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Analysis of Performance of Switched Capacitor Circuits

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ABSTRACT: In switched capacitor circuits, it is quite common to use MOSFET switches, integrated capacitors (IC) and non-overlapping clocks for carrying out switching operations. MOSFET switches are far from ideal switches mainly when they are operated with small operating voltages. Some investigations have been carried out on the performance of switched capacitor resistors (SCRs) with the switches operated under varied conditions. Further, an attempt has been made to find out how closely SCR represents conventional resistors. It has been found that the SCRs with ideal components satisfy the properties of series and parallel connected conventional resistors. Further, the energy dissipation in SCR is the same as that in conventional resistors when operated under fixed voltage difference. FET based SCRs exhibit higher resistance values, compared to SCRs with ideal switches depending on the operating conditions. When SCRs are loaded with conventional resistors or capacitors, their output is entirely different from those, where only conventional components are used. This paper aims to describe the efforts made to find out the limitations of FET based SCRs and caution the circuit designers about using SCRs in the place of conventional resistors.

Keywords: Switched capacitors resistors, parasites in SCR, FET, MOSFET, EMOSFET.

I. INTRODUCTION

The principles of operation of ideal SCRs and, the extent to which SCRs can be represented by a conventional resistor are described. The effect of switch resistance on the value of SCR and the attempts to compute the SCR values taking the I-V characteristics of the switches are discussed. The behavior of SCR [1] when connected along with conventional capacitors and resistors are considered. We caution on the use of SCRs in the place of conventional resistances as they mimic the behavior of conventional resistors only under some special circumstances. Switched capacitor circuits are based on the principle that “charge transfers from a higher voltage node to a lower voltage node”. This is generally carried out in two steps, charging a capacitor to a voltage V_1 through a switch and discharging it to a lower voltage V_2, through another switch.
Under equilibrium conditions the charge drawn from the high voltage node is the same as the charge delivered to the low voltage node. This charge transfer takes place [2] in one clock period and the average rate of charge transfer is taken as the DC current, even though the current is impulsive (for ideal conditions). The ratio of voltage difference to the current is taken as the effective resistance of the SCR. Switched Capacitor acts like a resistor whose value depends on capacitance Cs and switching frequency f. The switched capacitor resistor is used in place of simple resistors in integrated circuits. Many configurations are suggested, and two of these are given.

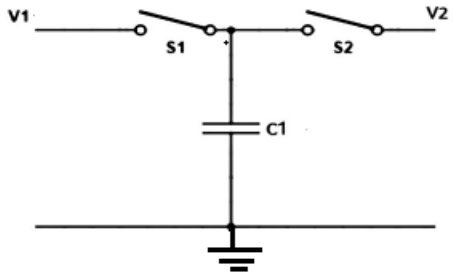

Fig. 1. Switched capacitor.

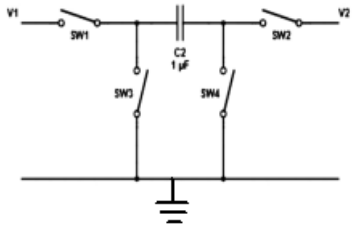

Fig. 2 (a) Configuration of switched- capacitor.

The switched capacitor is shown in Fig.1 and its configuration is shown in Fig. 2. S1 and S2 are the switches as in Fig. 1 and (S1, S1') and (S2, S2') are operated by non-overlapping clocks as shown in Fig. (2b). Switches close when Q is high and open when Q is low where Q is the control voltage.

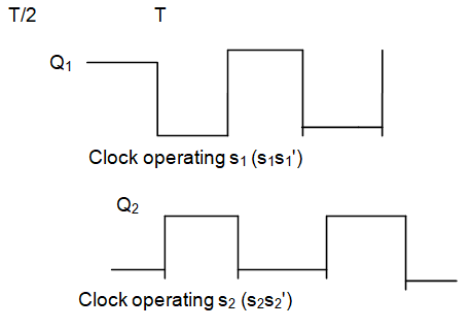

Fig. 2 (b) Operating clocks.

