Comparative Analysis of BJT Models for SCR Simulation Using Two-Transistor Analogy

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ABSTRACT

This paper presents an examination of the SCR simulation process through application and comparison of the Ebers-Moll and Gummel-Poon transistor models in a two-transistor configuration. The SCR was simulated in SPICE as two coupled PNP and NPN transistors; the same operating conditions were used to analyze the SCR's switching behavior. The Ebers-Moll model shows very sharp switching because it does not take into account any dynamic effects, whereas the Gummel-Poon model shows smooth transitions with transient oscillation that can be attributed to the charge storage effects and junction voltage effects considered by this model. Both models showed a similar time for switching when the voltage collapsed however, the Gummel-Poon model better represents the real-world SCR dynamics.

Keywords: BJT, Silicon Controlled Rectifier (SCR), Two-Transistor Model, Ebers-Moll Model, Gummel-Poon Model, SPICE Simulation.

I. INTRODUCTION

Silicon-Controlled Rectifier (SCR) is one of the most commonly applied power semiconductor devices [8] in areas of controlled rectification, motor drive, voltage and current control. A Two-Transistor Analogy can provide an effective way to describe how an SCR works, by creating a model that describes an SCR as an interconnect of two transistors [5], which allows designers to analyze the turn-on/off characteristics of the SCR.

With the advent of modern electronic systems design, simulation tools have become a vital component for simulating and analyzing circuit behavior before any actual physical implementation occurs. Of these many types of simulation tools available, the Simulation Program with Integrated Circuit Emphasis (SPICE) [3] is among the most commonly utilized tool for analyzing circuits in electronic systems. SPICE offers the ability to create models and simulate complex circuits utilizing a wide range of semiconductor devices ranging from Low-Power to High-Power.

The accuracy of simulations of such complex circuits especially when they include switching devices such as SCRs depends largely upon the quality of the models being simulated. Different BJT models are available in SPICE, among which Ebers-Moll model is a simple large signal model of transistor [2], while the Gummel-Poon model of the transistor considers charge storage effects, junction voltages and other non-ideal characteristics [1], unlike the former. This makes Gummel-Poon model more suitable for transient and switching analysis.

This paper presents a comparative analysis of Ebers-Moll and Gummel-Poon transistor models in simulation of an SCR using the two-transistor analogy. The switching characteristics and transient behavior are evaluated under identical operating conditions, highlighting difference of model parameters on overall performance of the device.

II. THEORY

Silicon controlled rectifier (SCR) is a semiconductor device with four layers and three junctions that operates as a unidirectional switch, remaining in a forward blocking mode (OFF state) until a positive gate signal is applied, this is called ‘Triggering’ or Firing of SCR. Upon triggering, it goes into forward conduction mode (ON state), acting as a closed switch and continues to conduct even after removal of the gate signal, this is known as latching.

The internal operation of an SCR can be effectively explained using the two-transistor analogy. The four-layer PNPN structure is represented in this way by combining a PNP transistor with an NPN transistor coupled in a regenerative feedback configuration [7]. Each transistor's collector is linked to the other's base to create a complete loop of positive feedback. When a gate signal is applied, it injects current into one of the transistors, increasing its collector current. This current then drives the base of the second transistor, further increasing its conduction. The process continues in a regenerative manner until both transistors are driven into saturation, resulting in a rapid transition from the blocking state to the conducting state.

The current gains of the two transistors can be used to define the condition for this regenerative operation. If (α_1) and (α_2) stand for the PNP and NPN transistors' respective common-base current gains, the device turns on when:

$$\alpha_1 + \alpha_2 \rightarrow 1 \qquad (1)$$

loop gain approaching unity at this time, which causes a slight increase in current to result in a significant increase in conduction.

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The underlying transistor models used to simulate the two transistors determine how accurate the SCR model is for circuit simulation. A basic model of bipolar junction transistors is the Ebers-Moll model, which describes transistor operation across all regions in terms of easily measurable transistor parameters of saturation currents and current gains [2]. Since its formulation, this model was used in all major general purpose network analysis programs [1].

