IMPLEMENTATION OF REAL TIME FUZZY CONTROL SVC

[1]**R.S. Dhekekar,** [2]**N. V.Srikanth**
[1]Research Scholar [2]Associate professor
Electrical and Electronics Engineering Department, National Institute of Technology, Warangal, India
E-mail rsdhekekar@gmail.com, n.srikanth@rediffmail.com

Abstract: ***Complete close-loop smooth control of reactive power can be achieved using shunt connected FACTS devices. Static VAR Compensator (SVC) is one of the shunt connected FACTS device which can be utilized for the purpose of reactive power compensation. Intelligent FACTS devices make them adaptable and hence it is emerging in the present state of art. This paper is about real time simulation and implementation of fuzzy controlled SVC for 750km lab model of artificial transmission line. PI controller and Fuzzy Control schemes implemented and investigated for the real-time control. With Matlab simulation and actual testing proves that these devices when installed, they keep the bus voltage same as reference voltage (sending-end voltage). The results are prominent and gives a way for real-time implementation of the above proposed control schemes***.

***Key words**: SVC, λ/8 - Fuzzy Logic, FACTS and Matlab.*

1. Introduction

The transmission line itself is the source of reactive power. A line that is open on the other end (without load) is like a capacitor and is a source of capacitive (leading) reactive power. The lengthwise inductances without current are not magnetized and do not introduce any reactive components. On the other hand, when a line is conducting high current, the contribution of the lengthwise inductances is prevalent and the line itself becomes a source of inductive (lagging) reactive power. Reactive power has significant effect on the operation of power system. For each line has a characteristic value of power flow Sk. If the transmitted power is above Sk, the line will introduce additionally inductive reactive power, and if it is below Sk, the line will introduce capacitive reactive power. The value of Sk depends on the voltage, for 400 kV line it is about 32% of the nominal transmitted power, for 220 kV line it is about 28% and for 110 kV line is about 22% [2]. The percentage will vary according to the construction parameters. The reactive power introduced by the lines themselves becomes a nuisance for the transmission system operator. When the demand is low it is necessary to connect parallel reactors for consuming the additional capacitive reactive power of the lines. Sometimes it is necessary to switch off a low-loaded line, in peak hours not only the customer loads cause big voltage drops but also the inductive reactive power of the lines adds to the total power flow and causes further voltage drops. In order to maintain the terminal voltage constant, reactive reserves are needed. FACTS devices like SVC can supply or absorb the reactive power in the transmission line, which helps in achieving better economy of power transfer [1, 2-3]. SVC control system is implemented in with software and modern industrial controller (using SIMATIC-DC) [4]. In deregulated environment reactive power generated by transmission line is one of the important aspects to be considered. Reactive current control through SVC considering load power factor discussed in [5]. TCR is analyzed with as PSCAD/EMTDC and PSPICE [6].Fuzzy control TSR based SVC and TCR-based SVC used as a FACTS-stabilizer in the SMIB system [7]. In this paper reactive power generated by artificial transmission line of 750km (λ/8) is compensated by SVC for better voltage regulation. The firing angle control circuit is designed for SVC and the firing angles are varied for various loading conditions to make the receiving end voltage equal to sending end voltage .In this paper different close loop firing angle schemes for SVC are implemented to achieve the better control of SVC, such that it maintains a constant voltage profile. General Control structure of single line SVC (close loop control) shown in Fig.1

This paper is organized as follows: section 2 introduces basic concepts in SVC controller design. The design of proposed firing angle control methods and corresponding modeling in Matlab are discuss in section 3. Section 4 presents hardware implementation of firing scheme of proposed methods. Test results, before and after compensation discussed in section 5 and contribution is summarized in section 6.

