim 1 wherein a plurality of the radiofrequency electromagnetic energy pulses are applied to the portion of the reservoir.

4. The method of claim 1 wherein the radiofrequency electromagnetic energy pulses are periodically applied to the portion of the reservoir.

5. The method of claim 1 further comprising the step before step a) of determining a suitable pulse strength for the at least one radiofrequency electromagnetic energy pulse.

6. The method of claim 1 wherein the at least one radiofrequency electromagnetic energy pulse is applied by radiating the at least one radiofrequency electromagnetic energy pulse

so as to propagate the at least one radiofrequency electromagnetic energy pulse at least partially through the portion of the reservoir.

7. The method of claim 1 wherein the expansion of the pore fluids results from thermal pressurization and electrokinetic pressurization.

8. The method of claim 1 wherein the expansion of the pore fluids results at least partially from vaporization of connate water in the portion of the reservoir.

9. The method of claim 1 wherein the fractures comprise micro-cracks.

10. The method of claim 9 wherein the micro-cracks reduce strength of the portion of the reservoir, enabling propagation of the fractures.

11. A method for improving permeability in a hydrocarbon reservoir, the method comprising the steps of:

a) applying at least one radiofrequency electromagnetic energy pulse to a portion of the reservoir;

b) expanding pore fluids within the portion of the reservoir via the at least one radiofrequency electromagnetic energy pulse;

c) increasing pore pressure via the expansion of the pore fluids; and

d) creating mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, thereby fracturing the portion of the reservoir to improve the permeability;

wherein the fracturing of the portion of the reservoir to improve the permeability is caused by a joint thermal-electrokinetic process via the application of the at least one radiofrequency electromagnetic energy pulse to the portion of the reservoir.

12. The method of claim 11 wherein a series of the radiofrequency electromagnetic energy pulses are applied to the portion of the reservoir.

13. The method of claim 11 wherein a plurality of the radiofrequency electromagnetic energy pulses are applied to the portion of the reservoir.

14. The method of claim 11 wherein the radiofrequency electromagnetic energy pulses are periodically applied to the portion of the reservoir.

15. The method of claim 11 further comprising the step before step a) of determining a suitable pulse strength for the at least one radiofrequency electromagnetic energy pulse.

16. The method of claim 11 wherein the at least one radiofrequency electromagnetic energy pulse is applied by radiating the at least one radiofrequency electromagnetic energy pulse so as to propagate the at least one radiofrequency electromagnetic energy pulse at least partially through the portion of the reservoir.

17. The method of claim 11 wherein the expansion of the pore fluids results from thermal pressurization and electrokinetic pressurization.

18. The method of claim 11 wherein the expansion of the pore fluids results at least partially from vaporization of connate water in the portion of the reservoir.

19. The method of claim 11 wherein the mechanical stresses reduce shear strength of the portion of the reservoir, causing the fracturing.

20. The method of claim 11 wherein the mechanical stresses cause tensile failure of the portion of the reservoir, causing the fracturing.

21. A method for improving production of hydrocarbon from a reservoir, the method comprising the steps of:

a) applying at least one radiofrequency electromagnetic energy pulse to a portion of the reservoir;

b) expanding pore fluids within the portion of the reservoir via the at least one radiofrequency electromagnetic energy pulse;

c) increasing pore pressure via the expansion of the pore fluids;

d) creating mechanical stresses in the portion of the reservoir exceeding fracture stress of the portion of the reservoir, thereby initiating and propagating fractures in the reservoir; and

e) producing the hydrocarbon through the fractures;

wherein the initiating and propagating of fractures in the reservoir is caused by a joint thermal-electrokinetic process via the application of the at least one radiofrequency electromagnetic energy pulse to the portion of the reservoir.

22. The method of claim 21 wherein a series of the radiofrequency electromagnetic energy pulses are applied to the portion of the reservoir.

23. The method of claim 21 wherein a plurality of the radiofrequency electromagnetic energy pulses are applied to the portion of the reservoir.

24. The method of claim 21 wherein the radiofrequency electromagnetic energy pulses are periodically applied to the portion of the reservoir.

