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2014 Plasma Sci. Technol. 16 716

(http://iopscience.iop.org/1009-0630/16/7/15)

Research on Reverse Recovery Transient of Parallel Thyristors for Fusion Power Supply*

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Abstract In nuclear fusion power supply systems, the thyristors often need to be connected in parallel for sustaining large current. However, research on the reverse recovery transient of parallel thyristors has not been reported yet. When several thyristors are connected in parallel, they cannot turn-off at the same moment, and thus the turn-off model based on a single thyristor is no longer suitable. In this paper, an analysis is presented for the reverse recovery transient of parallel thyristors. Parallel thyristors can be assumed as one virtual thyristor so that the reverse recovery current can be modeled by an exponential function. Through equivalent transformation of the rectifier circuit, the commutating over-voltage can be calculated based on Kirchhoff's equation. The reverse recovery current and commutation over-voltage waveforms are measured on an experiment platform for a high power rectifier supply. From the measurement results, it is concluded that the modeling method is acceptable.

Keywords: parallel thyristors, reverse recovery transient, commutating over-voltage, high power rectifier

PACS: *84.30.Jc*

DOI: 10.1088/1009-0630/16/7/15

(Some figures may appear in colour only in the online journal)

1 Introduction

The transient of reverse recovery is one of the most important research topics of thyristor electrical characteristics. Several reverse recovery models have been proposed. The macro-model [1,2] is considered to be over-complicated and difficult to implement. The lumped-charge model [3] and the hyperbolic secant function model [4] are not easy to implement in simulation packages and require knowledge of parameters not available to device users. The switch models [5,6] are easy to use but do not address reverse recovery adequately. The exponential function model has been used most commonly over the past 20 years because its accuracy meets engineering requirements and the model parameter is easy to obtain from the reverse recovery characteristic curve provided by manufacturers [7−10].

However, researchers have just focused on the reverse recovery transient process of a single thyristor up to now. In nuclear fusion power supply systems, the thyristors often need to be connected in parallel to sustain large current, so it is necessary to study the reverse recovery transient under the condition of parallel connected thyristors.

The parallel thyristors are assumed as one virtual thyristor in this paper. Based on the exponential function model of a single thyristor, a mathematical model is proposed for the reverse recovery current and commutating the over-voltage of the parallel thyristors.

2 Thyristor reverse recovery model

2.1 Single thyristor reverse recovery model

Fig. 1 shows typical current waveforms of a single thyristor during reverse recovery time, I_{F} is the peak forward current, which begins to decrease and cross zero at t=0 depending on the change of the external circuit; after t=0, the thyristor current continues to decreases at the same rate K because the excess-carriers cannot decay immediately. At t=T_1, the reverse current reaches its maximum value I_{rm}, after $t = T_1$, the thyristor recovers the reverse blocking capability, and the current falls to zero. Because of the series inductance of the thyristor circuit, large transient surge V_{c} is produced which is called commutating over-voltage.

*supported by the International Thermonuclear Experimental Reactor Project of China (No. 2008 GB104000)

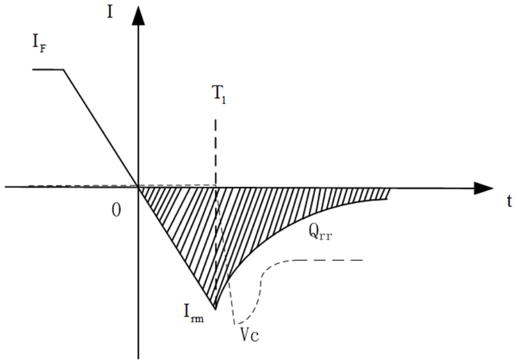

Fig.1 Reverse recovery current waveform of a single thyristor

The reverse recovery current $i_{\rm r}$ can be approximated by a waveform with constant slope K from zero to peak reverse current, followed by an exponential decay curve with time constant τ [7−9]. The peak reverse current $I_{\rm rm}$ and the reverse charge $Q_{\rm rr}$, which define the reverse recovery behavior, can be obtained from the device data sheet. Therefore, the reverse recovery current $i_{\rm r}$ can be modeled as [10]:

$$\begin{cases} i_{\rm r} = I_{\rm rm}{\rm e}^{-\frac{t-T_1}{\tau}} \\ \tau = \dfrac{Q_{\rm rr}}{I_{\rm rm}} - \dfrac{I_{\rm rm}}{2K} \end{cases} . \qquad (1)$$

2.2 Parallel thyristors reverse recovery model

Suppose two thyristors $\rm V_1$ and $\rm V_2$ work independently, there will be two peak values of the reverse recovery current $I_{\rm rm1}$, $I_{\rm rm2}$, and two reverse recovery charges $Q_{\rm rr1}$, $Q_{\rm rr2}$ corresponding to the decrease rates of each thyristor, respectively.

