

Snubbing Circuit Realization Based on Numerical Techniques

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Abstract

One of the most important and major problems that faces the controllable devices for industrial applications, and solid-state switches for pulsed power applications, is the high rate of current and voltage changes during the switching transients of the device. This problem can be overcome by suitable circuitry connected across the device which is well known as a Snubber Circuit.

In this paper, a proposed numerical solution using the Fourth Order Runge-Kutta numerical method is applied to evaluate the values of the snubber circuit parameters to maintain the effect of current and voltage rate of changes, during device turn – ON, at levels that the device can withstand. Comparison with other design procedures showed good agreement with reasonable results for the circuit parameters to validate the proposed method.

Key – words: Snubber circuits, rate of current and voltage changes, numerical methods, Runge-Kutta method.

الخلاصة:

يعتبر التغير المفاجيء للتيار الساري خلال أشباه الموصلات والتغير المفاجيء للفولتية (الجهد) المسطرة على البوابة الأنودية لشبه الموصل من أخطر المشاكل التي تواجه دوائر التحكم لتطبيقات أشباه الموصلات في المجال الصناعي، وخصوصا في اللحظات الإنتقالية أثناء تشغيل أو إطفاء شبه الموصل. لتخطي هذه المشكلة تربط على طرفي شبه الموصل دائرة خاصة تسمى دوائر النرجر (Snubber Networks).
قدم في هذا البحث تطبيقا للتحليلات العددية في تصميم هذه الدائرة باستخدام طريقة الرانج-كوتا (Kutta-Runge) من الدرجة الرابعة لغرض تقليل تأثير التغير المفاجيء للتيار و الجهد لمستوي يتحملة شبه الموصل المستخدم. تمت مقارنة النتائج مع نتائج طرق التصميم الأخرى لغرض التحقق من كفاءة الطريقة، و أظهرت المقارنة تقاربا معقولا للنتائج المستخرجة بالطريقة المقدمة.

Introduction

Snubber circuit is one of the most important protection techniques for reducing the effect of rate of changes of current (di/dt), and voltage (dv/dt) that may cause severe damages to the circuit switching drives if they can not afford these changes. Although snubber circuit is a network that is implemented with small parts, its functioning achieves many advantages in the power switching circuits. It reduces, or eliminates, voltage or current spikes; transfers power dissipation from the switch to a resistor or a useful load, and hence reduces total losses due to switching. All these advantages make a great influence to enhance the performance of the switching circuits and result in higher device reliability, higher efficiency, and higher switching frequency and lower EMI (Electro-Magnetic Interference). [1, 2]

Few, but significant works treated the design of snubber circuits. Franc Mihalic, et al. [3] have presented practical use of effective snubber circuits in the three-phase AC to DC buck converter, using the conventional matrix theory approach and investigating the commutation problem at high voltage rate for solving the optimal snubber circuits. Oto Tezak, et al. [4] had suggested a new approach to the design of snubber circuits for low power dc-dc converters based on the experimental analysis of current and voltage measurements, with the disadvantages of number of experimental readings requirements, and linear approximation of current and voltage during discharging times. At that work, a need for multiple readings of current and voltages with different values of snubber capacitance only requires attention regarding the equivalent series resistance (ESR) of the capacitor used. The ESR of the capacitor used varies with the capacitor value and type, which needs a new snubber resistance value, and introduces an exponential rather linear decay during discharging times.

M. Elmore, et al. [5] presented a neural network that has been used to model the simulation results of a complex Thyristor assembly. An Evolutionary Strategy optimization algorithm has been applied to the neural network model to find the minimum snubber capacitor, which constrains the peak **turn-off** voltage across each Thyristor to an acceptable level.

Irrespective of the aforementioned works and others [6 – 8], which are not mentioned here for shortness, none have proposed the use of numerical methods for solving the problem of how to calculate the snubber circuit parameters numerically for low frequency industrial applications. The proposed method presented in this work deals with solving ordinary differential equation ODE that starts from an initial condition. The differential equation is used to describe the snubber circuit parameters during device turn ON, with the help of critical specification for the power device provided by its manufacturer. [9]

For comparison purposes with the Time Constant Method (TCM) [9], and the Resonant Method (RM) [10], a practical numerical problem formulation has been introduced to validate the results obtained with the proposed method.