The average value of current flowing from V_1 to V_2 is

average value $I = \frac{C(V_1 - V_2)}{T}$ (1)

and the effective resistance is given by

$R = \frac{T}{C}\left(\frac{V1-V2}{I}\right)$ (2)

$= T/C = 1/Fc$ (iii), where $f = 1/T$ (3)

It may be seen from this description that SCR is a variable resistor whose value can be varied by varying the switching frequency. If this SCR is to be used to replace conventional resistors, [9] it is necessary to know to what extent this SCR resembles a conventional resistor.

II. SERIES CONNECTED SCRs

Case 1. Let two SCRs are operated by the same non - overlapping clocks are connected in series as shown in Fig. 3.

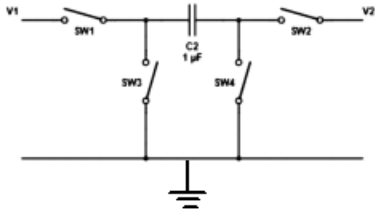

Fig. 3 (a) SCR's connected in series.

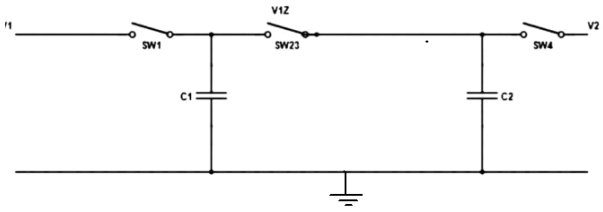

Fig. 3 (b) SCR's connected in series.

If we follow the sequence of operations for both the resistors as described for SCR in Fig. 1, we realize that S_1 and S_3, S_2 and S_4 are to be synchronously operated [8] in which either S_2 or S_3 is always open and hence no charge transfer can take place between V_1 and V_4. This clearly indicates that SCRs cannot be connected with the same sequence of operations for realizing the combined effect. To understand the impact of the series connection of resistors follow the logic that charge is to be transferred from node V_1 to node V_{23} and then to node V_4. In other words, the charge is transferred in steps (i.e.) from V_1 to C_1 from C_1 to C_2 and then C_2 to V2. This can be achieved by synchronously operating S_1 and S_4 and S_2 and S_3. A single switch S_2 can replace S_2 and S_3 and the operation is described as follows.

— Close S_1, S_4 and open S_{23}. C_1 is charged to V_1 and C_2 is discharged [12] to V_2.

— Then open S_1, S_4 and close S_{23}. Then some charge gets transferred from C_1 to C_2 and the voltage V_{23} is given by

$$V23 = \frac{C_1V_1 + C_2V_2}{C_1 + C_2} \quad (4)$$

(both C_1 and C_2 have this voltage)

— When step 1 is repeated charge is transferred from V_1 to C_1 and from C_2 to V_2. The charge transferred is Q $= C_1(V_1 - V_{23}) = C_2(V_{23} - V_2)$ (5)

Substituting for V_{23} from (42.1) in (52.2)

$$Q = \frac{C_1C_2(V_1 - V_2)}{C_1 + C_2} \quad (6)$$

The average current flowing = I= $\frac{C_1C_2(V_1 - V_2)}{T.(C_1 + C_2)}$ (7)

Effective resistance = $\frac{T}{C1} + \frac{T}{C2} = R_1 + R_2$ (8)

We can connect several SCRs in services as shown below. The sequence of operations to be followed is that alternate switches have to be synchronously operated by a non-over- lapping clock

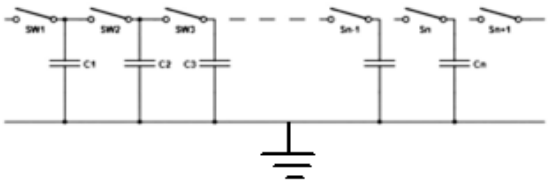

Fig. 4. SCRs in series.

Equivalent resistance = $R_1 + R_2 + R_m - R_n$ (9)

where $R_m = \frac{T}{Cm} = \frac{1}{f.Cm}$ (10)

This analysis shows that SCRs connected in series with the switching sequence described above behave like a stack of normal resistances [13] connected in series.

III. PARALLEL CONNECTED SCRs

SCRs may be connected in parallel as shown in the Figs. 5, 6.