25. The method of claim 21 further comprising the step before step a) of determining a suitable pulse strength for the at least one radiofrequency electromagnetic energy pulse.

26. The method of claim 21 wherein the at least one radiofrequency electromagnetic energy pulse is applied by radiating the at least one radiofrequency electromagnetic energy pulse so as to propagate the at least one radiofrequency electromagnetic energy pulse at least partially through the portion of the reservoir.

27. The method of claim 21 wherein the expansion of the pore fluids results from thermal pressurization and electrokinetic pressurization.

28. The method of claim 21 wherein the expansion of the pore fluids results at least partially from vaporization of connate water in the portion of the reservoir.

29. The method of claim 21 wherein the fractures comprise micro-cracks.

30. The method of claim 29 wherein the micro-cracks reduce strength of the portion of the reservoir, enabling propagation of the fractures.

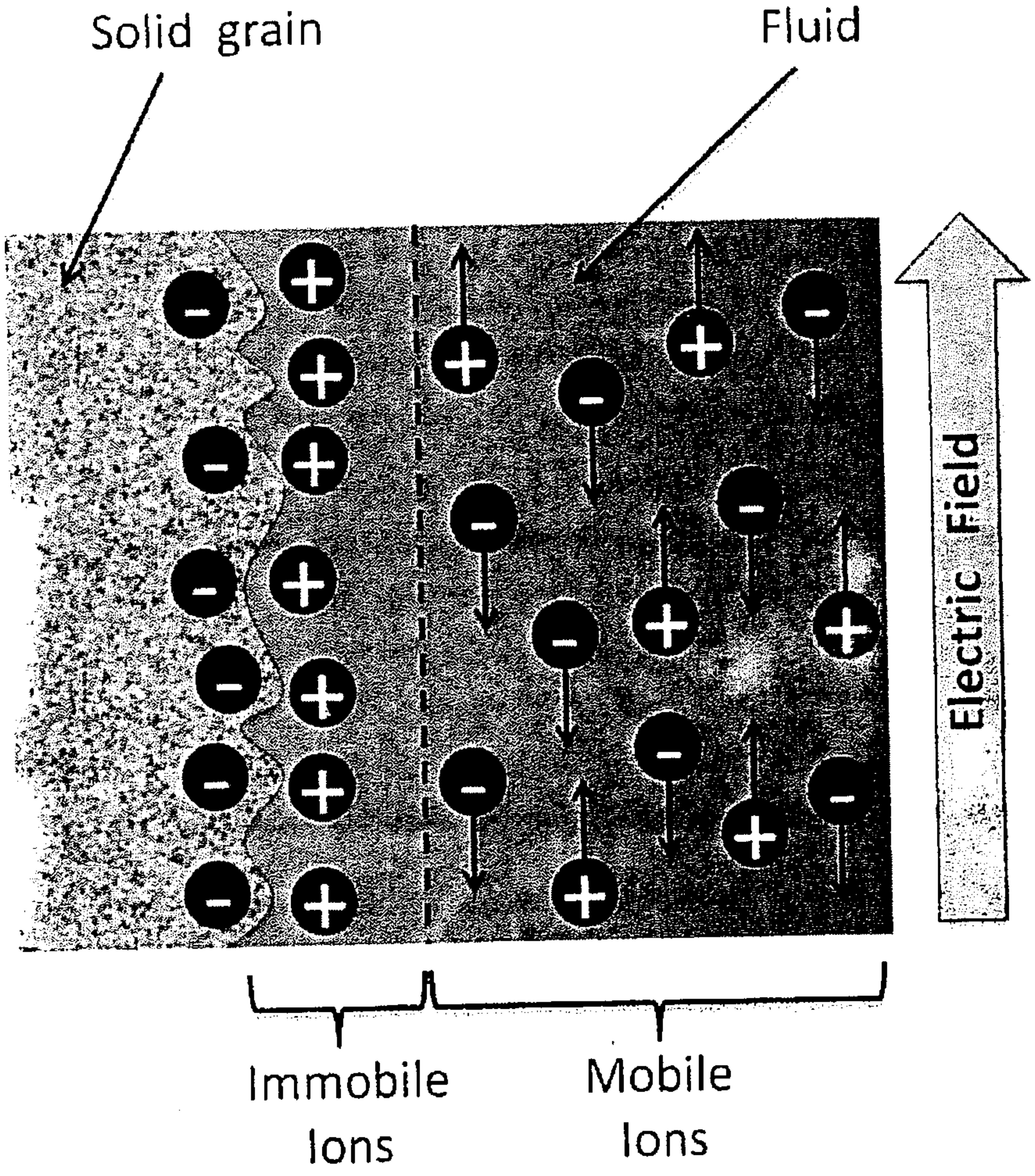
Solid grain
Fluid
Electric Field
Immobile Ions
Mobile Ions