Snubber Network Description and Connection

The basic intent of a snubber circuit is to absorb energy from the reactive elements in the power circuit. Snubber Network variations are shown in Fig. (1). Benefits of connecting snubber networks may include circuit damping, controlling the rate of change of current and voltage, or clamping voltage overshoot (spikes). In performing these functions a snubber limits the amount of the stress which the switch must endure and this increases the reliability of the switch and prevents false triggering in the device subjected to voltage changes. When a snubber is properly designed and implemented the switch will have lower average power dissipation, much lower peak power dissipation, lower peak operating voltage and lower peak operating current. [2, 11]

Snubber networks may be either passive or active networks. Passive snubber network elements are limited to resistors, capacitors, inductors and diodes. Active snubbers include transistors or other active switches, often entail a significant amount of extra circuitry and introduce another level of parasitics which must be dealt with, [8, 11].

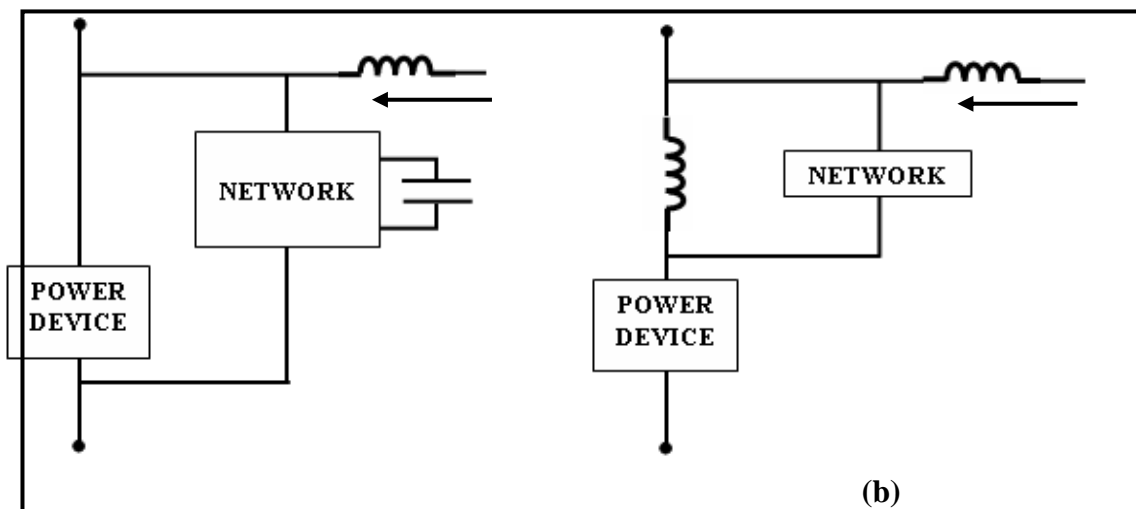


Figure (1): Snubber Network variation, [11]
(a) Voltage Snubber; (b) Current Snubber

According to the direction of the energy in and out of the snubber circuit, another classification is introduced. If this energy is dissipated in the resistor of the snubber circuit then the snubber is said to be dissipative snubber that results in a reduction of the system efficiency. On the other hand, non dissipative snubbers are those networks that absorb nothing from the energy stored in their passive elements which gives a higher efficiency. Also, a snubber is classified as polarized or non-polarized depending on whether energy moves in or out of the snubber on one edge of the switching waveform or both, [11].

It is worth mentioning that this work deals with dissipative snubber networks irrespective of their polarization type, and of the passive networks type. Also, the parasitic

effect of circuit inductances and capacitances will not be considered here, as the circuit is operating with the power frequency.

Many topologies are used to describe the snubber networks. A general topology is shown in Fig. (2). Inductance L_1 protects the power device from large (di/dt) during the turn-ON process. The auxiliary arm circuit made by R_1 and D_1 allows the discharging of L_1 when the device is turned OFF. The arm consisted of resistor R_2 and capacitance C_2 protects the device from large (dv/dt) during the turn – ON and turn – OFF processes.

