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Non-Linear Behaviour Compensation and Optimal Control of SCR using Fuzzy Logic Controller Assisted by Genetic Algorithm: A Case Study

Navdeep Kaur*, Yaduvir Singh #

Abstract--**This paper presents a combined model approach of Fuzzy Logic and Genetic Algorithm applied for non-linear behavioral compensation of Silicon Controlled Rectifier (SCR), for its improved performance (optimal variable output voltage). The optimized parametric compensation of SCR will be done by amalgamated algorithm of Fuzzy Logic Control and Genetic Algorithm. It is a shift from existing practice of Fuzzy Logic based control /compensation, as reported in the literature. In this work, a Fuzzy Logic based optimal control system has been developed for input voltage regulation of SCR, which is further optimized by Genetic Algorithm. The input voltage regulation of SCR is needed to meet the varying load current demand in various industrial applications of the device. The proposed scheme as presented in this paper leads to the optimal regulation of input voltage for SCR. The results have shown a remarkable reduction in the error which was otherwise existing in the device and its application circuit. The accuracy level at the output of the SCR after the implementation of the proposed amalgamated algorithm is ranging between 99.0 to 99.5%. It also suits the non-linearly varying load current requirement for a given industrial system employing SCR.**

Key Words: **Fuzzy Logic Control, Genetic Algorithm, Firing Angle, SCR**

I. INTRODUCTION

The Silicon Controlled Rectifier (SCR) is most important member of the thyristor family. It is widely used semiconductor switch, in the variety of industrial systems, dealing with the electrical signal control. Present day's industrial applications of SCRs include, speed controllers for sub optimal solution in obtaining feasible solutions to the complex industrial problems requiring global optimization.[3],[7],[10],[12] The Genetic Algorithm provides a balance, which is necessary for survival in many different environments. Simplicity of operation and power of effect are two of the main attractions of the Genetic Algorithm approach. Presently, researchers are implementing genetic i.e. along with other control algorithms especially in the industrial current (AC) and direct current (DC) , temperature and illumination controllers, AC and DC circuit breakers, variable frequency DC-AC inverters, variable voltage DC-DC converters, variable frequency AC-AC converters, variable voltage AC-DC rectifiers etc.[1] .The Fuzzy Algorithms are approximate reasoning codes generated by using the rules of fuzzy sets theory along with linguistic variables for generating the modified input(s) for the system(s) / plant(s) on real time and are better than conventional control algorithms viz. PID. In the present day's Fuzzy Logic Systems, the researchers across the globe had always the problems in learning & adaptation capability and absence of an optimizer & verifier module. [5] Few smart applications of fuzzy logic control system include, proper gearing in the automobile with automatic transmission, finding the best route and automatically guiding of an automobile in intelligent vehicular systems, processes signaling, scheduling and routing the channels in communication systems, predicting the performance of stocks in financial engineering, guiding and controlling movements, recognizing optical patterns and manipulating objects in robotics etc..[4],[9],[11] Fuzzy logic controllers are considered as a brawn and the present trend is to use them hybrid mode such as neuro-fuzzy or fuzzy plus GA so as to capture some attributes of industrial importance such as adaptability, optimality etc.. Genetic algorithm represents a class of general purpose stochastic adaptive search technique, which simulates natural inheritance by genetics and Darwin's "survival of the fittest principle" and eliminates the disadvantage of reliance on heuristic and hence applications requiring optimal control. One such an area is industrial electronics, which has motivated the alternating algorithm in hybrid mode researchers to take up this work, as reported in this paper. In this work, the researchers have used fuzzy logic control model along with genetic algorithm in a non-linear application of performance compensation of SCR. The various non-linearities occurring with in the SCR during its operation have been analyzed in this work, and optimal compensation has been provided using fuzzy and genetic algorithm.

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* Department of Electrical Engineering, Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, Punjab, INDIA.
# Department of Electrical & Instrumentation Engineering Thapar University, Patiala, Punjab, INDIA.
Email:-brarnav73@yahoomail.com