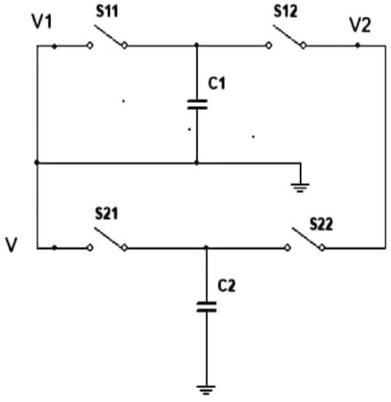

Fig. 5. SCRs in parallel.

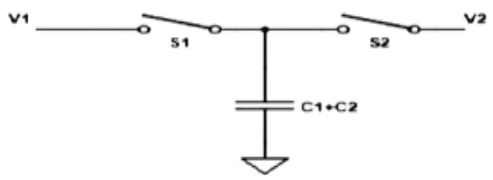

Fig. 6. SCR s in parallel.

From the figure, it is clear that there is no change in the sequence required and the overall resistance is

$$R = \frac{T}{C1+C2} \quad (11)$$

$$G = \frac{C1+C2}{T} = \frac{C1}{T} + \frac{C2}{T} = G1+G2 \quad (12)$$

SCRs when connected in parallel, they behave like parallel stack of conventional resistors.

IV. SCR WITH DIFFERENT OPERATING SWITCHING FREQUENCIES

In the first in stage, let there be two switches for each resistor and they are operated normally.

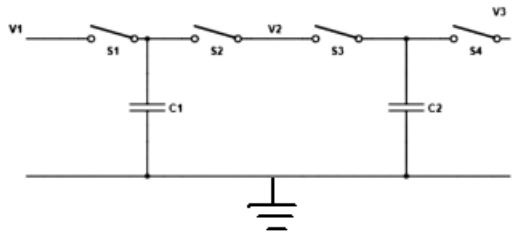

Fig. 7. SCRs in different operating frequencies.

Except that the clock is shifted from the other by a certain time 'S'.This shift enables S_2 and S_3 closed deriving 'S'. If 'S' is sufficient for the charge to get redistributed between C_1 and C_2, the resistors follow the law of addition (i.e. $R = R_1 + R_2$).

Let the switching frequency of one resistor [18] be double the switching frequency of the other but synchronized. In this situation the charge gets transferred from V_1 to V_2 only, at the rate decided by the lower switching frequency. This leads to the discrepancy in the effective resistance value. Normally the effective resistance should be $R = R_1 + R_2 = \frac{T1}{C1} + \frac{T1}{2C2}$.

However, in this case it would be

$$\frac{T1}{C1} + \frac{T1}{2C2} \quad (13)$$

Thus whenever resistors realized with different [20] frequencies are connected in series, the effective value of the stack is decided by the lower switching frequency.

A. Parallel connected SCRs

Since each branch of the parallel stack [6] generates an average current independent of other branch, the sum of all the average currents would be the effective average current and hence the parallel resistor property is still valid ever if the switching frequencies of operation are different.

Thus it may be mentioned that SCRs operating with different switching frequencies when connected in series, the effective value does not follow the normal rule of series-connected to conventional resistors follow whereas parallel SCR stack obeys the normal rules followed by conventional resistors.

B. Power dissipation in SCRs

One may wonder whether there is any power dissipation in SCRs as there is no visible dissipative element as it contains only capacitors and ideal switches. But there is hidden power dissipation in the form of switching losses. It is known that while a capacitor is charged to a voltage V_1, there is a loss of energy equal to ½ CV^2 and the stored energy is only ½ CV^2 (i.e.) the efficiency of charging is only 50%. When the capacitor discharges, there is energy loss. In this section, the energy losses and hence the power loss [22] in SCR because of switching is calculated.

C. Energy loss calculations

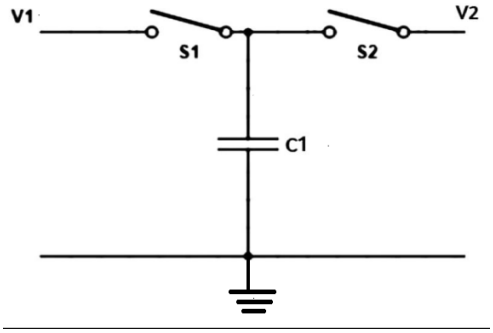

Fig. 8. Switched capacitor.