The auxiliary arm circuit made by D_2 and R_2 allows the discharging of C_2 when the device is turned-ON. The circuit of capacitance C_2 and inductance L_1 also limits the value of (dv/dt) across the device during forward blocking. In addition, L_1 protects the device (normally a Thyristor or a Triac) from reverse over-currents, [12].

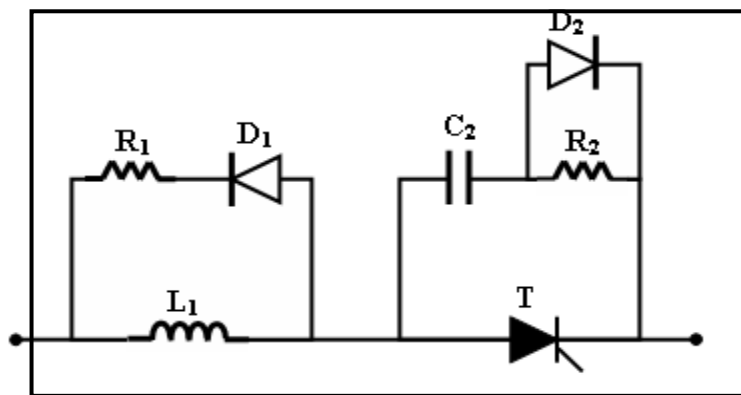


Figure (2) Turn-ON (top elements) and turn-OFF (bottom elements) snubber circuits for Thyristor [12]

Another snubber networks topology that is widely used for Thyristorized industrial power applications is the typical Resistor Capacitor Diode (RCD) snubber circuit, shown in Fig. (3 – a). In this topology, the resistor diode arm (R_1, D_1) is opened circuited (canceled), as this arm treated the energy stored in the load inductance (L_1) during device turn-OFF, which is not considered in our work. Fig. (3 – b) shows the simplest form of the RC Snubber circuit which is the most widely used passive snubber networks in controlling Triacs driving industrial loads which have no inductances, as heaters.

The topology shown in Fig.(3 – b) is a non-polarized dissipative snubber network, and is applicable for both rate-of-rise control and damping. Care must be taken in choosing the values of R and C for total system performance optimization.

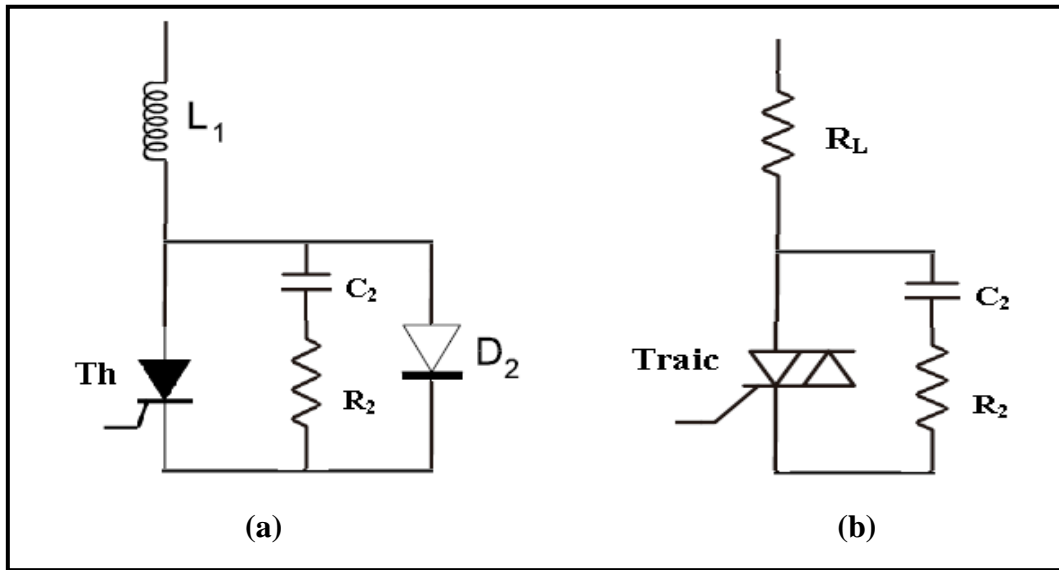


Figure (3) Snubber Circuits Variation for protecting power devices used in Industrial Applications
(a) RCD snubber network; (b) Simple RC snubber network