When the two thyristors work in parallel, the moment at which the reverse recovery current reaches its maximum value depends on the thyristor forward current and the decrease rate of the thyristor current. However, the parallel thyristors' circuit parameters cannot be completely symmetrical, so each thyristor current cannot enter the reverse recovery process at the same moment. Assume that the reverse current of thyristor $\rm V_1$ reaches its peak value firstly, and then the thyristor $\rm V_1$ recovers its reverse blocking capability, however, the reverse current of the thyristor $\rm V_2$ does not reach its peak value yet, and thus the thyristor $\rm V_2$ keeps on conducting and the current of the thyristor $\rm V_1$ is transferred to thyristor $\rm V_2$, which accelerates the reverse recovery current decrease rate of the thyristor $\rm V_2$. In fact, there is no commutating over-voltage across thyristor $\rm V_1$ during the time period of $\rm T_1-T_2$ because the total reverse recovery current does not decrease yet. At the moment of T_2, the thyristor $\rm V_2$ reaches its peak value $I'_{\rm rm2}$ instead of $I_{\rm rm2}$, the reverse recovery current of the thyristor $\rm V_1$ decreases to the value of $I'_{\rm rm1}$, then, the total reverse recovery current decays and a commutating over-voltage is produced. Fig. 2 shows a typical reverse recovery current waveform in the case of parallel thyristors.

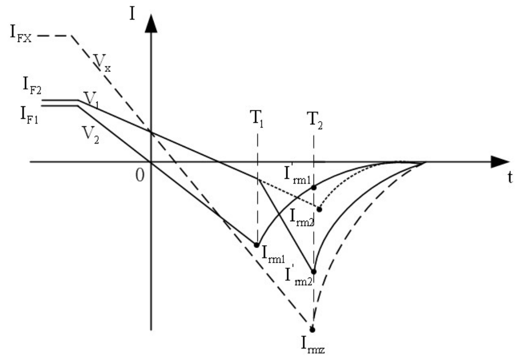

Fig.2 Reverse recovery current waveform of two thyristors connected in parallel

It is unnecessary to calculate how much reverse recovery current shifts from thyristor $\rm V_1$ to $\rm V_2$ because the commutating over-voltage value is affected by the total reverse recovery current of $\rm V_1$ and $\rm V_2$. Obviously, the total reverse recovery current is unaffected by the internal current transfer process between the two thyristors, the same for the total reverse recovery charge. Therefore, Eq. (2) can be deduced as follows.

$$\begin{cases} I'_{\rm rm1} + I'_{\rm rm2} = I_{\rm rm1} + I_{\rm rm2} \\ Q'_{\rm rr1} + Q'_{\rm rr2} = Q_{\rm rr1} + Q_{\rm rr2} \end{cases} . \qquad (2)$$

The reverse recovery current of each thyristor cannot be modeled by an exponential function, however, the total current of parallel thyristors can be modeled by Eq. (1). The commutating over-voltage value is affected by the total reverse recovery current, so it is unnecessary to calculate how much the reverse recovery current of each thyristor is, only the total reverse recovery current needs to be modeled. The two thyristors $\rm V_1$, $\rm V_2$ can be assumed as one thyristor, $\rm V_{\it x}$. It is easy to know that the reverse recovery current peak value of $\rm V_{\it x}$ is $I_{\rm rm1}$+$I_{\rm rm2}$, the reverse recovery charge of $\rm V_{\it x}$ is $Q_{\rm rr1}$+$Q_{\rm rr2}$; so the reverse recovery current of thyristor $\rm V_{\it x}$ can be modeled by Eq. (1). Similarly, for n parallel thyristors, the total reverse recovery current irmzcan be modeled with the following set of equations:

$$\begin{cases} i_{{\rm rm}z} = I_{{\rm rm}z}{\rm e}^{-\frac{t}{\tau_z}} \\ K_z = K_1 + K_2 + \cdots K_n \\ I_{{\rm rm}z} = I_{\rm rm1} + I_{\rm rm2} + \cdots + I_{{\rm rm}n} \\ Q_{{\rm rr}z} = Q_{\rm rr1} + Q_{\rm rr2} + \cdots + Q_{{\rm rr}n} \\ \tau_z = \frac{Q_{{\rm rr}z}}{I_{{\rm rm}z}} - \frac{I_{{\rm rm}z}}{2K_z} \end{cases} . \qquad (3)$$

Here K_z is the total decrease rate of parallel thyristors current, $I_{{\rm rm}z}$ is the total peak value of the reverse recovery current of parallel thyristors, $Q_{{\rm rr}z}$ is the total reverse recovery charge of parallel thyristors, τ_z is the total reverse recovery current decay time constant.

3 Commutating over-voltage model

As for the three-phase full-bridge rectifier, the circuit topology is shown in Fig. 3. $E_{\rm A}$, $E_{\rm B}$, and $E_{\rm C}$ are the secondary side phase voltages of rectifier transformer, L_s is the sum of the line distributed inductance and transformer leakage inductance, there are n thyristors in parallel on each bridge arm.

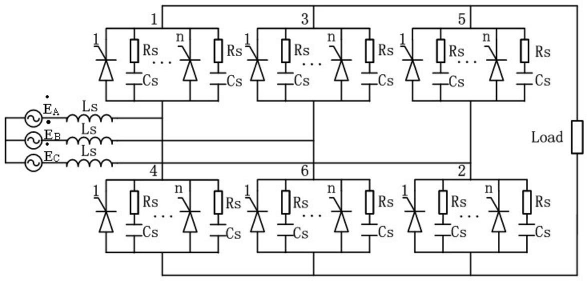

Fig.3 Three-phase full-pulse bridge architecture

Although each thyristor has its own RC snubber, as for the three-phase full-pulse bridge configuration, different bridge arm RC snubbers will interact with each other. When the arm 1 thyristors turn-off, arms 2 and 3 are conducting and short-circuit RC snubbers, however, thyristors 4, 5 and 6 are blocked and RC snubbers will also interact with the arm 1 snubbers. The equivalent circuit is given in Fig. 4(a), and the voltage source in the circuit of Fig. 4(b) can be assumed to be a constant DC voltage $E_{\rm eq}$ because of the slow variation of power-frequency voltage $E_{\rm AB}$, as compared to the fast reverse recovery transients in this circuit.

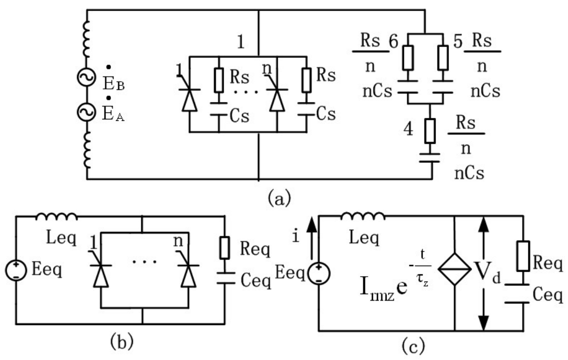

Fig.4 Commutating equivalent circuits

The parallel thyristors can be modeled as a controlled current source, then, the equivalent circuit given in Fig. 4(b) can be converted to the transient analysis circuit shown in Fig. 4(c).

$$E_{\rm eq}=\sqrt{2}E_{\rm AB}\sin(\alpha+\mu)\ , \tag{4}$$

$$C_{\rm eq}=\frac{5n}{3}C_{\rm s}, \tag{5}$$

$$R_{\rm eq}=\frac{3}{5n}R_{\rm s}, \tag{6}$$

$$L_{\rm eq}=2L_{\rm s}, \tag{7}$$

where α is the trigger delay angle, μ is the commutating overlapping angle. The equation of the circuit given in Fig. 4(c) can be expressed by using Kirchhoff's first law as follows:

$$L_{\rm eq}\frac{{\rm d}i}{{\rm d}t}+R_{\rm eq}(i-i_{{\rm rm}z})+\frac{1}{C_{\rm eq}}\int_0^t(i-i_{{\rm rm}z}){\rm d}t=E_{\rm eq}. \tag{8}$$