II. CASE STUDY: SCR INPUT / OUTPUT CHARACTERISTIC EXPERIMENTAL CIRCUIT

The SCR has a unique four-layer construction of alternating p-type and n-type regions. The forward.-bias portion of the SCR's I-V characteristic has two stable operating regions one being the on state and the other the off state. The reverse-bias portion of the characteristic is a blocking state. A current pulse applied to the gate will latch the SCR on, but then the gate cannot turn the device off. The external power circuit must reverse bias the SCR in order to turn it off. The SCR is a minority-carrier device and has the highest blocking voltage capabilities and the largest current conduction capabilities of any of the solid-state switching devices. The SCR is inherently a slow switching device compared to BJTs or MOSFETs because of the long lifetimes used for low on-state losses and because of the large amount of stored charge. It is therefore normally used at lower switching frequencies. The rate of rise or the on-state current must be kept within bounds because the slow spread of the plasma during the turn on transient leads to current crowding that could result in device failure if di/dt is too large. The rate of rise of the reapplied forward-blocking voltage after turn off must be limited or the device may be triggered back into the on state by induced displacement currents.[2]

Furthermore, the forward voltage must not be reapplied to soon after turn-off or the device will turn back on. Special structure modifications, such as highly inter digitated gate-cathode layouts and the use of cathode shorts, can substantially improve the di/dt and dv/dt ratings. SCRs will have large reverse- recovery currents. In the on state a high-power SCR can conduct average current as large as 2000-3000A.

In this research paper, the case study of SCR has been taken up for the purpose of providing non-linear behavioral compensation and optimal control using fuzzy logic control algorithm, which is further assisted by genetic algorithm. This case study has been taken up in the view of increasing importance of SCR, as reported in the various research journals/transactions, industrial publications and product catalogues.

Experiment details

The experimental set up taken for data collection on the SCR's behavior is shown in figure 1 along with the suitable instrument ranges. The behavioral data for SCR BT-136 was obtained under various supply voltages. Initially, 20 volts output from a variable 150 volts D.C power supply was connected across anode cathode terminals. Later, the data samples for the load current, load voltage and gate current were also taken by varying this voltage from 10-100 V. The anode voltage was set at a particular value and the gate current was increased gradually from a low value. It was observed that at a particular value of the gate current, the anode current increases suddenly from a negligible value to a very high value indicating turning on of SCR. A SCR is not completely latched in the on state until the plasma has spread across the entire cross section.

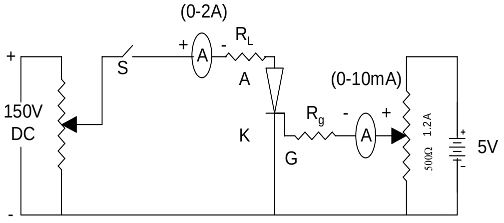

Figure 1: Experimental circuit for SCR BT-136

While turning off this SCR, the gate reduced to a low value and the switch indicated as "S" in the figure 1, to "on" state. Subsequently, the anode circuit power supply was reduced to zero and gate power supply was left unchanged by retaining the same potentiometer setting. The output of anode power supply was varied gradually, in steps, and the observations were made for the values of anode-cathode voltage as "V_{AK}" and anode-cathode current "I_{AK}", at every step. This process was repeated till the SCR BT-136 had triggered.

The characteristics obtained from experimental setup as shown in figure 1 have been shown in figure 2, which is designated as "manual". It has been analyzed for its variance with the "ideal" characteristic. The ideal characteristics have been obtained from the mathematical model of the device and circuit and the attributes / relationships, as given in the product catalogue.

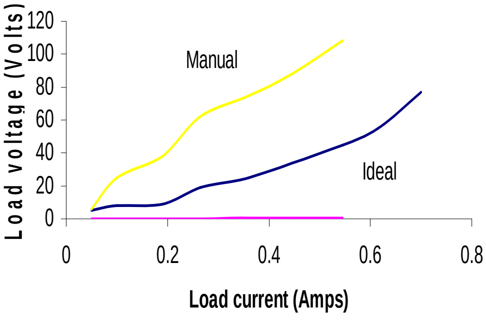

Figure 2: Load current versus load voltage characteristic for the SCR BT-136

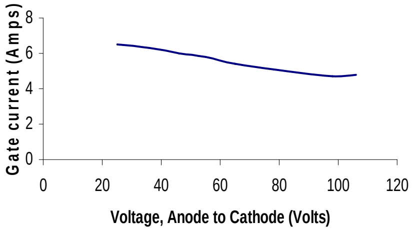

Figure 3: Anode to cathode voltage versus gate current characteristic for the SCR BT-136.

As, it is evident from figure 2, the manual characteristic is at variance with the ideal characteristic, and hence, the load current needs to be compensated by regulating the input variable supply. The deviation between the two plots is nonlinear and hence it is a fit case for the implementation of fuzzy logic controller. Fuzzy logic controller will take the deviation between the two plots (error) as an input, and the actuating signal i.e. the output of this controller is variable supply voltage. Further, as an added control dimension, this variable supply voltage has been optimized using genetic algorithm, as reported in this research paper

III. MATHEMATICAL MODELING

The mathematical modeling has been carried out in order to develop a software code for the SCR and its circuit, as shown in the figure 1. The mathematical model as developed below is the mainstay for the non-linear behavioral analysis and the control problem formulation of the SCR and its circuit, as undertaken in this work.