Snubber Network Parameter's Calculation requirements

In this work benefit of using snubber circuits in protecting the device from sudden changes in its current (di/dt) or voltage (dv/dt) is concerned. The snubbing circuit parameters to be evaluated are the resistance (R), the capacitance (C) and (or) inductance (L). The first step in calculating these values regards the RC time constant of the snubber circuit. The time constant should be small compared to the switching period but long compared to the voltage rise time. Secondly, the snubber capacitance must be small enough to minimize the power dissipated in the snubber resistance, hence reducing the power capability of the snubber resistor used. It is worth mentioning that larger capacitor value is needed if the parasitic resonance is considered which gives a factor of (3 – 4) times the parasitic resonance capacitor value as a general assumption, [1,2].

The power loss in the snubber resistor may be known from the energy stored in the capacitor. The energy stored in the capacitor (E_C) transferred to the snubber resistor during switch turn-ON, [2], and may be expressed as:

$$E_C = \frac{1}{2} C \cdot V_A^2(\text{max}) , \text{ J} \dots\dots\dots (1)$$

Where:

$V_A(\text{max})$: capacitor peak applied voltage (charging voltage)

And C : the snubber capacitor value.

This energy is to be discharged as a power that is dissipated in the snubber resistance. This may be written in terms of the switching frequency as:

$$P = f \times V_A^2(\max) \times C, \quad W \dots\dots\dots (2)$$

Equation (2) is very useful in calculating the wattage requirement of the snubber resistance such that a reasonable optimization could be made between the capacitor and resistor values. Also, if the snubber is to be designed for Thyristor power application with half – wave control, half the power calculated using (2) is used to calculate the wattage requirements of the snubber resistance.

Runge-Kutta Method

Numerical methods are usually used for solving differential equations [13, 14]. Many methods are used for this purpose, such as the Euler's Method. This method is used for solving differential equations given as:

$$\frac{dx}{dt} = f(t, x); \quad x(0) = x_0 \dots\dots\dots (3)$$

Because the Euler method is relatively simple, as the step size (h) is made smaller the error decreases fairly slowly; halving step size will only halve the error. Numerical methods that are used in practice generally have much better error properties. One popular method is the Runge – Kutta Method.

The Fourth – Order Runge-Kutta method used for solving differential equations of the form given by (3) using a step size (h) is given as:

$$x_{n+1} = x_n + \frac{1}{6}(c_1 + 2c_2 + 2c_3 + c_4) \dots\dots\dots (4)$$

Where c_1, \dots, c_4 are defined as:

$$\begin{aligned} c_1 &= h.f(t_n, x_n) \\ c_2 &= h.f\left(t_n + \frac{1}{2}h, x_n + \frac{1}{2}c_1\right) \\ c_3 &= h.f\left(t_n + \frac{1}{2}h, x_n + \frac{1}{2}c_2\right) \\ c_4 &= h.f(t_n + h, x_n + c_3) \end{aligned} \dots\dots\dots (5)$$

Fourth order Runge-Kutta method needs an initial point (x_0), such that the final value can be reached after number of iterations with an acceptable margin of error. The number of iterations and the error margin can be reduced if the initial value is chosen as close as possible to the final value where this choice depends upon the experience of the user. It is worth mentioning that higher accuracy is obtained with smaller step size (h), with the disadvantage of raising the number of iterations, and hence more computational processing time.

From equation (3) one can find that the Left Hand Side (LHS) of the equation may represent either (di/dt) or (dv/dt) . The Right Hand Side (RHS) represents the formula that evaluates the parameters of the snubber circuit, thus a problem formulation that relates these parameters together has been obtained.