The Gummel-Poon model overcomes limitations of Eber-Moll model, due to approximations, by considering For the analysis presented in this paper, the Xschem schematic editor is used along with NGSPICE, which is an open-source circuit simulator based on Spice3f5. Xschem was used for circuit design and schematic capture and NGSPICE was used to perform numerical simulation of the circuit behavior.

A custom SCR model was developed in Xschem using two-transistor analogy, where the SCR is represented using an interconnection of a PNP and an NPN bipolar junction transistor [4], [5], [6], [7]. This way we could substitute different transistor models and assess their impact on SCR operation [4]. The Ebers-Moll model and the Gummel-Poon model are two transistor modelling techniques that are taken into consideration. A minimum set of large-signal parameters is used to implement the Ebers–Moll model, representing ideal Corners are calculated as 0.164 V, 0.204 V, 0.19 V and 0.153 V respectively. The best performance can be seen junction voltages, charge storage and non-ideal characteristics of the transistor. It also accounts for base charge modulation, and current-dependent variations in gain. This makes it more suitable for transient analysis [1], as it provides a more accurate representation of switching behavior, including finite turn-on time, gradual current rise, and dynamic effects observed in practical devices.

III. METHODOLOGY

transistor behavior without dynamic effects. In contrast, the Gummel-Poon model incorporates additional parameters such as junction voltages and transit times to account for charge storage and transient behavior.

To evaluate the SCR under practical operating conditions, the model is integrated into a single-phase fully controlled full-wave bridge rectifier with an RL load, as shown in Fig-1. Gate triggering is implemented using pulse sources, where the firing angle (α) is controlled by introducing a time delay given by:

$$TD = \frac{\alpha}{(360f)} \qquad (2)$$

Where (f) is the supply frequency. Appropriate phase shifts are applied to trigger diagonally opposite SCR pairs in the bridge configuration.

at FS process corner while the SF corner serves as the worst performing process corner.