FIG. 1

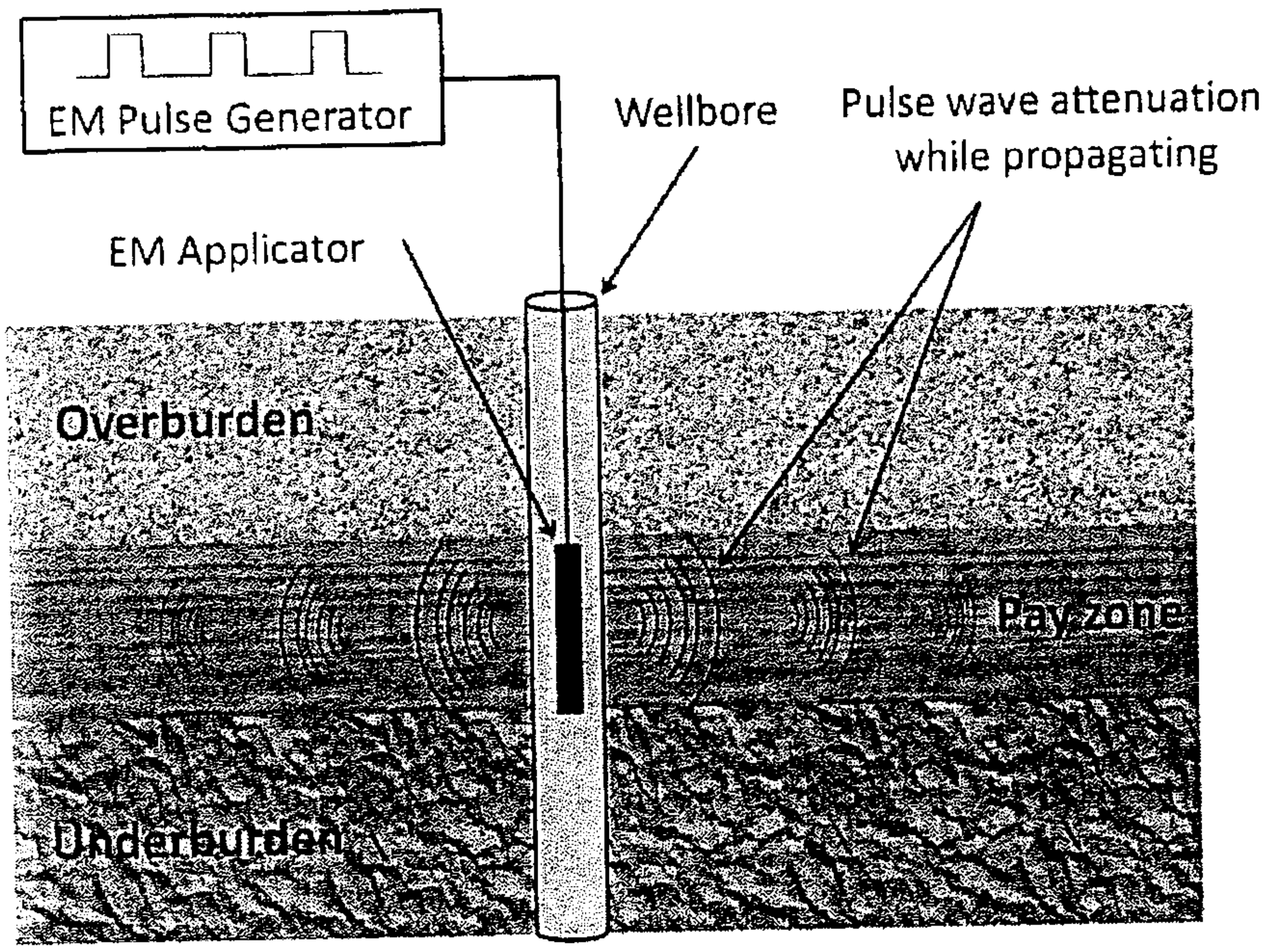
EM Pulse Generator
Wellbore
Pulse wave attenuation while propagating
EM Applicator
Overburden
Pay zone
Underburden