In this paper, the RHS of (3) represents the problem formulation. The formulation will be applied to a practical problem that is borrowed from [9]. The results obtained by [9] using the (Time Constant Method), and those obtained using the (Resonant Method) given in [10] are to be compared with the results obtained numerically.

Problem Formulation

AC phase control using Triac for driving heaters in Plastic Machines, shown in Fig. (4), may describe the problem, [9]. The heater is used to heat plastic materials to a certain temperature depending on the material type. According to the variation of the plastic machine size and plastic material type both the heater wattage and its drive are varied. For a specified temperature setting and continuous flow of plastic materials, continuous device turning ON and OFF is required. This introduces continuous transients (di/dt) , and continuous voltage spikes (dv/dt) at the device terminals, and a snubber circuit is required to protect the power device from these transients.

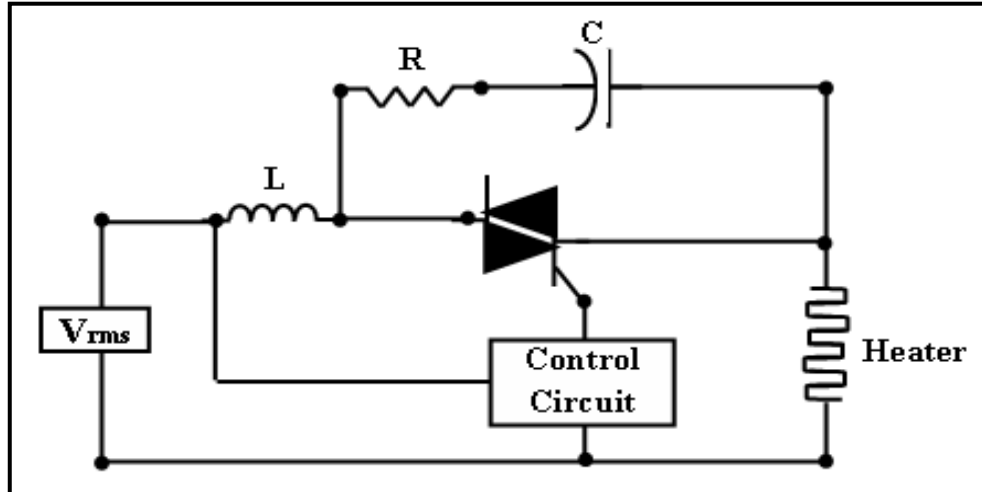


Figure (4) : Triac Heater Circuit (AC phase control)

The power device that is used for driving the heater in the plastic machine is a Triac type MAC2237 that has the critical manufacturer specifications listed in Table I. The power circuit is supplied from a source with a voltage of ($V_{rms} = 208V$, 60Hz). The heater is 1.2 KW with a cold resistance, when starting from rest, of 5Ω which represents the load resistance.

Three approaches will be discovered here. The first approach is explained in [9], and is known by the Time Constant Method (TCM). The second method is the Resonant Method

(RM) given in [8] and is explained, too. Finally, the proposed numerical method using the Fourth Order Runge-Kutta method (RKM) is introduced.

Table IMAC2237 Triac manufacturer specifications, [9]

Symbol	Terminology	Rating
V_{DSM}	Maximum Non-Repetitive Forward Blocking Voltage	500 V
I_{TSM}	Half Cycle Surge Current	250 A
di/dt	Maximum rate of change of current	13.5 A/ μ s
dv/dt	Maximum rate of change of voltage	50 V/ μ s
$I_T(\text{rms})$	Maximum on state rms current	25 A
S	Safety Factor, [2, 9]	0.1→0.4

1- Applying TCM approach

One of the methods that are often used in practice for designing Snubber Circuits is the Time Constant Method. The main feature of this method is that it practices the design according to the device manufacturer specifications. Therefore according to the specifications listed in Table I, the design procedure using (TCM) is demonstrated here.

