International Conference on Renewable Energies and Power Quality (ICREPQ'15)
La Coruña (Spain), 25th to 27th March, 2015
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.13, April 2015

STUDY OF INDUCED VOLTAGE BY LIGHTNING ON TRANSMISSION LINES

P.C.A. Mota[1], J.R. Camacho[1] and M.L.R. Chaves[1]

[1] School of Electrical Engineering
Universidade Federal de Uberlândia
Campus Santa Mônica, 38400-902 Uberlândia. MG (Brazil)
Phone/Fax number: +55.24.3239.4704, e-mail: pmdemota@yahoo.com.br, jrcamacho@ufu.br, lynce@ufu.br

Abstract. In performance analysis of transmission lines facing lightning, it is extremely important the study of voltages induced by indirect discharges because they occur frequently. The voltages induced by such discharges, can reach high amplitudes, that requires more attention to this phenomenon. The induced voltages can cause shutdowns of the network and even damage the equipment connected to it. As an alternative to analysis of the induced voltage by indirect discharges, this paper proposes the computational modeling of the phenomenon, based on the methodology developed by Sune Rusck, which is highly regarded and used for this type of study. The environment used will be EMTP/ATPDraw, which is public domain, besides being widely used as reference in studies of electromagnetic transients in power systems. From computer simulations, induced voltages are obtained, and presented the analyzes of the influence of some parameters in its amplitude and waveform.

Keywords Induced voltage, transmission lines, atmospheric discharges, EMTP/ATPDraw.

1. Introduction

Induced voltage transmission lines, due to indirect lightning strikes, is a phenomenon that attracts the attention of researchers, because it brings several losses, either directly with damage to hardware and electrical equipment or, indirectly, due to a simple shortage in power supply.

Since 1908, with the work of K.W Wagner, this phenomenon is studied , but only in 1957 that this area gain strength, with the publication of Sune Rusck [1], which presented an electromagnetic perspective for voltage induction by indirect lightning strikes.

The computational evolution has brought the possibility of a fast and reliable analysis of this type of phenomenon, in order to determine causes of disconnections of transmission lines, defects in equipment and compensation analysis.

Based on the theory of Rusck, a computational model of induced voltage in transmission lines, will be developed in a EMTP/ATPDraw environment, which is a free of charge software and widely used by the electric sector for the calculus of electromagnetic transients in power systems.

2. The Return Current

The atmospheric discharge consists of consecutive current peaks, which directly influence the electromagnetic field that is formed.

However, the largest peak current occurs in the return current [4], causing it to have greater prominence during the atmospheric discharge process. As a result, this current is normally chosen for analysis of the performance of the transmission lines facing atmospheric discharge.

The return current has a peculiar feature of presenting very small parameters or very big ones (for example microseconds and kilo-amperes).

Thus, any error in the estimation of these parameters leads to inconsistent results. Following are some of these parameters, which will be used in this study.

- Peak value of the return current (Io): value given in kilo-amperes (kA) which has average values of 30 to 50kA, which may reach 300 kA [3].
- Wave-front time or crest time (tcr): time interval, given in microseconds, between the beginning of the return current and its peak value. The crest time is standardized by the IEEE in 1.2 μs [5] -[6].
- Half-wave time or tail time (tcl): time slot, given in microseconds, between the beginning of the discharge and the point where its amplitude drops to 50% of the peak value. This value is standardized by the IEEE in 50 μs [5] -[6].

3. The Return Current Mathematical Modeling

The simulations and result analysis, relate directly to the computer representation of the waveform of the return current. Thus it is important to choose a mathematical model, that is true to the actual waveform, in order to obtain results that are as reliable as possible.

Although there are several models to represent the return current, in this paper we will use the model of the "Double Exponential". This model simplifies the process of differentiation and integration of the wave in time, and also facilitates the computational implementation of the return current. Furthermore, this is the formulation used in traditional pulse generators in laboratories.

The model of "Double Exponential"[7], uses exponential functions combined with other variables, as shown in (1) to reach the expected wave form.

$$I_{retorno} = k * I_o * \left(e^{-\alpha * t} - e^{-\beta * t}\right), \text{para} t \geq 0 \ (1)$$

Where:

k is a correction factor of current amplitude, given by:

$$k = I_o \Big/ \left(e^{\alpha * t_{cr}} - e^{\beta * t_{cr}}\right);$$

I_o is the magnitude of the return current.