FIG. 2

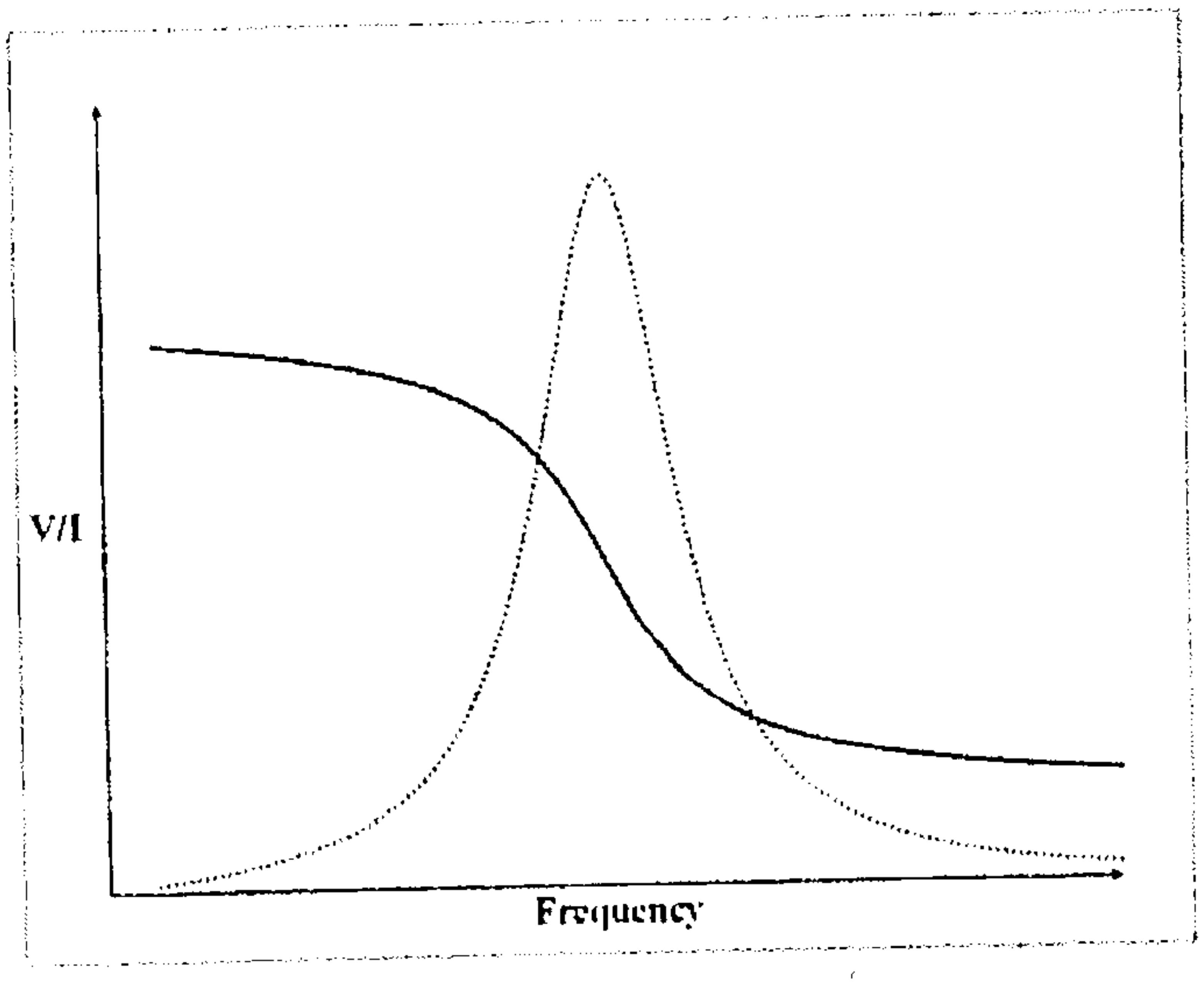
V/I
Frequency

FIG. 3