SCR circuit

The applied gate voltage at SCR is given as

$$E_s = V_g + I_g R_s \text{ ....(1)}$$

where, Es, Vg, Ig and Rs are gate source voltage, gate-cathode voltage gate current and gate-source resistance, respectively. The SCR voltage equation V_T as a function of the its current I_T from the V-I characteristics, as obtained from the device circuit as shown in the figure 1, for a conducting SCR are give as below.

$$V_T = V_O + I_T R_T \text{ ....(2)}$$

where R_T is the dynamic resistance of the device and V_0 is a constant

The instantaneous dissipation is given as below.

$$P_d = V_T I_T = V_O I_T + I^2{}_T R_T \text{ ....(3)}$$

and the average power dissipation is obtained as below.

$$P_{dav} = V_O I_{Tav} + R_T I^2{}_{TRMS} \text{ ....(4)}$$

The average power dissipation is a function of the average and RMS values of the forward current. Their ratio is obtained as below.

$$k = \frac{I_{TRMS}}{I_{Tav}} \text{ ....(5)}$$

The ratio "k" depends on the waveform of the current and therefore on the applied voltage. If the SCR is in a dc circuit, then k =1. The load current I_l is same as the SCR current I. The current and the voltage through the SCR are further analyzed in equations 6 to 9, for the purpose of identifying parameters and their sources for the operational non-linearities.

$$I_l = I_m \sin\omega t' = \frac{\alpha_2 I_g + I_{CB01} + I_{CBO2}}{1-(\alpha_1+\alpha_2)} \text{ ....(6)}$$

$$I_{lav} = \frac{1}{2\Pi}\int_0^{2\Pi} I_m \sin\omega t d\omega t \text{ ....(7)}$$

$$I_{lrms} = \frac{1}{2\Pi}[\int_0^{2\Pi} I_m^2 \sin^2 \omega t d\omega t] \text{ ....(8)}$$

and

$$V_{lrms} = Z_{load} \times I_{lrms} \text{ ....(9)}$$

where I_1 is load current, I_m is maximum current through load, ω is fundamental frequency, $I_{CBO1}$and I_{CBO2} are common base leakage currents, α1 and α2 are common base current gains, I_{lav} is average load current, I_{lrms} is rms or effective value of load current, V_{lrms} is rms or effective value of load voltage and Z load is load impedance.

Case study circuit

The various voltage equations as obtained from the various loops of the electrical circuit as shown in figure 1 are given as below.

$$150K - IR_L - V_{AK} = 0 \text{ ....(10)}$$

$$5K' - I_g R_g V_{KG} = 0 \text{ ....(11)}$$

where K and K′ are constants, I load current, R_L load resistance, V_{AK} voltage between anode and gate and V_{KG} is voltage between cathode and gate. The various losses in the elements of the electrical circuit as shown in the figure 1 are related, as shown below in equation 12.

Total power loss = Loss in R1 + Loss in diode + Loss in Rg ……………….….(12)

The peak off-state voltage, gate trigger current and the peak on-state current affect the turn-on time. For a given turn-on time, the minimum gate current required, and the pulse width T is obtained. If the frequency of firing f is known, the peak instantaneous gate power dissipation $P_g$max is obtained as

$$P_g \max = V_g I_g = \frac{P_{gav}}{fT} \text{ ....(13)}$$

Where P_{gav} is the specified maximum permissible average gate power dissipation.

The energy dissipated in the device during turn-on transition can be approximated as

$$W_c(on) = 1/2\, V_d I_o t_{c(on)} \ldots\ldots\ldots\ldots\ldots..(14)$$

Where $t_{c\ (on)}$ is turn- on crossover interval and Wc (on) is energy dissipated in the device during this turn-on transition.

The other major contribution to the power loss in the switch is the average power dissipated during the on-state P_{on} which varies in proportion to the on-slate voltage as given in the equation 15.

$$P_{on} = V_{on} I_o \frac{t_{on}}{T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

IV. PROBLEM FORMULATION AND SIMULATION

Operating the circuit as shown in the figure 1 made the practical observations as given by various relational plots between the voltage and current shown in the figures 2 and 3. The plots as illustrated in the figures 4, 5 and 6 have been contrived from observation plots, as shown in the figures 2 and 3, for the purpose of developing fuzzy logic controller and genetic algorithm.