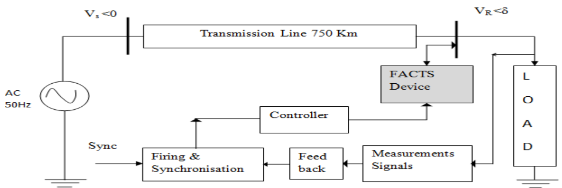


Fig.1. General Control structure of single line SVC (close loop control)

2. Operating principle of SVC

An elementary single-phase Thyristor controlled reactor (TCR) shown in Fig.3, consists of a fixed reactor of inductance L and a two anti parallel SCRs. The device brought into conduction by application of synchronized gate pulses to SCRs. In addition, being a current operated device it will automatically block immediately after the ac current crosses zero, unless the gate signal reapplied. The current in the reactor can be controlled from maximum (SCR closed) to zero (SCR open) by the method of firing delay angle control. That is, the SCR conduction delayed with respect to the peck of the applied voltage in each half-cycle, and thus the duration of the current conduction interval is controlled.

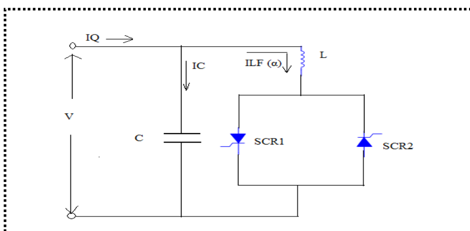


Fig.3. Basic Thyristor Controlled Reactor SVC.

When the gating of the SCR is delayed by an angle α ($0 \le \alpha \le \pi/2$) with respect to the crest of the voltage, the current in the reactor can be expressed as follows

$$iL = \int_{\alpha}^{\omega t} V(t)dt = \frac{V}{\omega L}\left(Sin\omega t - Sin\alpha\right) \qquad (1)$$

The amplitude $I_{LF}(\alpha)$ of the fundamental reactor current is expressed as a function of angle α [1].

$$I_{LF\,(\alpha)} = \frac{V}{\omega L}\left[1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}Sin\,2\alpha\right] \qquad (2)$$

Where V is the amplitude of the applied voltage, L is the inductance of the Thyristor-controlled reactor, and ω is the angular frequency of the applied voltage. The effective reactance admittance, as a function of angle α is given as

$$B_{L(\alpha)} = \frac{1}{\omega L}\left[1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}Sin\,2\alpha\right] \qquad (3)$$

The admittance $B_L(\alpha)$ varies with α in the same manner as the fundamental current $I_{LF}(\alpha)$. The meaning of equation (3) is that at each delay angle α effective admittance $B_L(\alpha)$ can be defined which determines the magnitude of the fundamental current $I_{LF}(\alpha)$. Substituting $I_{LF}(\alpha) = Ic - IQ$, hence firing angle α can be estimated as

$$\alpha = \frac{\pi}{2}\left[1 - \frac{V}{\omega L}(I_C - I_Q) - \frac{Sin2\alpha}{\pi}\right] \qquad (4)$$

The main concept behind controlling TCR is the control of the firing time of the thyristor to control the current in the reactor, thus controlling the reactive power absorbed by the TCR. Using appropriate switching controls, the VAr output can be controlled continuously from maximum capacitive to maximum inductive output at a given network voltage. The delay angle control results in a non-sinusoidal current waveform in the reactor, i.e. the TCR generate harmonics. For identical positive and negative current half cycles, only odd harmonics are generated. The amplitudes of these harmonics are a function of the angle α as follows

$$I_{Ln(\alpha)} = \frac{V}{\omega L} \times \frac{4}{\pi} \frac{Sin\alpha \cdot Cosn\alpha - nCos\alpha \cdot Sinn\alpha}{n(n^2 - 1)} \qquad (5)$$

Where n =2k+1, k =1, 2, 3 . . . The most significant harmonics components in this case are the 3rd, 5th, 7th and 13^{th} .The detail analysis of harmonics is given in [6,7].

3. Firing angle control methods

Three controlling strategies for SVC's firing are implemented.