α and β are parameters that depend on the time variables of the return current and are given by:

$$\alpha = \ln(2)/\left(t_{cr} - t_{cl}\right); \qquad \beta = \ln(\alpha/\beta)/t_{cr} + \alpha;$$

It is known that to obtain the parameters α and β isn't a spontaneous procedure, these can be obtained from the *trust region method* [8].

4. The Rusck Methodology

In 1957 Sune Rusck, published the theory [1], that would be the basis of studies of voltage induced by indirect lightning strikes. The importance of this work was due to the fact that proposed an analytical expression, grounded in the theory of electromagnetic fields, to estimate the induced voltage in close proximity to reality.

Due to the wide acceptance and satisfactory results, this work will be based on Rusck´s research. Therefore the understanding of the theory is necessary in order to implement a faithful model to this study.

A. *Considerations on Rusck's model*

Rusck based this theory in a three conductor system positioned horizontally, at a certain height above ground level - representing a three-phase transmission line, and a discharge channel through which the return current flows towards the ground to the cloud, arranged vertically and near the line - representing the atmospheric discharge cause of induced voltages on the line.

Rusck still made some considerations to simplify the analytical equation to calculate the induced voltage, without significantly altering the expected results. Such considerations are mentioned below:

- Despite the atmospheric discharge consist in phases, taking in to consideration the current flowing through it, and analyzing their characteristics, the return current was considered the main cause of induced voltage.
- Was estimated a perpendicular discharge upon the ground, that is, a straight and vertical discharge channel. This account has significantly simplified the analytical calculus, but the results weren´t influenced significantly.
- The distribution of electrical charges in the discharge channel isn´t uniform, due to the variation of the capacitance, according to the proximity to the ground. However, in less high altitudes (a few hundred meters), the loads are more evenly distributed. This implies that, for the study of transmission lines (low altitudes), was considered uniform the load distribution from the discharge channel.
- The return current waveform was considered the type "step", traveling without distortion along the channel.
- It was supposed the soil as a perfect conductor. The soil resistivity in this calculus only begins to be significant for long distances between the discharge channel and the transmission line. However the discharges are capable of generating substantial voltage induced stresses on the line, only to a few hundred meters. Accordingly, Rusck employed the method of images to calculate the involved electromagnetic field.
- The line was considered infinite and continuous.

Figure 1shows the arrangement described, considered by Rusck in the developed theory.

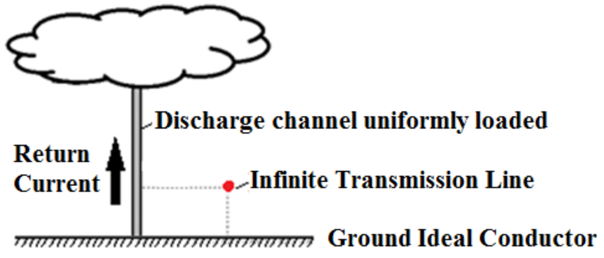

Figure 1. Model considered by Rusck for the calculation of induced voltage in transmission lines.

Thus Rusck took advantage of a model composed of a straight conductor and positioned vertically, which is the discharge channel, and this has a uniform charge distribution, and through it flows the return current which is a "step" current waveform towards the ground to the cloud.

Despite its simplicity, Rusck´s theory brings satisfactory results in most studies of voltage induced by indirect discharges, making it a reference in this type of study.

B. *Induced Voltage Calculation*

In this study, Rusck noted that the induced voltage by lightning depends directly of the produced electromagnetic field rate of change. In other words, the induced voltage varies according to the derivative over time of the electromagnetic field wave.

Thus, to calculate the induced voltage, first it is important to understand the electromagnetic fields which are produced by the incidence of an atmospheric discharge.

Generally, an electromagnetic field can be written as the sum of a portion associated to the scalar potential (Vi) and another associated with the magnetic vector potential ($\vec{A}$) [2]; resulting in (2):

$$\overrightarrow{E_\iota} = -\overrightarrow{\nabla V_\iota} - \frac{\partial \overrightarrow{A_\iota}}{\partial t} \qquad (2)$$

From the electromagnetic field, a methodology was developed to calculate the induced voltage in the lines, so that, was represented the interaction of the field with the line conductors, for the origin of these voltages.