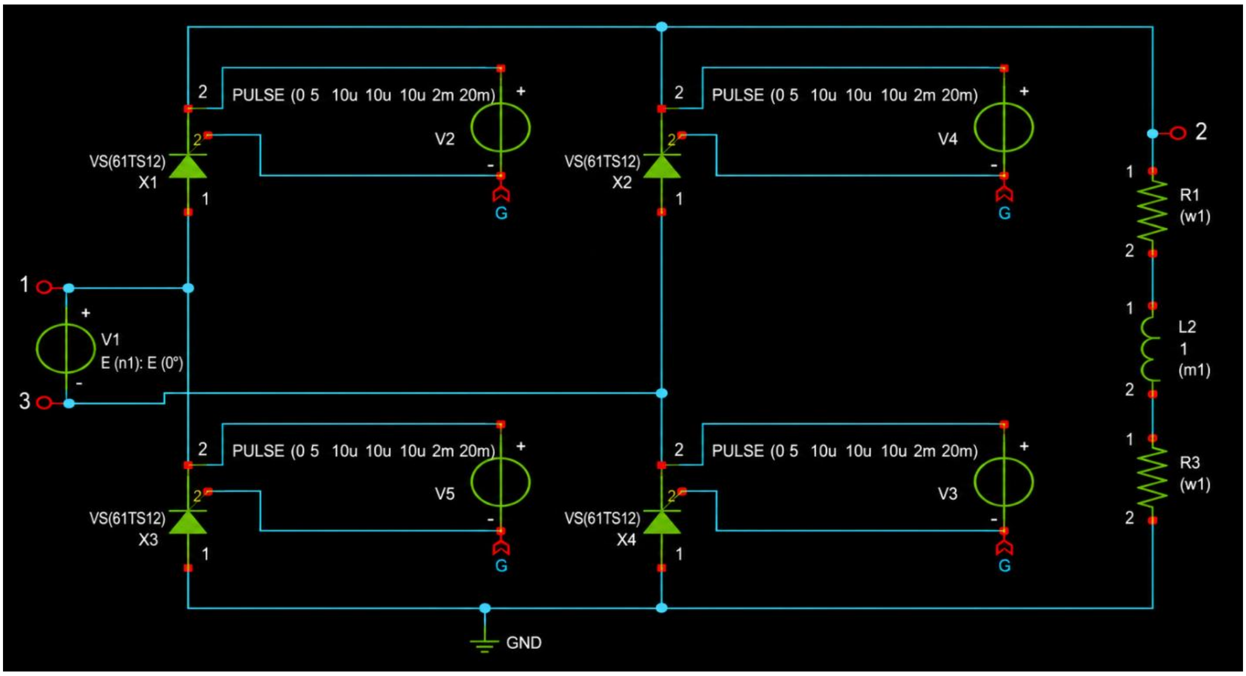

Fig. 1. Circuit schematic

Transient analysis was carried out to study the switching characteristics of the SCR. The same circuit and operating conditions were used for both transistor models for comparison. To improve convergence stability [5] and reduce unwanted oscillations in the simulation, the Gear numerical integration method of NGSPICE is used [8]. This introduced numerical damping, resulting in good convergence and more stable waveforms.

The same circuit configuration and operating conditions are maintained for both transistor models to ensure a

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consistent basis for comparison. During the transient analysis, key waveforms including input voltage, output voltage of the rectifier, SCR current, and gate current are observed and plotted. These waveforms are used to analyze the switching characteristics and dynamic behavior of the SCR for different transistor models.

The transistor model parameters are selected from existing literature where parameter extraction is well established [3], [4], [9], [10], [11], [12]. In this paper, only core parameters are used and thermal dependency of parameters is not considered to reduce computational complexity and avoid convergence and numerical stability issues [8], as their inclusion led to convergence instability.

The SPICE parameters used for Ebers-Moll and Gummel-Poon models are summarized in Tables I and II, respectively.

TABLE I
EBERS-MOLL MODEL PARAMETERS

Parameter	Symbol	Description
Saturation Current	IS	Transport saturation current of the transistor
Forward Current Gain	BF	Forward current gain (βF)
Reverse Current Gain	BR	Reverse current gain (βR)
Emission Coefficient	NF	Forward emission coefficient
Reverse Emission Coefficient	NR	Reverse emission coefficient

TABLE II
GUMMEL-POON MODEL PARAMETERS

Parameter	Symbol	Description
Saturation Current	IS	Transport saturation current
Forward Current Gain	BF	Forward current gain
Reverse Current Gain	BR	Reverse current gain
Early Voltage	VAF	Forward Early voltage
Reverse Early Voltage	VAR	Reverse Early voltage
Forward Beta Roll-off	IKF	High-current roll-off parameter
Reverse Beta Roll-off	IKR	Reverse high-current roll-off
BE Built-in Voltage	VJE	Base-emitter junction potential
BC Built-in Voltage	VJC	Base-collector junction potential
BE Capacitance	CJE	Base-emitter junction capacitance
BC Capacitance	CJC	Base-collector junction capacitance
Forward Transit Time	TF	Charge storage during turn-on
Reverse Transit Time	TR	Charge storage during turn-off

```
value=".SUBCKT SCR 10 20 30
* PINS:  ANODE CATHODE GATE
Q1 10 5 6 QPNP
Q2 5 20 30 QNPN
R1 6 5 50
R2 5 30 50
.MODEL QPNP PNP(IS=1E-14 BF=50 BR=1)
.MODEL QNPN NPN(IS=1E-14 BF=100 BR=1)
.ENDS SCR"
```

Fig. 2 (a). SPICE syntax for Eber-Molls Model

```
value=".SUBCKT SCR 10 20 30
* PINS: ANODE CATHODE GATE

Q1  10 5 6 QPNP_GP
Q2  5 20 30 QNPN_GP
R1  6  5 50
R2  5 30 50

* -------- NPN MODEL (GUMMEL-POON) -------
.MODEL QNPN_GP NPN (
+ IS=1E-14
+ BF=100
+ BR=1
+ VAF=100
+ VAR=100
+ IKF=0.1
+ IKR=0.1
+ VJE=0.75
+ VJC=0.75
+ CJE=10p
+ CJC=5p
+ TF=1n
+ TR=10n
)
* ------- PNP MODEL (GUMMEL-POON) -------
.MODEL QPNP_GP PNP (
+ IS=1E-14
+ BF=50
+ BR=1
+ VAF=50
+ VAR=50
+ IKF=0.1
+ IKR=0.1
+ VJE=0.75
+ VJC=0.75
+ CJE=10p
+ CJC=5p
+ TF=1n
+ TR=10n
)
.ENDS SCR"
```