The minimum allowable value for the snubber resistance in terms of the maximum applied voltage at the device terminal ($V_A(\text{max})$), the device half cycle surge current (I_{TSM}), the load current (I_L) and a safety factor (S), is defined as:

$$R = \frac{V_A(\text{max})}{(I_{TSM} - I_L) \cdot S} \dots\dots\dots (6)$$

During the device turn ON, the (dv/dt) stress on the device is defined as:

$$\frac{dv}{dt} = \frac{V_2 - V_1}{t_2 - t_1}, \text{ V/sec} \dots\dots\dots (7)$$

Where:

- V_1 : Voltage corresponding to 10 % of peak applied voltage
- t_1 : Time corresponds to V_1 .
- V_2 : Voltage corresponding to 63 % of peak applied voltage
- t_2 : Time corresponds to V_2 .

The important voltage value in (7) is (V_2), since this voltage value is used for calculating the time constant as:

$$\tau = \frac{0.63 \times V_{DSM}}{(dv/dt)} = C \cdot R_L \dots\dots\dots (8)$$

With:

- dv/dt Minimum rate of voltage change specified by manufacturer, V/sec.
- R_L Load resistance, ohm.

Equation (8) is used for calculating the snubber capacitance, with a known load resistor.

The capacitor discharges its stored energy into the snubber resistance. The discharging current is given as:

$$I_{dis} = \left(\frac{V_A(\max)}{R} \right) \cdot e^{-\frac{t}{R \cdot C}} \dots\dots\dots (9)$$

Differentiating (9) with respect to time and assuming worst case during device turn ON, t_{on} = 0, gives:

$$\frac{di}{dt} = \frac{V_A(\max)}{R^2 \cdot C} \dots\dots\dots (10)$$

Equation (10) is solved to obtain the minimum snubber resistance value, with the maximum rate of current change given in the device manufacturer specification ((di/dt)_{max}), as:

$$R_{min} = \sqrt{\frac{V_A(\max)}{C \cdot (di/dt)_{max}}} , \text{ ohm} \dots\dots\dots (11)$$

During device turn ON, The snubber inductance value may be calculated from the inductor induced voltage as follows:

$$V_L = L \frac{di}{dt} \Rightarrow L_{min} = \frac{V_L(\max)}{(di/dt)_{max}} = \frac{V_A(\max)}{(di/dt)_{max}} , \text{ H} \dots\dots\dots (12)$$

Using equations (8, 11, 12) one can calculate the snubber circuit parameters. Also, the snubber resistance power dissipation, and hence the wattage requirement, is calculated using equations (1, 2) that were explained previously. The results obtained with this method are listed in Table II, at the end of the third method.

2- Applying the RM approach

Assuming R, C and L are chosen to resonate, an over damping results as will be shown later. This is the result of a damped quarter-cycle of oscillation. In this case the rate of voltage change must be related to an operating frequency which must be calculated.

Since the source is a sine wave voltage, as:

$$V(t) = V_m \sin \omega t \quad \dots\dots\dots (13)$$

Differentiating (13) with respect to time and maximizing the results yields:

$$\left(\frac{dv}{dt}\right)_{\max} = V_m \cdot \omega = V_m \cdot 2\pi f \quad \dots\dots\dots (14)$$

Thus, from equation (14) one can calculate the resonance frequency, as:

$$f = \frac{\left(\frac{dv}{dt}\right)_{\max}}{2\pi \cdot V_m} \quad \dots\dots\dots (15)$$

Also, since the R, C and L are connected in series, at resonance frequency one may conclude that:

$$f = \frac{1}{2\pi\sqrt{L \cdot C}} \Rightarrow C = \frac{1}{(2\pi f)^2 \cdot L} \quad \dots\dots\dots (16)$$

and

$$R = \sqrt{\frac{L}{C}} \quad \dots\dots\dots (17)$$

For convenience the inductance should assumed and the other circuit parameters may then be calculated. Also, for inductive loads, as induction motor, load inductance can be measured to be used as the snubber series inductance, and solving equations (16) and (17) for other circuit parameters. The results using this approach may be obtained using (15), (16) and (17), and are listed in Table II.