To develop equations that represents this interaction, the system shown in Figure 2 was taken into account.

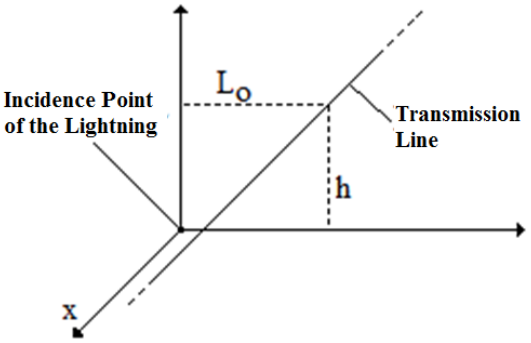

Figure 2. Line orientation relatively to the discharge.

It should be noted, that the equation developed by Rusck results in an induced voltage value at a point in the line. For this expression, was considered two contributions of the induced voltage field: V_1 and V_2, representing the contribution of the left and right x-axis from the discharge point of incidence, respectively. Thus, it can be said that the induced voltage is the sum of these two portions, and that because the continuity of the line, these two portions are equal in magnitude.

It is also known that these values are related to the line analysis (x-axis of Figure 2) and the elapsed time from the start of the return current (t). From the equations for the fields, Rusck developed an analytical expression for voltage values, shown in (3).

$$V_2(x,t) = V_1(-x,t) = Z_O I_O hB \left[\frac{v_O t + x}{L^2 + B^2 (v_O t + x)^2} \right] * \left[1 + \frac{-x + B^2 (v_O t + x)}{\sqrt{B^2 (v_O t)^2 + (1 - B^2)(x^2 + L^2)}} \right] \qquad (3)$$

Where:

Z_O – Characteristic impedance of the discharge channel, given by: $Z_0 = \frac{1}{4\pi} \sqrt{\mu_0 / \varepsilon_0} =$ 30 Ohms **;**

μ_0 – Vacuum magnetic permeability (H/m);

ε_0 – Electric permissiveness of vacuum (F/m);

I_0 – Peak value of return current (kA);

h - Height of the transmission line conductor (m);

$$B = v / v_0 \;;$$

v_0 – Speed of propagation of light (m/µs);

v – Propagation speed of return current (m/µs);

t – Time elapsed from the beginning of the return current(s);

x – Distance between the calculation point of the induced voltage and the point nearest to the discharge (m);

L – Shortest distance between the line and the discharge channel. (m).

Considering only the point nearest to the discharge line, namely for x = 0, one can write the equation for induced voltage as a function of time, reaching the equation below (4).

$$V_t = 2 Z_O I_O h \frac{vt}{L^2 + (vt)^2} \left[1 + \frac{Bvt}{\sqrt{(vt)^2 + L^2 (1 - B^2)}} \right] \qquad (4)$$

From this equation it is possible to obtain the curve representing the induced voltage waveform in a transmission line.

5. Computational Model of Induced Voltage

The developed model was based on Rusck´s theory applied to the software EMTP/ATPDraw to study the effects of the induced voltage waveform in a transmission line.

The EMTP/ATPDraw software works in the time domain and, thereby, the induced voltage source model must follow this criteria, regarding the characteristics of its waveform.

With the use of (4) to create the computational model it is possible to check the influence of the variation of some parameters on the induced voltage wave, for example: the speed of propagation of the wave of the return current, its amplitude, the transmission line height and the distance between the discharge and the line.

Firstly it was determined the user input parameters, namely, the variables that the user chooses, and changes according to the characteristics of the simulated case. In the implemented model, these variables are:

- Amplitude of the return current, given in kilo-amperes;
- Transmission line height, given in meters;
- Shortest distance between the line and the discharge, given in meters;
- Speed of wave propagation of the return current, given in meters per microseconds;
- The line surge impedance, given in ohms.

It was also used the constants involved in the phenomenon, necessary in modeling, namely:

- Intrinsic impedance of the discharge channel, considered equal to 30 Ohms [9], and;
- The speed of propagation of light, equal to 300m/µs.