Fig. 2 (b). SPICE syntax for Gummel-Poon Model

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IV. RESULTS

The transient simulations of the scr were performed using both the ebers-moll and gummel-poon transistor models under identical operating conditions. A single-phase fully controlled bridge rectifier with an RL load was used to implement the scr, and phase-controlled gate triggering was used. The resulting waveforms, including input voltage, output voltage, and scr current, were analyzed to evaluate switching behavior and transient characteristics.

The overall output voltage waveform along with the input ac waveform for the gummel-poon model is shown in fig. 3(a). Prior to triggering, the scr remains in the forward blocking state, during which output voltage follows input waveform. At firing instant, scr transitions into conduction, resulting in a sharp drop in voltage across the device. After conduction begins, the output voltage follows the expected rectified profile corresponding to the applied firing angle.

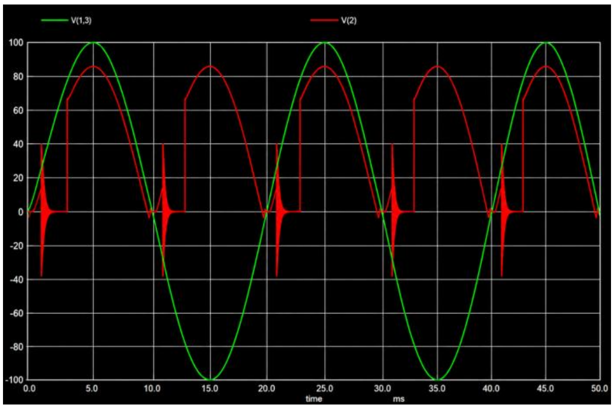

Fig. 3 (a). Gummel-Poon Output waveform

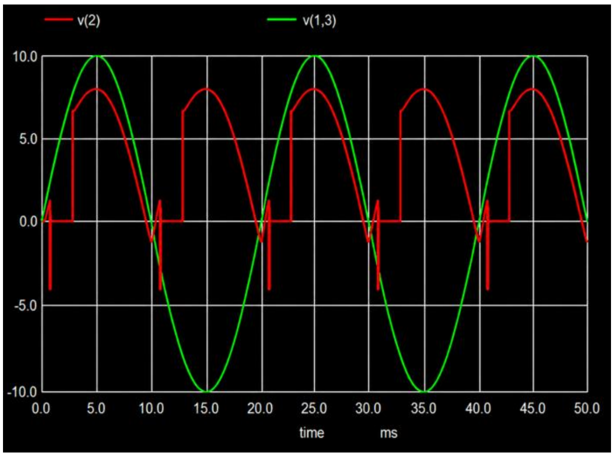

Fig. 3 (b). Ebers-moll Output waveform

A similar behavior is observed for the Ebers-Moll model, as shown in Fig. 3(b). The voltage follows the input waveform before triggering and collapses at the firing instant. However, it can be seen that the transition in the Ebers-Moll model is cleaner and more abrupt, with no visible oscillations during switching.

To further examine the switching behavior in detail, Fig. 4(a) presents a magnified view of the turn-on region for the Gummel-Poon model. We can see large oscillations right after SCR turn on. These oscillations are underdamped and gradually decay with time. These oscillations are present due to the interaction between the regenerative feedback of the two-transistor SCR structure and the internal junction capacitances (CJE and CJC) in Gummel-Poon model. Also, finite forward transit time (TF) adds delay in charge transport, leading to a mismatch between voltage and current response that contributes to the large oscillations.

In contrast, the zoomed view of the turn-on region for Ebers–Moll model is shown in Fig. 4(b). The sudden change from blocking to conduction is accompanied by very little oscillations. This is because Ebers-Moll model lacks capacitance effects, transit time effects and charge storage, which results in an idealized switching response without dynamic interactions.