Step 1: Energy stored (extra) when the capacitor is charged from V_2 to V_1.

$$V_1 = \frac{1}{2}C(V^2_1 - V^2_2) \quad (13a)$$

Energy drawn from V1 to store this energy

$$Ev_1 = v_1 \int_{V2}^{V1} C\, dv = C(V_1^2 - V_1V_2) \quad (14)$$

Energy dissipated during charging

$$C(V1^2\text{-}V1V2) - \frac{1}{2}C(V1^2\text{-}V2^2) \quad (15)$$

$$Ed_1 = ½\, C(V_1 - V_2)^2 \quad (16)$$

Similarly the charge dissipated during discharging from V_1 to V_2 can be shown to be

$$Ed_2 = \frac{1}{2}\, C(V_1 - V_2)^2 \quad (17)$$

Total energy dissipated 'E' during one cycle (i.e.) in a period T is given by

$$\text{Energy dissipated } E = C(V_1 - V_2)^2 \quad (18)$$

$$\text{Power dissipated} = P = \frac{C(V1-V2)^2}{T} = (V_1 - V_2)^{2/} (T/C) \quad (19)$$

Thus, the energy dissipated in SCR operating between V_1 and V_2 or with voltage difference of $(V_1 - V_2)$ is the same as that takes place in the case of a conventional resistor operating under the same conditions.

$$\frac{(V1-V2)^2}{R} \quad (20)$$

From the above analysis we may conclude that the [4] SCR under ideal situations can mimic the behaviour of a resistor from the point of series and parallel connected resistors and power dissipation. However when the resistors are realized with different switching frequencies and if they are connected in series [16], the effective [3] resistance is controlled by lowering the switching frequencies. .

D. Behaviour of SCR when connected to normal components

From the circuit given above, it may be seen that during charging [5] from V_1 the current is impulsive and while discharging the current varies exponentially with time and the voltage VR_L and I can be obtained as

$VR_L = V1e^{\frac{-T}{2R_LC}}$ (21)

and the average current

$$I = \frac{C(V1-V1e^{\frac{-T}{2R_LC}})}{T} \quad (22)$$

The equivalent resistance R_{eq} is given by

$$R_{eq} = \frac{T}{C(1-e^{\frac{-T}{2R_LC}})} \quad (23)$$

This value is different from the expected value of $R_{eq} = \frac{T}{C}+R_L$ (24)

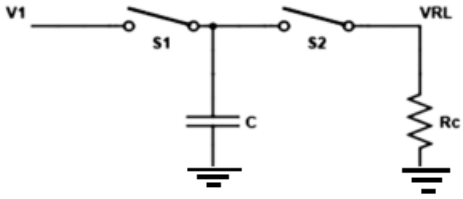

Fig. 9. SCR connected to normal components.

Thus, when SCR is connected with [14] conventional resistor in series. One should be very careful in computing the effective resistance. However, when connected in parallel, the conductance can be calculated using the normal rules.

V. SCRs WITH PRACTICAL SWITCHES

When SCRs are realized with electromechanical switches, which have almost ideal characteristics "on resistance is very close to zero and off resistance is very high". The SCRs are expected [7] to behave like ideal SCRs. However, when they are realized with switches like BJT or FET switches, SCR behaviour is expected to change. The following investigations are carried out on SCR with EMOSFET switches.

A. EMOSFET as a switch

"On and off" states (between same and drain) are controlled by the gate to source voltage (V_{gs}). The following may be kept in mind while realizing SCRs with FETs.

– FET conducts reasonably well when $V_{gs} > V_T$

– There is a voltage [8] drop V_{DS} depending on the current I_D or I_S which gives rise to resistance.

– There is a channel charge stored under the gate when conducting and it has to be discharged in the off conditions.

– There are FET capacitances like C_{Ds} and C_{gs}

B. Charging of a capacitor using FET

In SCR, the charging and discharging are carried out using FETs and the FETs go through varying currents and voltages (V_{gs} and V_{Ds}) with time. Thus, the resistance offered is a variable resistance with time. This results in a gradual variation of current while charging [15] or discharging unlike in the case of ideal switches. In view of this charging and discharging process in SCR, the I-V relation of FETs are calculated and the equivalent resistance is obtained.