Since Eq. (8) is a linear ordinary differential equation with constant coefficients, it can be solved with proper initial conditions: inductance current is equal to $I_{{\rm rm}z}$ and capacitance voltage is equal to zero. Once current i is obtained, the analytic expression for commutating over-voltage $V_{\rm d}$ can be easily obtained.
Let

$$p=\frac{R_{\rm eq}}{2L_{\rm eq}},w=\frac{1}{\sqrt{L_{\rm eq}C_{\rm eq}}},\xi=\frac{p}{w}=R_{\rm eq}\ /\ (2\sqrt{\frac{L_{\rm eq}}{C_{\rm eq}}}\ ).$$

(I) $\xi>1$ (over damped case)

$$V_{\rm d}=E_{\rm eq}+L_{\rm eq}[(p-b)A_1{\rm e}^{bt}+(p+b)A_2{\rm e}^{-bt}]{\rm e}^{-pt}+L_{\rm eq}\frac{g}{\tau_z}{\rm e}^{-\frac{t}{\tau_z}}, \tag{9}$$

where

$$b=\sqrt{p^2-w^2}\ , \tag{10}$$

$$A_1=\frac{(p+b)(I_{{\rm rm}z}-g)+\frac{E_{\rm eq}}{L_{\rm eq}}+\frac{g}{\tau_z}}{2b}\ , \tag{11}$$

$$A_2=-\frac{(p-b)(I_{{\rm rm}z}-g)+\frac{E_{\rm eq}}{L_{\rm eq}}+\frac{g}{\tau_z}}{2b}, \tag{12}$$

$$g=\frac{\tau_z(\tau_z-\frac{2p}{w^2})I_{{\rm rm}z}}{\tau_z(\tau_z-\frac{2p}{w^2})+\frac{1}{w^2}}\ . \tag{13}$$

(II) $\xi<1$ (under damped case)

$$V_{\rm d}=E_{\rm eq}+L_{\rm eq}[(pB_1-bB_2)\cos bt+(bB_1+pB_2)\sin bt]{\rm e}^{-pt}+L_{\rm eq}\frac{g}{\tau_z}{\rm e}^{-\frac{t}{\tau_z}}, \tag{14}$$

where

$$b=\sqrt{w^2-p^2}\ , \tag{15}$$

$$B_1=I_{{\rm rm}z}-g\ , \tag{16}$$

$$B_2=-\frac{p(I_{{\rm rm}z}-g)+\frac{E_{\rm eq}}{L_{\rm eq}}+\frac{g}{\tau_z}}{b}\ . \tag{17}$$

(III) $\xi=1$ (critical damped case)

$$V_{\rm d}=E_{\rm eq}+L_{\rm eq}[(pC_1-C_2)+pC_2t]{\rm e}^{-pt}+L_{\rm eq}\frac{g}{\tau_z}{\rm e}^{-\frac{t}{\tau_z}}, \tag{18}$$

where

$$C_1=I_{{\rm rm}z}-g\ , \tag{19}$$

$$C_2=\frac{E_{\rm eq}}{L_{\rm eq}}+\frac{g}{\tau_z}+p(I_{{\rm rm}z}-g). \tag{20}$$

4 Experimental verification

A commutating over-voltage experiment has been carried out to test the analysis method on a three-phase full-bridge rectifier. The experimental circuit diagram and the experimental setup in the field are respectively shown in Fig. 5 and Fig. 6. The experiment circuit parameters are listed in Table 1.