3.1. *Feed forward control*

Automatic computation of firing angles, by estimating the susceptance for different loading condition is done using the expression (4). This equation is to be solved repeatedly to determine the exact optimum SVC firing angle. This technique is good when performing load compensation because, at any time the load characteristics can be measured and optimum compensating susceptance can be

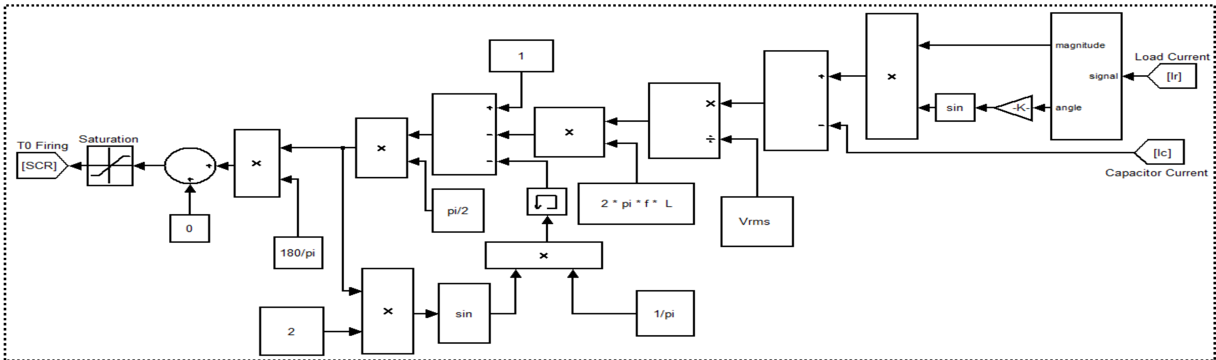


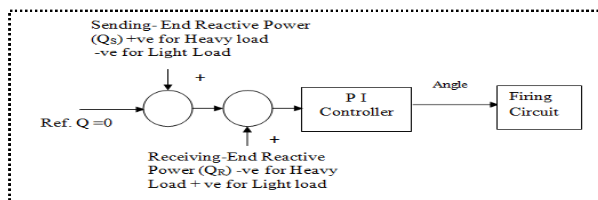
Fig.4. Modeling of feed forward control system in MATLAB which generates firing angle to be is given to firing circuit

calculated. The close loop firing angle can be achieved with modeling the (4); hence the required firing angle can be generated automatically. The Matlab Simulink model of the control circuit designed and modeled is shown in Fig.4.The signal of the reactive current I_Q absorbed by the system is utilized as the reference signal. The capacitive current I_C is subtracted from the I_Q current to obtain the required reactor current. The net value of the reactor current is converted to the delay angle α through the use of equation (3).The delay angle α is then fed to the SVC firing circuit module shown in fig.4.The advantages of this method is that it is solving only a non-linear algebraic equation and not a differential equation (like PID controller), hence it is fast in operation with reduced computational burden and also the order of the system will not increase further. But this requires reference current I_Q should be harmonic free.

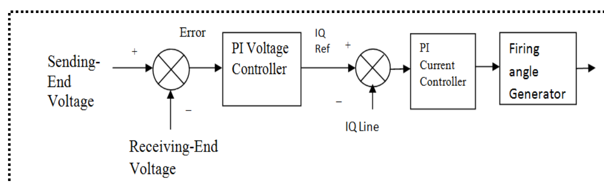
3.2 Firing angle with PI controller

This method of feedback control is useful when minimization of error signal is a primary goal. Fig.5(a) shows the simulation block diagram of control circuit which is based on reactive power request. Reference reactive power is set as zero , comparing sending-end and receiving- end reactive power, the generated error signal is given to PI controller (tuned to Kp = 0.0001 and Ki = 5.7).This automatically generates SVC firing angles for given input conditions.

Another method of PI controller is designed, error signal generated by comparing the sending-end and receiving-end voltage signals as shown in Fig.5 (b). Here two PI blocks are used for voltage and current regulations. The PI voltage regulator has Kp= 0.5 and Ki= 0.1 and PI current regulator has Kp=2.5, Ki= 0.1. The Sending-End voltage is taken as reference signal and compared with Receiving-End voltage, which generates reference I_Q for comparing with line. I_{QLine} and error is given to PI current controller which generates firing angle to be given to SVC. The main advantage of these controls is its flexibility; the required SVC compensation current can be automatically generated.



(a)



(b)

Fig.5 (a) PI Controller with reference input is inductive or capacitive VAr request. (b) Voltage and current PI controller.