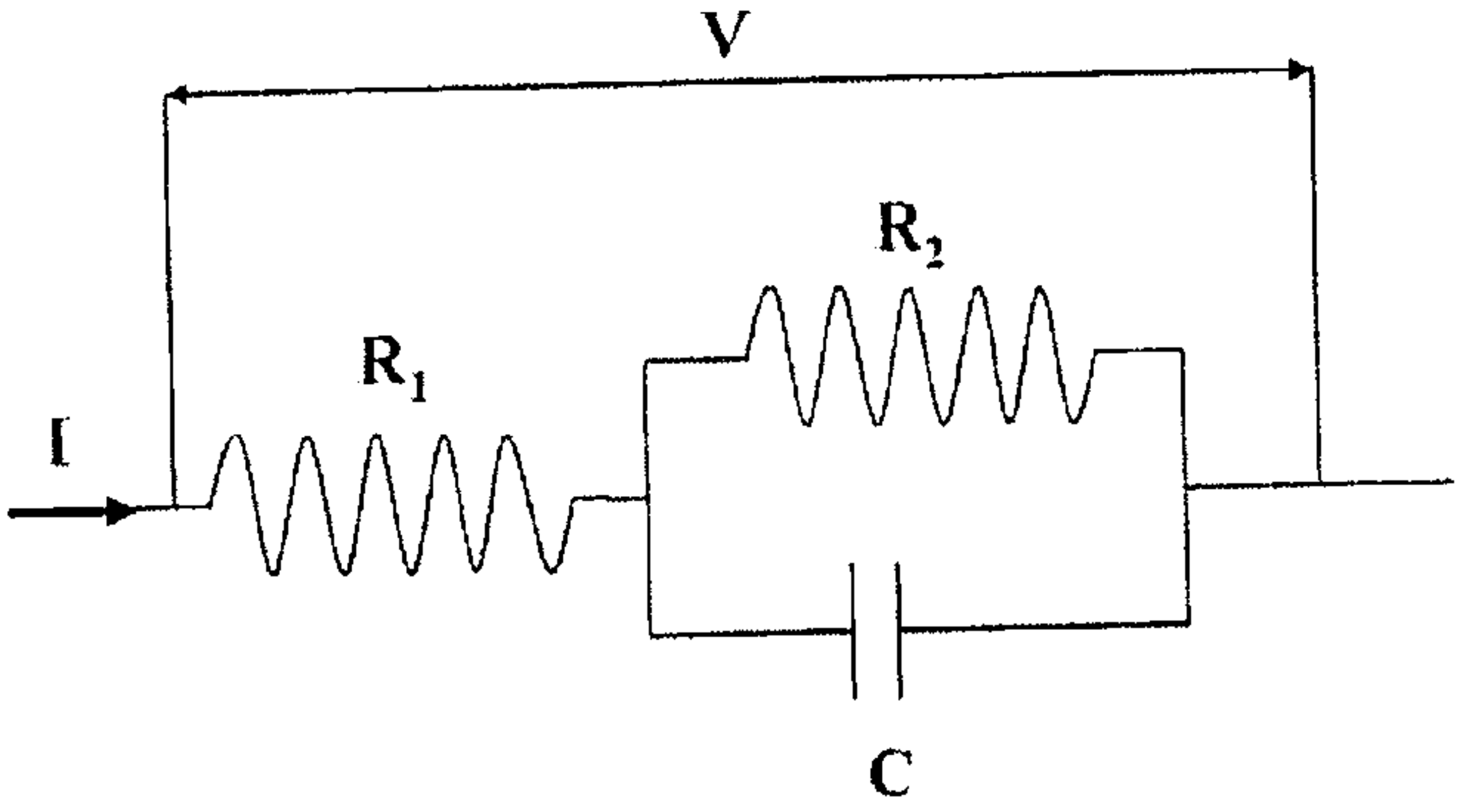

FIG. 4

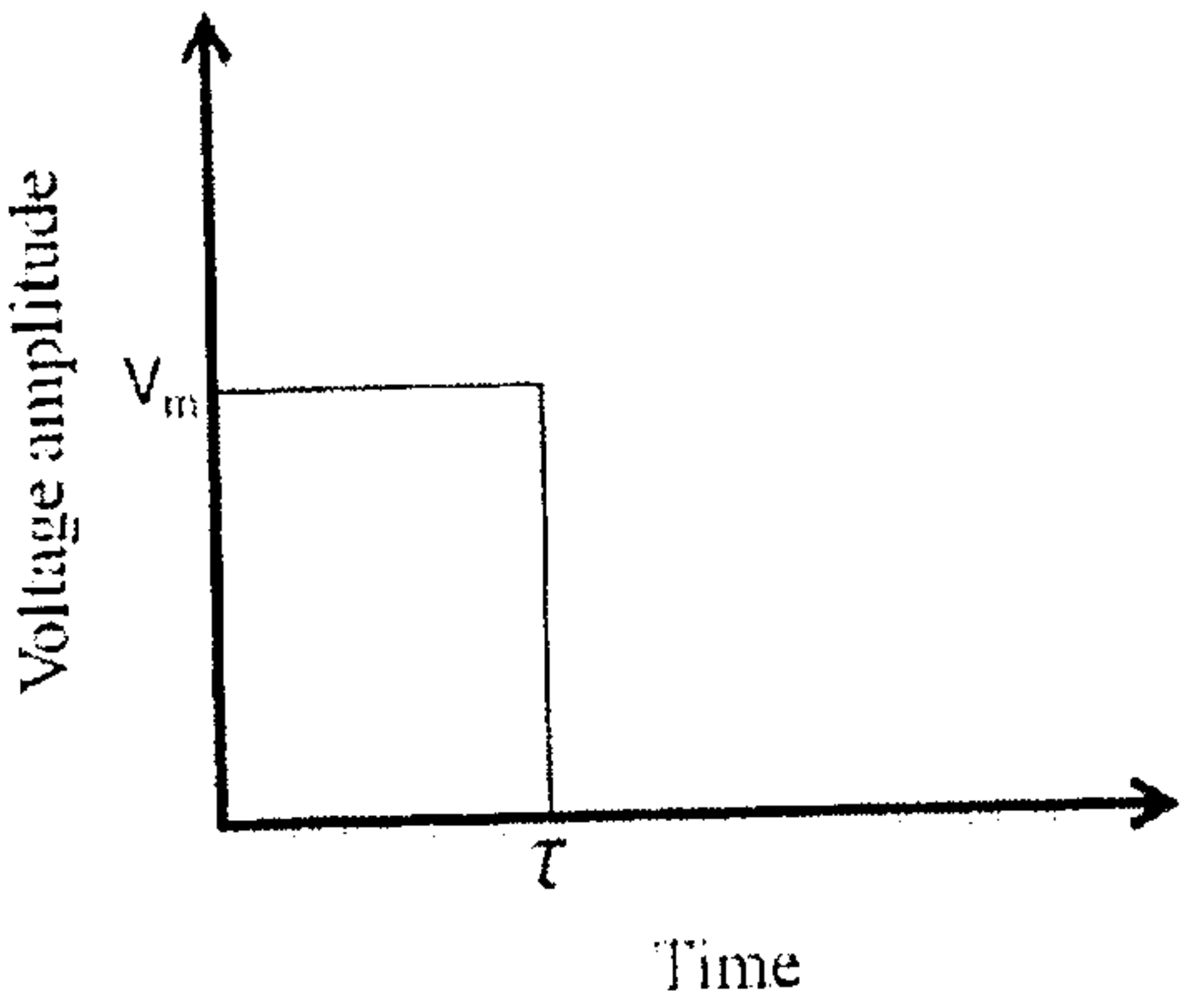