The plot shown in the figure 4 relates load current with the error in the load voltage through SCR BT-136. The variation of the error in the load voltage with respect to the load current is linear up to 0.3 amperes and then exponentially increasing with the increase in the load current values.

The plots as shown in the figures 2 and 3 above, give the plot as shown in the figure 5, which relates load current and the gate current in SCR BT-136. The gate current with the load current is decreasing non-linearly.

The plots as shown in the figures 4 and 5, give the plot as shown in the figure 6, which relates the gate current with the error in load voltage during operation of SCR BT- 136.

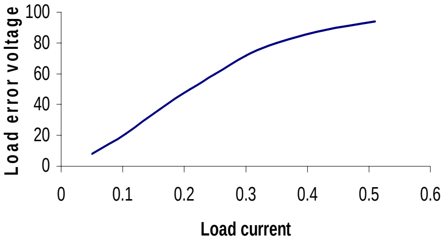

Figure 4: Load current versus error in load voltage characteristic for SCR BT-136.

As shown in figure 1, the error in load voltage is decreasing monotonically with increase in the gate current of SCR BT-136. The variation is non- linear.

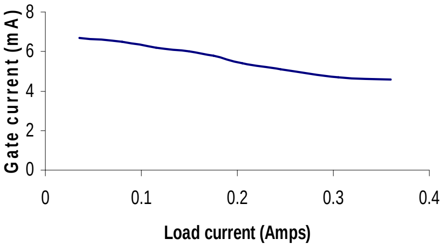

Figure 5: Load current versus gate current for SCR BT-136

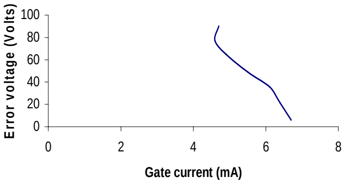

Figure 6: Gate current versus load voltage error characteristic for SCR BT-136

Fuzzy logic controller and genetic algorithm design & development

The steps involved in the design and development of fuzzy logic control model and genetic algorithm have been described below.

Fuzzy logic controller algorithm

The various steps taken in the design of fuzzy logic control model in this case study are given below.[6],[8]

1. Start
2. Give crisp input
3. Generate Fuzzy sets for input(s)
4. Create knowledge base
5. Formulate Fuzzy rules
6. Fire Fuzzy rules
7. Composition and aggregation of rule outputs
8. Defuzzify the aggregated effects
9. Get the crisp value for the output
10. Stop

The various fuzzy antecedents and consequence sets designed and implemented in this case given as below.

Genetic algorithm

The various steps taken in the design of genetic algorithm in this case study are given below.

1. Start: Generate random population of n chromosomes (suitable solutions for the problem).
2. Fitness: Evaluate the fitness of each chromosome in the population.
3. New Population: Create a new population by repeating following steps until the new population is complete.

(i) Selection: Select two parent chromosomes from a population according to their fitness, (the bigger fitness, the bigger chance to be selected).

(ii) Crossover: With a crossover probability, crossover the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.

(iii) Mutation: With a mutation probability mutate new offspring at each locus (position in chromosomes).

(iv) Accepting: Place new offspring in a new population.

4. Replace: Use new generated population for a further run.

5. Test: If the end condition is satisfied, Stop and Return the best solution in current population.

6. Loop: Go to Step 2.

Cost function developed in this case, for the optimization of SCR parameters is given as below.

$$C: A\times\lambda_1 + B\times\lambda_2 + C\times\lambda_3 + D\times\lambda_4 \text{………………..}(16\ )$$

where A, B, C and D are attributes ,and λ_1 , λ_2, λ_3 and λ_4 are their eigen values, respectively.

V. SIMULATION AND TESTING

The simulation and testing results have been obtained and collated as given in the performance metric

Performance metric

The simulation test results of Fuzzy Logic based control and Fuzzy + Genetic Algorithm have been collated with manual control, down in the tables I, II and III below.