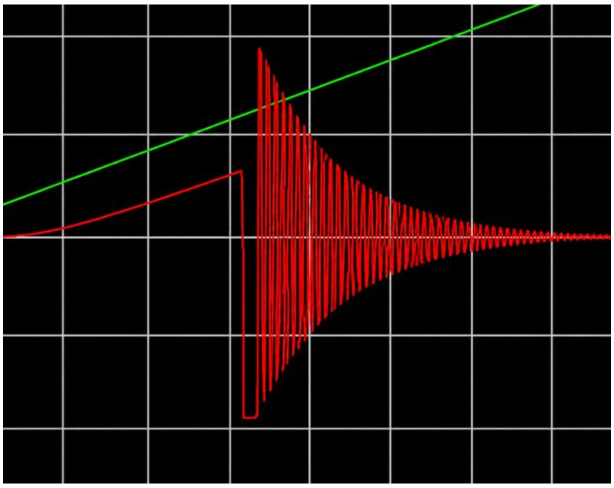

Fig. 4 (a). Gummel-poon initial oscillations waveform

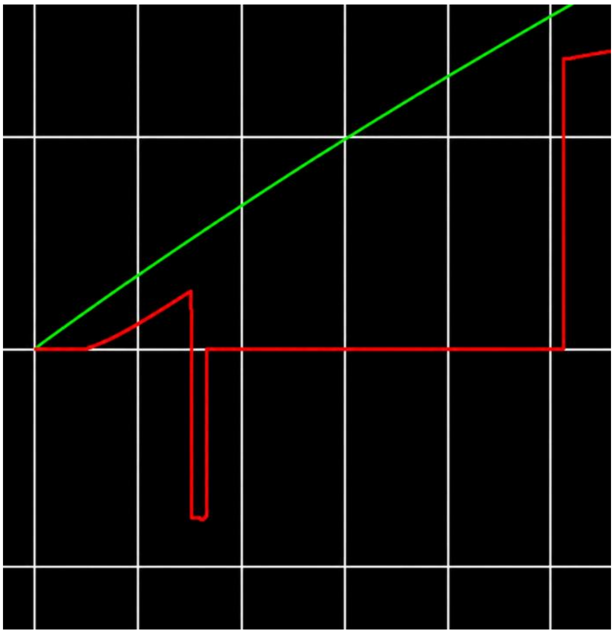

Fig. 4 (b). Ebers-moll initial oscillations waveform

The SCR current waveforms for both models are shown in Fig. 5(a) & 5(b). In the Gummel-Poon model, the current exhibits a sharp and nearly instantaneous rise after triggering, indicating the presence of charge storage and finite carrier transit time. In

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contrast, the Ebers-Moll model exhibits a more gradual rise in current, reflecting the absence of dynamic effects.

Additionally, small bumps are observed just before the current rise and after the current fall in both models. These arise due to the interaction of the switching action with the inductive load and gate triggering. We can see that bumps are more prominent in the Ebers–Moll model, due to the absence of internal charge storage and capacitance which lead to a less damped response. On the other hand, the Gummel-Poon model shows smoother transitions because of the inclusion of internal capacitances and charge storage provides a damping effect on these disturbances.