A simulation was considered, in which a line in normal operation is swept by an induced voltage of an indirect discharge. It is expected that the voltage on this line rises from its nominal value, adding to this, the value of the modeled source and after some time returning to the starting voltage (disregarding the effects of any kind of protection).

However, in EMTP/ATPDraw, the voltage source is represented by an ideal source connected to a common reference. This makes the point at which this unit is connected, the voltage strictly equal to the voltage from the source itself.

So, the voltage at this point, would initially be null, passing a peak, and after some time returning to null. In order to overcome this inconvenience and apply only one voltage input to that already present in the system, we chose to use in the modeling, a current source.

The model adaptation for this source consists in transforming the calculated induced voltage values, in current values.

Therefore, the current value of this source is given by the relation between the induced voltage and the surge impedance of the transmission line.

6. Case Studies Using the Developed Model

In this section, will be presented results of the developed model using EMTP/ATPDraw. These results allow an analysis of the parameters influencing the induced voltage wave.

For comparison of results of simulations and measurements, situations were simulated similar to those registered in the study conducted by P. P. Barker [10]. With the support of the EPRI - Electric Power Research Institute, Barker performed measurements of induced voltages in an experimental line of approximately 680 meters.

This line had two conductors in vertical distribution, the upper one 7.5 meters in height and the second one 1.82 meters below the first one. The line was also composed of 15 wooden light poles with an average porthole of 45.33 meters. The surge impedance of the line was 455 ohms, and the ends of them were grounded by means of a resistance of 455 ohms. Figure 3 shows the characteristics of the line.

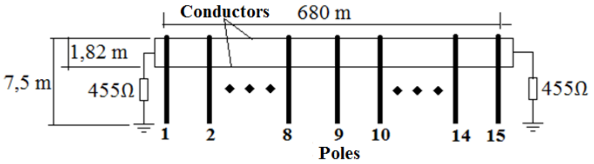

Figure 3. Scheme of the system used by Barker to measure induced voltages.

The discharges were caused artificially, by the launching of rockets, at a distance of 145 meters of the 9th pole of the line, being the shortest distance between the line and the discharge. The induced voltages were measured at the beginning and end of the line (poles 1 and 15) and also at post 9. Instantly, the return currents were also measured in order to obtain more details of the phenomenon. Figure 4 shows a wave return current and induced voltage, registered simultaneously.

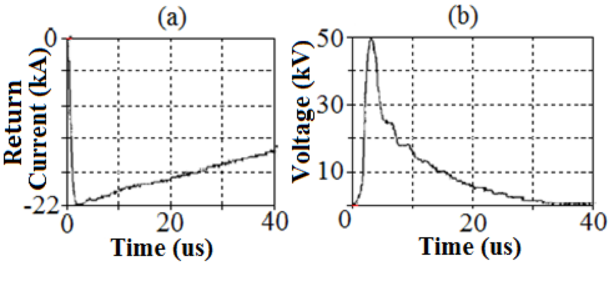

Figure 4. Simultaneous measurement of (a) return current and (b) the induced voltage on the line.

Among the discharge parameters, the wave speed of the return current is the only one that cannot be determined using the described measuring system (Figure 3 and Figure 4 respectively). The IEEE guide for line performance [6] recommends using the wave speed of the return current at 120 m/µs.

However, in this study simulations will be performed, based on the return current of the Figure 4(a), for current speed values equal to 80, 120, 160, 180 and 200m/µs, in order to get closer to the wave measured by Barker (Figure 4(b)).

Figure 5 shows the induced voltages outcome of the simulation for mentioned speed values.

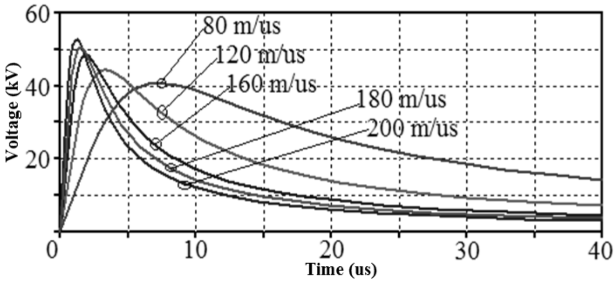

Figure 5. Induced voltage waves, resultant from the simulations based on the return current Figure 4(a).

To compare the measured and simulated voltage waveform, should be taken in account some basic criteria. Analyzing figure 4(b) it can be noticed that the peak of induced voltage reaches 50kV and decreases quickly.