C. SCR analysis using FET switches using I-V relation

Consider the following circuit for SCR

Under equilibrium conditions let the capacitor C gets charged from V_1 to V_c while charging and let it get discharged from V_C to V_D during the discharging period.

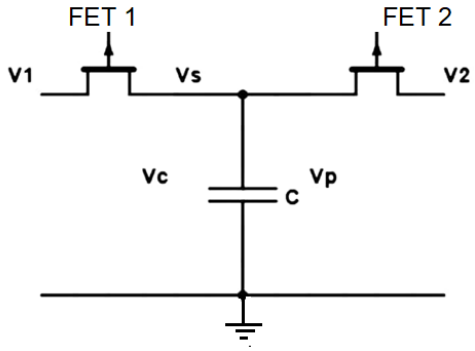

Fig. 10. SCR using FET.

The I-V relation used for MOSFET$_1$ is

$I_o = I_{DSS}\ [(V_G – V_S – V_T)(V_1 - V_S) - 1/2(V_1 - V_S)^2]$ (25)

The voltage V_s charges with time and is given by

$$\frac{dVs}{dt} = \frac{I}{C} \quad (26)$$

using the equations 25 and 26 and with the boundary conditions $V_S = V_D$ at t = 0 and $V_s = V_C$ at t = T/2 V_c is shown as below.

$$V_c = V_1 - \left[\frac{2b}{e^{\frac{-Idss\ bT}{2C}}\left(1+\frac{2b}{v1-vd}\right)-1}\right] \quad (27)$$

Where $b = (Vg – V_T – V_T)$ (28)

During discharge, the V_{gs} remain constant and V_{DS} changes. We can show that

$$V_d = V2+\frac{2a}{1+\left(\frac{2a}{(vc-v2)}-1\right).e^{\frac{Idss.at}{2c}}} \quad (29)$$

D. Evaluation of SCR resistance taking the I-V characteristics of FET switches

Consider Fig. 10. The charging and discharging controlled by [7] FET switches, taken place following the I-V characteristics of the FETs. The equation describing I -V relation of FET is taken as

$I_D=I_S=I_{DSS}\ [(V_{gs}-V_T)V_{DS} - 1/2\ V^2_{DS}]$ (30)

When FET 1 is put on with a gate voltage Vg and FET 2 is put off. Then the capacitor [8] gets charged from a voltage V_D to Vc from the source V_1 where, V_D is the voltage at t = 0 across the capacitor and [22] V_C is the voltage at t = T/2, V_c [19] and V_D are the equilibrium or steady state values.

It may be noted that during charging, the capacitor voltage [10] which is the source voltage continuously changes with time. The variation source voltage may be obtained by

$$\frac{dVs}{dt} = \frac{I}{C} \quad (31)$$

$$I = I_{DSS}\ [(V_G – V_S – V_T)(V_1 - V_S) - \frac{1}{2}(V1 - Vs)^2 \quad (32)$$

The above equation may be written as given below.

$I = I_{DSS}\ [(V_g – V_1) + (V_1 – V_S) – V_T]\ (V_1 – V_s) – ½\ (V_1 – V_s)^2$ (33)

Det $V_1 – V_s = X$ and (33a)

$V_g – V_1 – V_T = B$ (33b)

Then $I = I_{dss}\ [(b+x) - \frac{1}{2}X]\ X$ (34)

From (30) and (33)

$$\frac{dVs}{dt} = \frac{dx}{dt} = \frac{I}{e} = \frac{I_{DSS}}{C}[(b+x)x = \frac{1}{2}x^2 \quad (35)$$

Integrate this Eqn. (8) with respect to time realizing

At t= 0, $x = V_1 – V_d$ and (36)

$T = T/2.\ X = V_1 – V_C$ (37)

We obtain

$$Vc = V_1 - \frac{2b}{me^{\frac{IdssbT}{2c}-1}} \quad (38)$$

Where $m = \frac{2b-v1-vd}{v1-vd}$ (39)

$b = V_g - V_1 - V_T$ (40)

During discharging of the capacitor, FET1 is off and FET2 is on. The capacitor discharges from V_c (at t = 0 beginning of discharging) to V_D (at T = T/2 end of discharging). Further it may [11] be noted that Vs remains constant at V_2 and V_D changes with time.