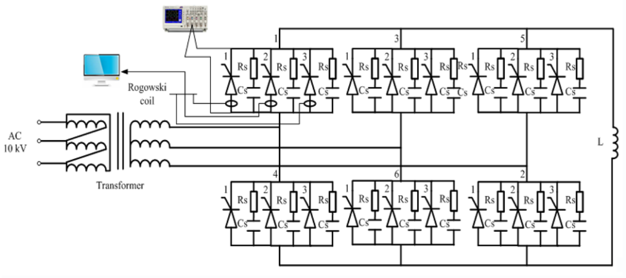

Fig.5 Experimental circuit diagram

Fig.6 Experimental setup in the field

Table 1. Experimental circuit parameters

Parameter	Value
Transformer leakage inductance	2.7 μH
Transformer secondary rated voltage	103.8 V
Trigger delay angle	84°
Parallel number of thyristors	3
Commutating snubber capacitance	1.5 μF
Commutating snubber resistance	16 Ω

The reverse recovery current of each thyristor is measured by a Rogowski coil. As shown in Fig. 7, at cursor 1, the parallel thyristors circuit parameters cannot be completely symmetrical, so the current of V_1 reaches the reverse peak value firstly, and then the current of thyristor V_1 is transferred to thyristors V_2 and V_3, which accelerates the reverse current decrease rate of the thyristors V_2 and V_3; at cursor 2, the thyristor V_3 reaches its maximum value, and the current of V_2 decreases at a higher rate.

From the measured waveform, the decrease rates of thyristors V_1, V_2, V_3 are 10.3 A/μs, 7.4 A/μs, 9.5 A/μs, respectively, before they enter the reverse recovery process. Experiments have been conducted to obtain the thyristor peak reverse recovery currents and reverse recovery charges under the decrease rate of 7.4 A/μs, 9.5 A/μs and 10.3 A/μs. The measured reverse recovery current curves under different slopes are shown in Figs. 8-10 and the measured data are listed in Table 2.

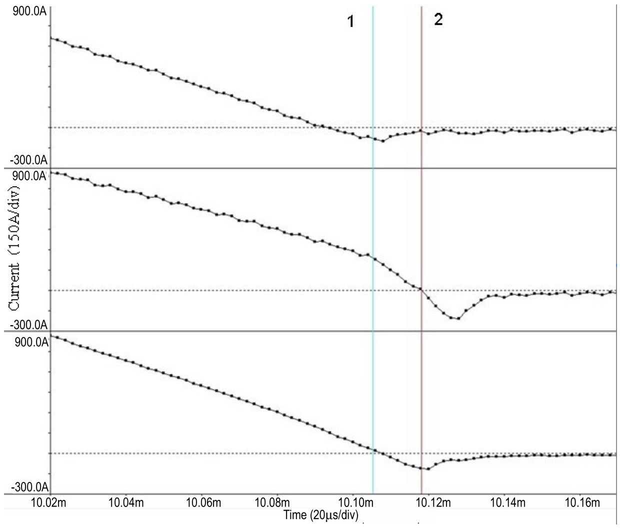

Fig.7 Measured reverse recovery current of each thyristor

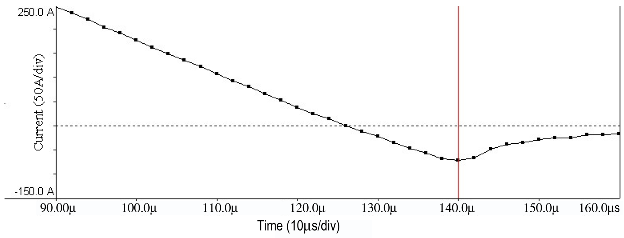

Fig.8 Measured reverse recovery current curve under a decrease rate of 7.4 A/μs

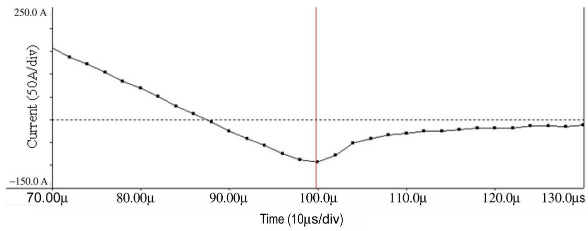

Fig.9 Measured reverse recovery current curve under a decrease rate of 9.5 A/μs

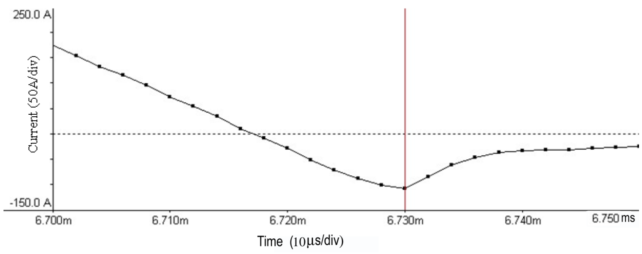

Fig.10 Measured reverse recovery current curve under a decrease rate of 10.3 A/μs