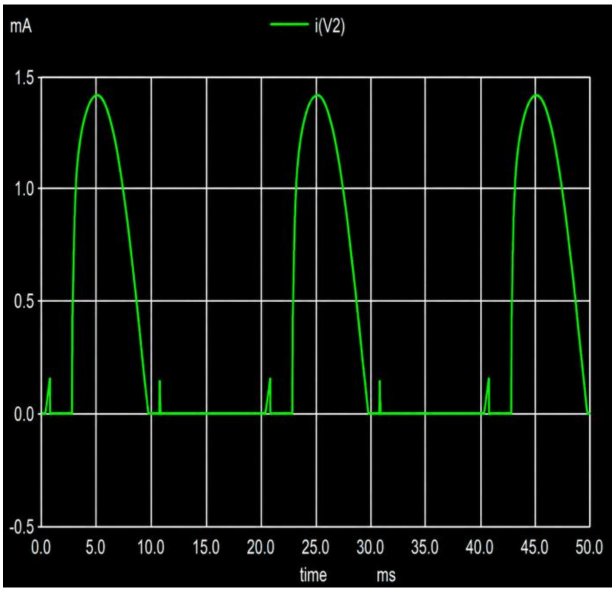

Fig. 5 (a). Gummel-poon SCR current waveform

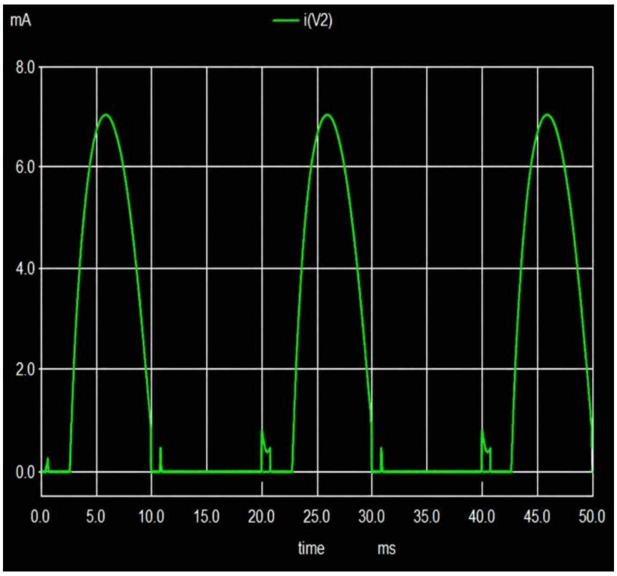

Fig. 5 (b). Ebers-moll SCR current waveform

Both models have similar switching instants when observed through voltage collapse, but the Gummel-Poon model shows important transient effects such as oscillations, gradual current rise, and charge storage, unlike the simpler Ebers–Moll model that provides an idealized representation.

TABLE III
COMPARATIVE ANALYSIS

Feature	Ebers-Moll Model	Gummel-Poon Model
Model Type	Static large-signal model	Dynamic charge-control model
Switching Nature	Abrupt and idealized	Gradual and physically realistic
Voltage Collapse Timing	Appears instantaneous	Appears similar (voltage-based)
Internal Turn-on Dynamics	Not represented	Includes finite delay and charge buildup
Current Rise	Smooth and gradual	Instantaneous
Charge Storage Effects	Not included	Included (base charge modeling)
Junction Capacitances	Not included	Included (CJE, CJC)
Turn-on Transients	Absent	Present (oscillations observed)
Oscillations at Turn-on	None	Present (due to capacitance + feedback interaction)
Oscillations at Turn-off/End	None	Present due to stored charge release and RL interaction
Effect of Inductive Load	Minimal influence	Significant due to interaction with stored charge
Numerical Stability	Very stable	May require damping
Physical Realism	Low	High
Suitability	Basic analysis	Accurate transient simulation

V. CONCLUSION

This paper used the two-transistor analogy in SPICE to simulate a silicon-controlled rectifier (SCR) with the Ebers-Moll and Gummel-Poon transistor models, and compared them. This SCR was implemented in a fully controlled bridge rectifier circuit and analyzed under identical operating conditions using transient simulation for both BJT models.

From the results, significant differences are observed in the transient behaviour. The Ebers-Moll model showed abrupt and idealized switching characteristics with no oscillations or dynamic effects whereas the Gummel-Poon model shows the effects of charge storage, junction voltages, junction capacitances and finite carrier transit time which result in smoother current transitions and noticeable transient oscillations during switching.

The oscillations seen in the Gummel-Poon model that highlight the effect of internal device capacitances and the regenerative feedback mechanism especially when the rectifier has inductive loads, cannot be seen in the Ebers-Moll model making it less suitable for accurate transient analysis.

This paper concludes that the Ebers-Moll model is useful for basic analysis as it has simple model parameters and simple computation; the Gummel-Poon

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model shows a more realistic SCR switching behavior. Hence, the selection of an appropriate transistor model is essential for accurate simulation of power electronic devices, especially in applications involving dynamic and transient conditions.

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