Considering this criteria, the Figure 5 voltage waveform that is closest to that measurement, is the wave obtained from the simulation of the return current at 180m/µs. Thus, in the following simulations, will be considered that speed for such current.

It is important to note, that these measurements are originated from atmospheric discharges produced by rocket launching. Although these types of discharges, have amplitudes similar to the natural discharges, some parameters, like the crest time and the wave tail current time, are different [10] . Therefore, speed values can also be different for the two types of discharges.

In Figure 6 is shown another measurement registered by Barker [10].

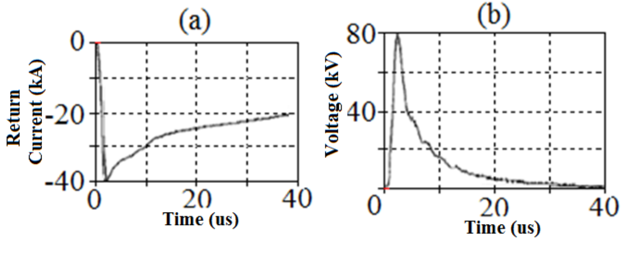

Figure 6. Measurement of (a) the return current, and (b) the induced voltage for a second event of atmospheric discharge.

The result using the simulated model, with a return current according to Figure 6 is shown in Figure 7.

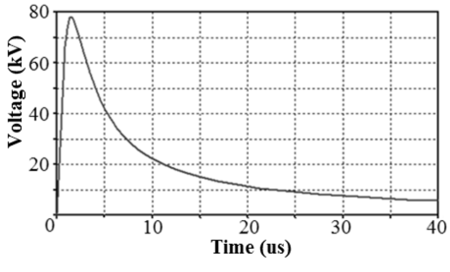

Figure 7. Simulation results for the atmospheric discharge of Figure 6.

It can be observed in Figure 6 a peak return current of 35 kA, which causes an induced voltage of 80kV. The simulation for this case returns a voltage waveform similar to that registered by Barker, as shown in Figure 7.

From the moment that, all the parameters of the developed model were chosen (including the speed of the current wave) it was possible to verify the influence of some of these parameters on the induced voltage.

In this context, an analysis to be held is the influence of the speed of the current wave in the outcome of the induced voltage. In figure 5 it can be observed that lower the speed, smaller the peak induced voltage. Furthermore, lower speed values result in long rise time and accommodation of the induced voltage waveform.

Another aspect is to check the variation of the return current peak. For a better comparison of the results, Figure 8 shows the induced voltage waves in simulations with three peaks of return currents: ***22***, ***38*** and ***45*** kA.

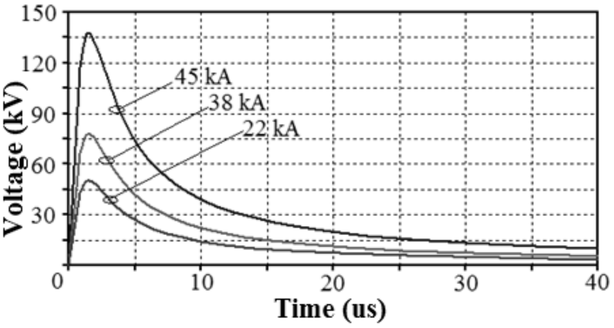

Figure 8. Induced voltages obtained from simulations with different return currents: 22, 38 e 45 kA.

As observed, with an increase in the return current, the induced voltage value also rises. Such an analysis can also be held by observing (6).

In Barker´s measurements, wasn't verified the impact of the line height on the variation of the induced voltage, because it would be impossible to change the structure of the existing line or even create another line with a different height.

Similarly, the distance between the line and place where the discharges were originated, did not change, due to difficulties in moving equipments. Thus, we will not be able to make a comparison between results of the simulation model with the measurements, by modifying these two length magnitudes.