The current flowing through FET during this period is given by

$I = Idss [[(V_G - V_2 - V_T) (V_D - V_2) - 1\2(V_D - V_2)^2$ (41)

Further,

$dv_D/dt = - I/c$ (42)

Also let $V_D - V_2 = y$,

$dV_D / dt = dy/dt$ (47)

$V_g - V_2 - V_T = a$

Then $\frac{dy}{dt} = \frac{-Idss}{2C}(2a-y)y$ (48)

Integrating this equation w.r.t y and using the boundary conditions

$Y = V_c - V_2$ at t = 0 (49)

$Y = V_d - V_2$ at t = T/2 (50)

Then

$$V_d = V_2 + \frac{2a}{1+ne^{\frac{IdssaT}{2c}}} \quad (51)$$

$n = \frac{2a-Vc+V2}{Vc-V2}$ (52)

$a = V_g - V_2 - V_T$ (53)

Table 1.

Tnsec	Vc(V)	Vd(V)	C	V1	V2	Res of SCR
16	1.996	1.921	2pF	2.0	1.0	53 kΩ
30	1.999	1.910	2pF	2.0	1.0	84.34 kΩ

If we examine equations from (33) to (42) we find that they contain V_c and V_d and they are related by these equations. For a given V_1 and V_2 and for specific values of T, C, and I_{DSS} one can solve for V_C and V_d using a method like graphical method. In this paper, graphical method is used and typical values of Vc and Vd are given in table for different values of T.

The average current is $(Vc-V_d)C /T$ (43)

and the resistance is $(V_1 - V_2)/V_c - V_d) . T/C$ (44)

the equations 41 and 42 are simultaneously solved for Vc and V_d (using a graphical method) for a set of V_1 and V_2 and FET knowing the value of Vc and V_D, the total charge transferred in a cycle is

$Q = C(V_C - V_D)$ and the average current is

$$I = \frac{Q}{T} = \frac{C(vc-vd)}{T} \quad (45)$$

is calculated and hence the resistance R as

$$R = \frac{V1-V2}{I} = \frac{(V1-V2)}{(vc-vd)}\left(\frac{I}{C}\right) \quad (46)$$

This shows that for a given $V_1 > V_2$ the value of resistance increases by a factor $1/V_C - V_D$ for a time period of 30n sec and

$I_{DSS} = V_g V1, V_2$ are calculated.

The expected resistance has gone up by a factor of 5 times. (84 kΩ instead of 15kΩ).

The SCR [23] is simulated and the resistance is measured and it is about twice the ideal value.

From this it is clear that the switch resistance increases the effective value by as much as 2-5 times that of ideal resistance values since the actual value (measured value) is far from that of ideal SCR and the calculated value, and also it is too complicated to calculate the SCR value taking the I-V characteristics into account, The charging characteristics of the capacitor with FET is measured as shown in Fig. 11.

$V_g = 2V$

The variation of V_0 with time is noted, the time needed for V_0 to reach about 65% V_D(2V) is noted then the equivalent resistance of FET to charge the capacitor in the same time period is calculated (i.e.) FET may be replaced by this resistor for charging and discharging purpose.

SCR with FET represented (modelled) by Req (described above)

The charging and discharging characteristics with equivalent resistor present in SCR are calculated and the V_C and V_D (as defined in the earlier case are shown.

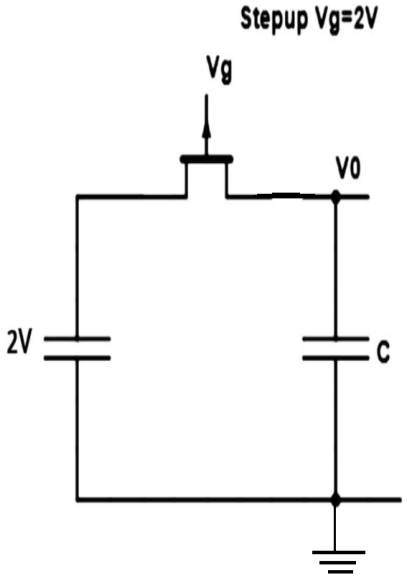

Fig. 11. Circuit diagram of FET.