Table 2. Thyristor $I_{\rm rm}$ and $Q_{\rm rr}$ value under given $\mathrm{d}i/\mathrm{d}t$

$\mathrm{d}i/\mathrm{d}t$ (A/μs)	$I_{\rm rm}$ (A)	$Q_{\rm rr}$ (μAs)
7.4	70.2	1258
9.5	90.5	1365
10.3	105.8	1595

According to Eq. (3), the total reverse recovery current peak value I_{rmz} is 266.5 A, the total reverse recovery charge Q_{rrz} is 4218 μAs. According to Eq. (3), the reverse recovery current of the thyristor V_x can be modeled as:

$$i_{rrz} = -266.5e^{-\frac{t}{9.7\times10^{-6}}}. \qquad (21)$$

Based on the data in Table 1, the curve of commutating over-voltage can be obtained by solving Eq. (8), as shown in Fig. 11. The measured curve of three thyristor total reverse recovery current is shown in Fig. 12, in which I_{rmz} is 248.6 A with relative error of 7%, and Q_{rrz} is 4350 μAs with relative error of 3%.

The commutating over-voltage across the thyristor is measured by an oscilloscope, as shown in Fig. 13.

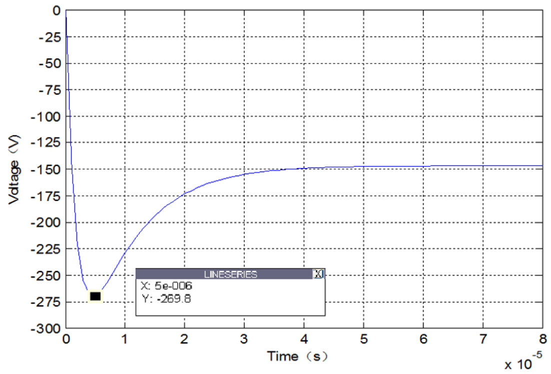

Fig.11 Theoretical over-voltage waveform

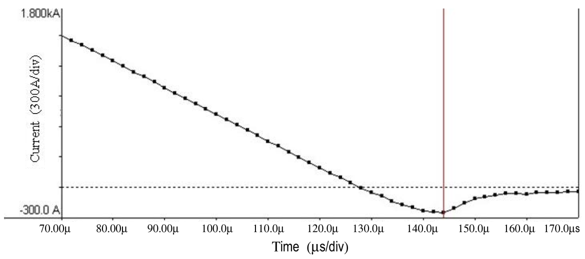

Fig.12 Measured total reverse recovery current curve in the case of three thyristors

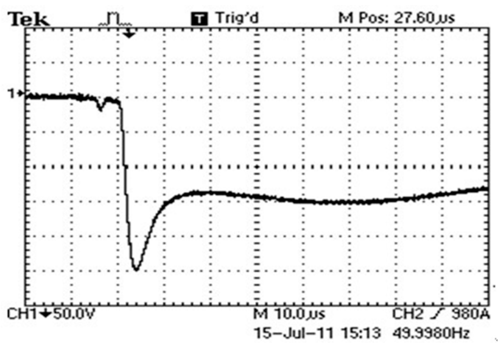

Fig.13 Measured over-voltage wave

The theoretical over-voltage peak value is 269.8 V, the measured one is 250 V, and thus the relative error is 8%. Experiments have also been conducted on other arms and the relative errors have not gone beyond 10%. From the measured results, it is concluded that the modeling method is acceptable.

5 Conclusions

There is current transfer between parallel thyristors since each thyristor cannot turn-off at the same moment, so the exponential function model based on a single thyristor is no longer applicable. The parallel thyristors can be assumed as one virtual thyristor, and then the reverse recovery current can be modeled by the exponential function model. Through the equivalent transformation of the rectifier circuit, the commutating over-voltage can be calculated based on Kirchhoff's equation.

Although the modeling method of the parallel thyristor commutating over-voltage is deduced for three-phase full-bridge rectifiers, in fact, the modeling method is also applicable to other fusion power supply systems with different architectures which involve parallel thyristors.

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(Manuscript received 8 July 2013)
(Manuscript accepted 22 September 2013)
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