3- Applying the Numerical Solution using (RKM)

In order to obtain a differential equation in the form that is given in equation (3), a proper formulation is necessary for this purpose. This may be explained in steps. Firstly, using equation (8) to express the snubber capacitor in terms of the load resistance and the rate of voltage change, one can get that:

$$C = \frac{0.63 \times V_{DSM}}{\left(\frac{dv}{dt}\right)} \cdot \frac{1}{R_L} \quad \dots\dots\dots (18)$$

Secondly, using (18) into (10) with rearranging, it can be shown that:

$$\frac{di}{dt} = \left(\frac{R_L}{R^2}\right) \cdot \left(\frac{V_A(\max)}{0.63V_{DSM}}\right) \cdot \left(\frac{dv}{dt}\right) \dots\dots\dots (19)$$

If the device voltage drop is neglected during device turn ON, the applied voltage on the device terminal is applied at the load (heater), hence a maximum load current is injected into the heater with maximum applied voltage. Thus, with $(V_A(\max) = I_L(\max) \cdot R_L)$, equation (19) may be rewritten as:

$$\frac{di}{dt} = I_L(\max) \cdot \left(\frac{R_L^2}{R^2}\right) \cdot \left(\frac{1}{0.63V_{DSM}}\right) \cdot \left(\frac{dv}{dt}\right) \dots\dots\dots (20)$$

Equations (19) and (20) are the necessary problem formulation. Expressing the rate of current change in terms of load voltage (or current) current has been formulated. Now, the Forth – Order Runge – Kutta method can be applied.

At starting from rest the heater resistance is (5 Ω), hence the load current starts from (58 A). Heater resistance increases as the temperature increase, which results in decreasing the load current until it reaches its steady – state value of (5.77 A). Now, using (20) with the maximum starting current ($I_0 = 58$ A) and the required specifications listed in Table I, with rearranging, one may get:

$$R^2 = 0.294 \times I_0 \dots\dots\dots (21)$$

Now, using equation (3) with step size (h=0.5), snubber resistance calculation using 4 iterations are shown for more explanation.

1st iteration

$$\begin{aligned} C_1 &= 0.5 \times 0.294 \times 58 = 8.526 \\ C_2 &= 0.5 \times 0.294 \times (58 + C_1/2) = 9.1526 \\ C_3 &= 0.5 \times 0.294 \times (58 + C_2/2) = 9.1987 \\ C_4 &= 0.5 \times 0.294 \times (58 + C_3) = 9.878 \\ R &= \sqrt{58 + \frac{(C_1 + 2C_2 + 2C_3 + C_4)}{6}} \\ &= 8.128 \Omega \end{aligned}$$

3rd iteration

$$\begin{aligned} C_1 &= 0.5 \times 0.294 \times 57 = 8.38 \\ C_2 &= 0.5 \times 0.294 \times (57 + C_1/2) = 8.923 \\ C_3 &= 0.5 \times 0.294 \times (57 + C_2/2) = 8.962 \\ C_4 &= 0.5 \times 0.294 \times (57 + C_3) = 9.623 \\ R &= \sqrt{58 + \frac{(C_1 + 2C_2 + 2C_3 + C_4)}{6}} \\ &= 8.096 \Omega \end{aligned}$$

2nd iteration

$$\begin{aligned} C_1 &= 0.5 \times 0.294 \times 57.5 = 8.452 \\ C_2 &= 0.5 \times 0.294 \times (57.5 + C_1/2) = 9.073 \\ C_3 &= 0.5 \times 0.294 \times (57.5 + C_2/2) = 9.119 \\ C_4 &= 0.5 \times 0.294 \times (57.5 + C_3) = 9.793 \\ R &= \sqrt{58 + \frac{(C_1 + 2C_2 + 2C_3 + C_4)}{6}} \\ &= 8.126 \Omega \end{aligned}$$

4th iteration

$$\begin{aligned} C_1 &= 0.5 \times 0.294 \times 56.5 = 8.352 \\ C_2 &= 0.5 \times 0.294 \times (56.5 + C_1/2) = 8.843 \\ C_3 &= 0.5 \times 0.294 \times (56.5 + C_2/2) = 8.882 \\ C_4 &= 0.5 \times 0.294 \times (56.5 + C_3) = 9.5373 \\ R &= \sqrt{58 + \frac{(C_1 + 2C_2 + 2C_3 + C_4)}{6}} \\ &= 8.056 \Omega \end{aligned}$$

If the steady – state current (5.77 A) is chosen as the initial point, the value of snubber resistance R will be (2.526 Ω). This is the typical value of snubber resistance that is suitable for running the system with its minimum voltage drop and minimum power loss in the snubber resistance. On the other hand, this resistance cannot withstand the rate of current change at starting from rest causing the power device to be damaged. The snubber circuit capacitance and inductance are calculated using (10) and (12) respectively. Table II shows the results of the three approaches. The wattage required for the snubber resistance is also included.