E. Evaluation of SCR resistance with FET represented by a constant equivalent resistor, using the same notation as in (D)

Replacing the FETs by their "On resistances" when they are closed and by ∞ resistance when they are open the values of V_c and V_d are calculated using the following procedure. The SCR equivalent circuit may be sketched as shown in the Fig. 11.

During charging 'C' gets charged from V_d to V_c from voltage V_1 and during discharging its gets [17] (c) discharged from V_c to V_d into V_2. The current I following into C during charging is

$$I = C\frac{dv}{dt} = \frac{V1-V}{R} \quad (54)$$

This equation may be solved for V with the boundary condition that V = Vd at t = 0 and V = Vc at t = T/2.

This resulting in $Vc = V1+(Vd-V1)\, e^{\frac{-T}{2RC}}$ (55)

Similarly the value of Vd can be shown to be Vd = $V_2+(Vc-V_2)\, e^{\frac{-T}{2RC}}$ (56)

The average current is given by

$$I_{av} = \frac{Vc-Vd}{T}\ C \quad (57)$$

The resistance of SCR is given by $R = \frac{(V1-V2)}{(vc-vd)}\left(\frac{T}{C}\right)$ (58)

using different values of 'R' corresponding to different operating ranges resistance value of SCR are calculated and it is found that value of R corresponding to about 70% charging of the capacitor with FET gives reasonable value of SCR.

$$V_c = V_1+(V_d-V_1)e^{\frac{-T}{2RC}} \quad (59)$$

$$V_d = V_2+(V_c-V_2)\, e^{\frac{-T}{2RC}} \quad (60)$$

These two equations are solved for V_D and V_C for a given V_1 and V_2. Then the average current is calculated as

$$C(Vc-V_D)/T \quad (61)$$

and the resistance as

$$R = \frac{(V1-V2)}{(vc-vd)}\left(\frac{T}{C}\right) \quad (62)$$

The calculated value for a time period of 30ns is about 17kΩ.The ideal value is 15kΩ. However, the corresponding measured value of SCR is 32.89 KΩ. This corresponds to the equivalent resistor corresponding to 70% of V_D.

VI. CONCLUSION

From this analysis, it is clear that the SCR resistance with FETs is generally higher than ideal resistance. If FET is replaced by an equivalent resistor corresponding to that of 65% value (refers charging of capacitor with FET) .The SCR value would be the same as that of ideal one. However, the measured resistance of SCR with FETs is higher than that of ideal one by a factor of 2, where SCR is replaced by resistor of value equal to the equivalent resister needed for charging the capacitor to 65% of the peak value in the slew time.

In addition to the above investigation, resistance of SCR with FETs switches is measured with a small capacitance connected between source and drain of the FETs. It is found that the effect of the capacitor on SCR resistance value is not significant as long as this capacitance is small compared to the main capacitor. Similarly the effect of leakage of the switching capacitor is found to be negligible as long as the leakage current is small compared to the average current. The following observations are mentioned.

– SCR with ideal switches can mimic the behaviour of conventional resistor from the point of connecting SCR in series, in parallel and from the point of power dissipation.

– SCR with MOSFET switches exhibits resistance values and the FET parameters if it is connected. In a typical case the effective resistance is approximately the value of ideal SCR with the same switching frequency and the charging capacitor.

– SCRs when connected in series, operating with different frequencies, the value of the effective resistance is decided by the lower switching frequency.

– When SCRs are connected in parallel the effective resistance follows the rule applicable to conventional resistors and the operating frequencies.

– When SCRs are loaded with resistive loads the effective resistance is not same as the sum of the resistors values.

– Even with capacitive loads, the output wave forms obtained with the SCRs is different from those obtained with the conventional resistors by the same value.

– SCRs can take small parasitic capacitances across the switches.

In the end we may caution on the use of SCRs in the place of conventional resistances as they mimic the behavior of conventional resistors only under some special circumstances. However, one can evaluate the performance of the circuits using SCRs, taking the actual charging and discharging characteristics of the capacitor through the equivalent resistance of the FET switches.

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