Table I: Simulation / test results table for set point load current of 0.05Amperes

Sr. no.	**Load current error**	**Voltage compensation / control**		
		Manual compensation	**Fuzzy Logic control system**	**Fuzzy + Genetic algorithm control system**
1	-0.02	5.9(-)	5.7(-)	6.1(-)
2	-0.05	13.5(-)	14.8(-)	13.3(-)
3	-0.10	26.4(-)	28.3(-)	26.7(-)
4	-0.15	40.0(-)	37.5(-)	39.5(-)
5	-0.20	52.7(-)	48.1(-)	52.3(-)
6	-0.25	64.1(-)	67.0(-)	64.7(-)
7	-0.30	71.8(-)	72.8(-)	72.0(-)
8	-0.35	78.1(-)	74.3(-)	78.3(-)
9	-0.40	82.7(-)	84.4(-)	82.4(-)
10	-0.45	84.8(-)	81.1(-)	85.1(-)
11	-0.50	87.7(-)	85.1(-)	87.3(-)
12	-0.55	87.9(-)	89.5(-)	87.4(-)

Table II : Simulation / test results table for set point load current of 0.35Amperes

Sr. no.	**Load current error**	**Voltage compensation / control**		
		Manual compensation	**Fuzzy Logic control system**	**Fuzzy + Genetic algorithm control system**
1	+0.3	72(+)	70.3(+)	72.8(+)
2	+0.25	58(+)	60.1(+)	57.1(+)
3	+0.2	47(+)	48.4(+)	45.8(+)
4	+0.15	32(+)	30.3(+)	32.9(+)
5	+0.1	20(+)	24.2(+)	20.7(+)
6	+0.05	7(+)	6.6(+)	6.8(+)
7	0.0	0	1.8 (+)	1.2(+)
8	-0.05	6(-)	5.8(-)	6.1(-)
9	-0.10	10(-)	11.1(-)	9.8(-)
10	-0.15	13(-)	11.7(-)	13.1(-)
11	-0.20	15(-)	14.5(-)	14.7(-)
12	-0.25	15(-)	14.8(-)	15.1(-)

Table III: Simulation / test results table for set point load current of 0.5Amperes

Sr. no.	**Load current error**	**Voltage compensation / control**		
		Manual compensation	**Fuzzy Logic control system**	**Fuzzy + Genetic algorithm control system**
1	+0.45	85(+)	80.5(+)	85.2(+)
2	+0.40	72(+)	73.8(+)	71.7(+)
3	+0.35	59(+)	57.2(+)	58.5(+)
4	+0.30	46(+)	44.5(+)	45.5(+)
5	+0.25	30(+)	32.1(+)	30.3(+)
6	+0.20	21(+)	22(+)	21.2(+)
7	+0.15	10(+)	10.5(+)	10.2(+)
8	+0.10	3(+)	2.8(+)	3.0(+)
9	+0.5	2(+)	2.2(+)	1.9(+)
10	0.0	0	0.8(+)	0.8(+)
11	- 0.05	2(-)	1.8(-)	1.9(-)
12	- 0.10	2(-)	1.8(-)	1.9(-)

Table IV: Abridged comparison table for % error due to various set point load currents

Control system models	**% Control voltage accuracy**		
	Set point load current 0.05 Amps.	Set point load current 0.35 Amps.	Set point load current 0.5 Amps.
Manual Control System	100	100	100
Fuzzy Logic Control System	95.24	93.64	93.72
Fuzzy + Genetic Algorithm Control System (expected)	99.06	98.04	98.03

VI. RESULTS AND DISCUSSION

The developed Fuzzy Logic Model was provided with supervisory training. The Fuzzy Logic algorithm for diode anode to cathode voltage compensation for the circuit as given in figure 1, was trial run for three different set point load current levels, as indicated in tables (I), (II), and (III).Fuzzy Logic based diode anode to cathode voltage compensation has shown medium grade accuracy. The accuracy level, for three different set point load current of 0.05A, 0.35A & 0.5A are 95.24%, 93.64% & 93.72%, respectively. The Genetic Algorithm fine tunes the diode's anode to cathode voltage generated by Fuzzy Logic control system. The results of implemented amalgamated algorithm (fuzzy plus genetic algorithm) as obtained and shown in this research paper reveal highly accurate generation of diode's anode to cathode voltage with an average accuracy level of 98.37%. Also, the earlier experiences of Genetic Algorithm developed for other applications have resulted in grade "A" accuracy in the process / system output(s), typically varying between 98 to 99%. It is so because Genetic Algorithm will terminate only after generating globally optimum diode's anode to cathode voltage, for each case of variable set point load current requirement.

VII. CONCLUSIONS

Fuzzy Logic system lacks adaptability to the new set of parameters which are not considered during its design stage as a result, it yields medium grade control accuracy. However, it is one of the available faster intelligent control techniques. Genetic Algorithm, if used with conventional control techniques as the one proposed in this work will certainly value-add the optimal control related aspects of industrial systems in other higher order non-linear systems.

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