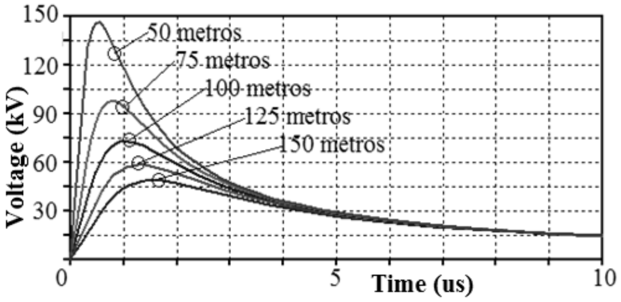

Figure 9. Induced voltages obtained from simulations varying the distance between the discharge and the line.

In the following simulation, was considered a return current with a 22kA peak, with a propagation speed of 180m/us and line height of 10 meters. In this case, distance values between the discharge duct and line were considered, obtaining the results shown in Figure 9. The parameters of the previous simulation were maintained, considering in addition the line height of 10 meters.

The induced voltages in Figure 9 were obtained from the distances 50, 75, 100, 125 and 150 meters, between the discharge duct and the line.

It can be observed that, the shorter the distance considered, higher the peak induced voltage in the first two microseconds. Soon after the peak voltage, the wave settles down quickly to the given value, of approximately 25kV and 6µs, regardless the distance considered.

Therefore, it is concluded that the distance between the discharge and the line influences only in the initial stage of the wave induced voltage, which is responsible for its peak value.

The observation of this parameter is interesting in compensation studies, because the difference of only some meters in the distance of the discharge to the line may decide the responsibility of the burning of electric equipment.

7. Conclusions

This study, addressed the computational representation of the analytical method developed by Rusck, to calculate voltage induced by indirect atmospheric discharges, focused on conducting line performance studies, considering the effects of this phenomenon.

From data on discharges, collected in regions where transmission lines are installed, it is possible, with the developed computational model, conduct a study and determine causes of shutdowns, since the parameters of discharges that influence directly the induced voltage (such as speed and amplitude of the return current) are different for each region, thus requiring specific studies.

Another possible application of this article is in the compensation study to consumers, by energy distributors. Voltage induced by atmospheric discharges can be held responsible for damage to equipments, since this cause is difficult to observe.

Using return current measurements, can be determined from simulations, the voltage induced in lines that can affect equipments connected to the system.

So, computational analysis of voltage induced in transmission lines, would be a cheap and reliable alternative, to determine causes of problems in the electrical system.

References

[1] S. RUSCK, "Induced lightning over voltages on power transmission lines with special reference to the overvoltage protection of low voltage networks", Ph.D. dissertation, Stockholm, Royal Institute of Technology, 1957.

[2] C. S ASSIS, " Induced Voltage Calculation of Atmospheric Discharges in Polyphase and Multi- grounded Lines: Implementing PSCAD®/ EMTDCTM ". Master Thesis, Universidade Federal de Minas Gerais, Minas Gerais, 2006. [*in portuguese*]

[3] J. C. S. FILHO," The Effect of Atmospheric Discharges in Transmission Line Performance - Modeling in the Time and Frequency Domains", Doctoral Thesis, Universidade

Federal do Rio de Janeiro, Rio de Janeiro, 2006. [*in portuguese*]

[4] U.S. DEPARTMENT OF DEFENSE, MILITARY, “Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware”, Department of Defense, Standard MIL-1757, Washington, D.C., USA, 1983.

[5] IEEE. “Guide for Improving the Lightning Performance of Transmission Lines”, IEEE P1243, Jun 1996.

[6] IEEE. “Guide for Improving the Lightning Performance of Electric Power Overhead Distribution lines”, IEEE Std 1410TM, Feb. 2004.

[7] JIA, W., XIAOQING, Z., “Double-Exponential Expression of Lightning Current Waveforms, Environmental Electromagnetics”, The 2006 4th Asia-Pacific Conference on.

[8] D.Y., GRIFFITHS, I.M. SMITH, Numerical Methods for Engineers, CRC Press, Inc., Florida - USA, 2006.

[9] P. C. A. MOTA, " A Study on Voltages Induced by Atmospheric Discharges in Transmission Lines", Master Thesis, Universidade Federal de Uberlândia, Uberlândia, 2011.[*in portuguese*]

[10] P. P. BARKER, T. A. SHORT; A. R. EYBERT-BERARD; J. P BERLANDIS, “Induced voltage measurements on an experimental distribution line during nearby rocket triggered lightning flashes”, IEEE Transactions on Power Delivery, v. 11, n. 2, p. 980-995, 1996.