FIG. 5

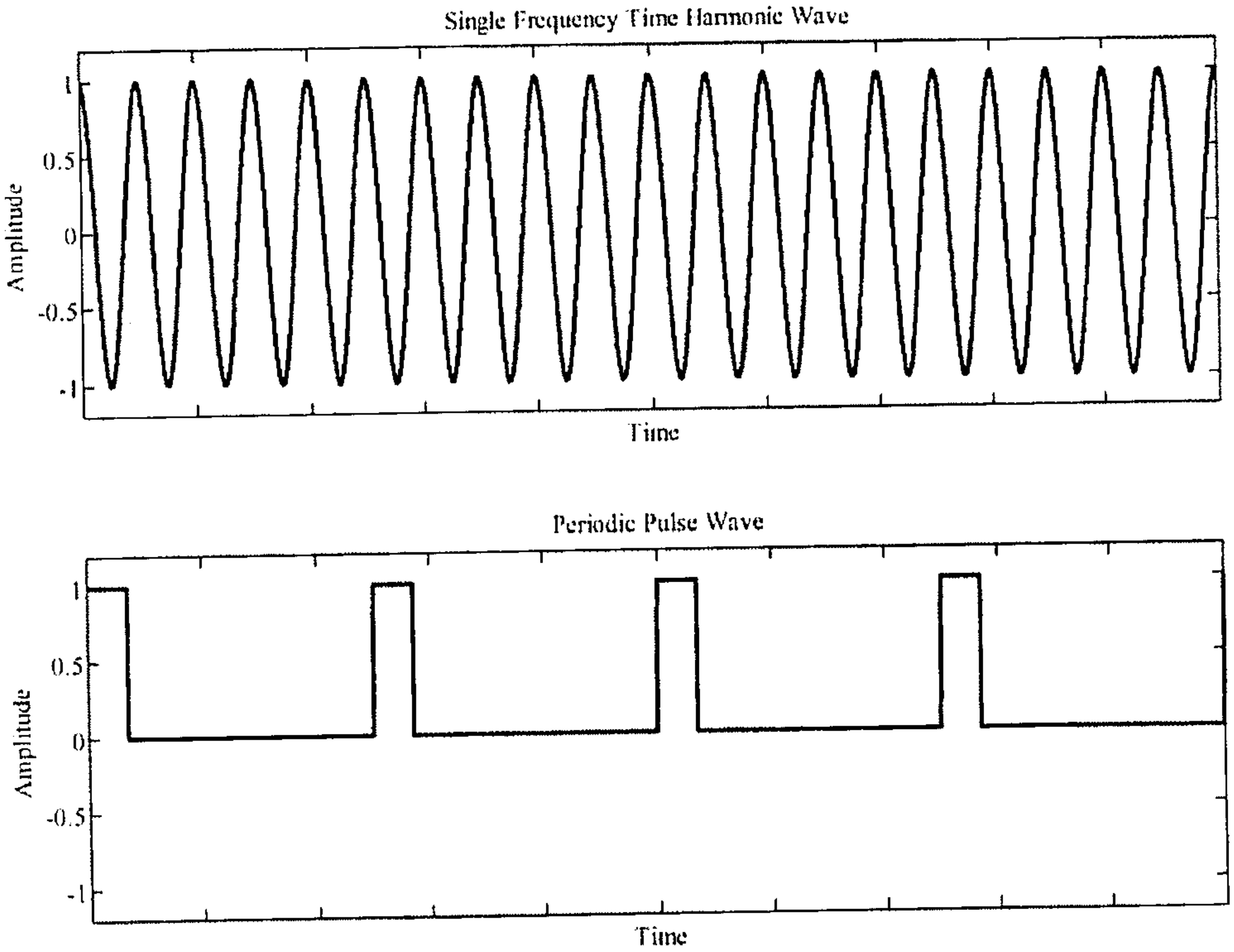
Single Frequency Time Harmonic Wave
1
0.5
0
-0.5
-1
Amplitude
Time
Periodic Pulse Wave
1
0.5
0
-0.5
-1
Amplitude
Time