Table II Snubber circuit parameters results

Method	R (Ω)	Resistance Wattage (W)	L (μ H)	C (μ F)
TCM	4.15	6.535	21.7	1.26
RM	8.5	3.58	50	0.69
RKM	8.056	1.763	21.7	0.34

Results listed in Table II clarify that the snubber resistance value obtained with the proposed (NM) has the minimum value of resistance wattage, thus the circuit has a minimum power loss other than other methods. Also, a minimum snubber capacitance is obtained resulting in a minimum area for fixing snubber components on the power circuit PCB as another benefit.

Figure (5) shows the step response of the three methods that were obtained with a Matlab/Simulink model that has been built for this purpose.

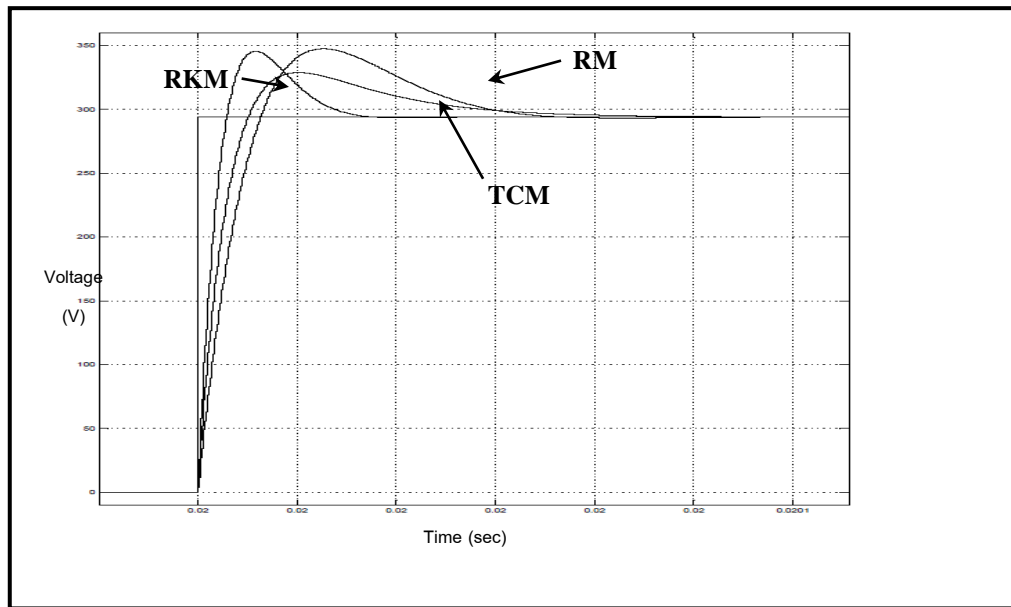


Figure (5) Snubber circuit step response

Conclusions

A numerical solution in designing snubber circuit has been presented. The approach makes use of the benefits of solving differential equations using numerical methods. Adopting the Fourth Order Runge-Kutta for solving a differential equation that relates the device specification given by manufacturer with the circuit resistances. Results showed that during device turning ON from rest with high starting current, this approach results in resistance value that has a value which lies between those obtained with other approaches. As a result, reduced power dissipation is obtained as a reduced value for the snubber circuit is used. The step response clarifies that minimum voltage spike is obtained with (RKM) over that of (RM) which, also leads to reducing the power loss at the snubber active element and improves the overall system efficiency. The problem formulation is applied at power frequency of 60 Hz, and may be extended to higher frequencies.

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