FIG. 6

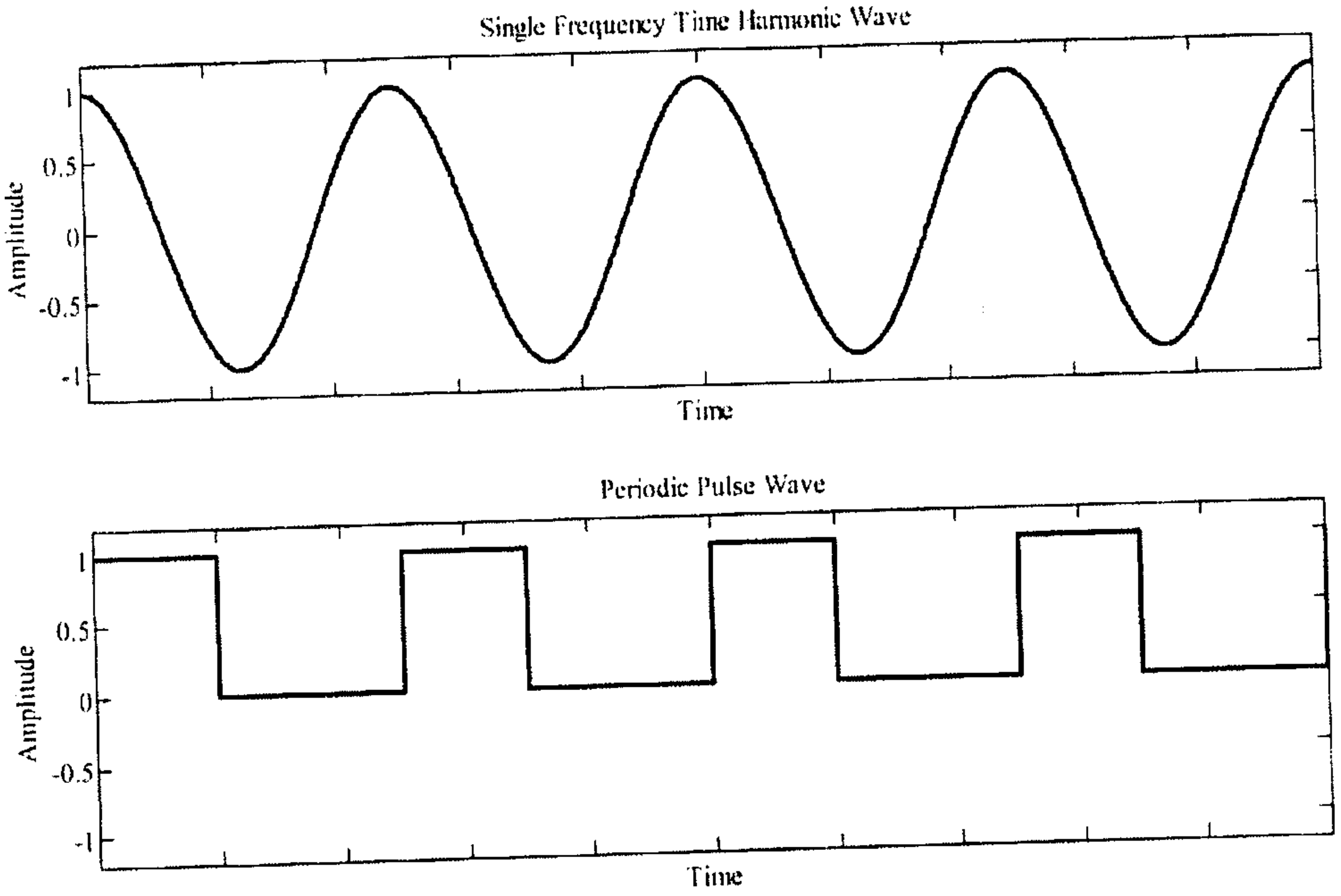
Single Frequency Time Harmonic Wave
Amplitude
1
0.5
0
-0.5
-1
Time
Periodic Pulse Wave
Amplitude
1
0.5
0
-0.5
-1
Time

FIG. 7