3.3 Fuzzy control firing scheme

Fuzzy logic is a new control approach with great potential for real time applications. Fuzzy tools mostly used off line analysis of system [7].The Fuzzy Logic being rule based controller, where a set of rules represents a control decision mechanism. Load voltage and load current signals are taken as inputs to fuzzy system, or input signals can be selected as current, voltage or impedance, according to the type of control. If error and rate of error are the input to the fuzzy system rules are well given in [8] can be adopted. Fig.6 shows the structure of the fuzzy logic controller (FIS-Fuzzy inference system) in Matlab Fuzzy logic toolbox [10].The output of fuzzy controller is given as the reference control signal and the pulse generator provides synchronous firing pluses to thyristors as shown in fig.9 In order to achieve better control action, the five linguistic variables expressed by fuzzy sets defined on their respective universes of discourse. Table-I shows the suggested membership function rules of TCR-FC controller. The rule base of this table can be chosen based on practical experiences, simulations and also from the behavior of system around its stable / unstable equilibrium points.

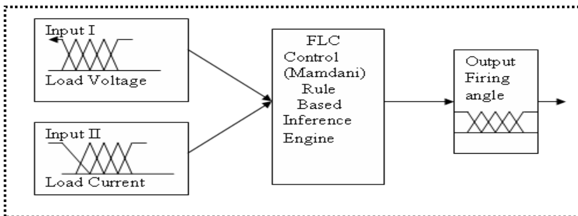


Fig.6. Structure of fuzzy logic controller.

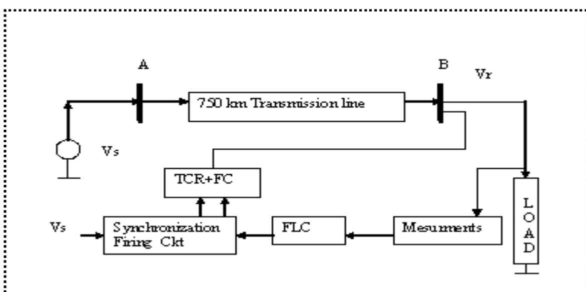


Fig.7.Single Phase equivalent circuit and fuzzy logic control structure of SVC.

Table 1 Membership function rules.

	Load voltage					
		NL	NM	P	PM	PB
Load current	NL	PB	PB	NL	NM	NL
	NM	PB	PB	NM	P	NL
	P	P	PM	NM	NM	P
	PM	NM	NM	NM	NM	PM
	PB	NL	NM	NM	NL	NL

4. Hardware Implementation

The primary objective is to control the reactive power of line and not the reactive power of load hence only resistive load is considered. An available scale down Artificial transmission λ/8 - line model is used which is available in laboratory having 4 π line segments with 750 km distributed parameters as follows

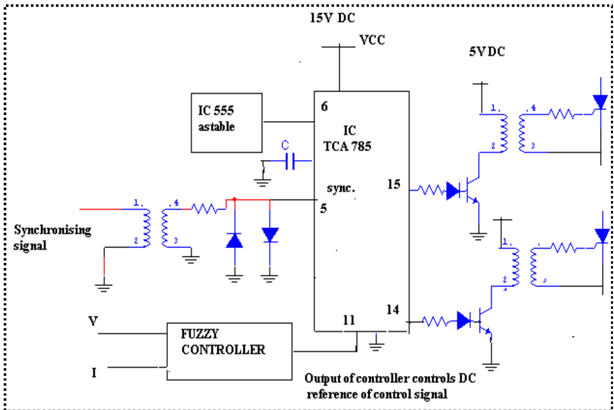
The line inductance = 0.1mH /km.
Capacitance = 0.10 μF/km.
Line resistance = 0.001Ω /km.
Surge Impedance $Zc = \sqrt{(L/C)}$) = 31.6 Ω.
Supply voltage = 230V- 50 Hz.

In order to maintain the receiving end voltage constant, shunt inductor and capacitor is added for different loading conditions to compensate for reactive power of transmission line. With the change of load and due to Ferranti effect, the variation in voltages is observed at receiving end without and with SVC. The practical values of shunt elements varied for different loading conditions to get both sending and receiving end voltages equal. In most of the transmission lines Ferranti effect is predominant and receiving end voltage is greater than that of the sending end voltage at light load. Therefore the shunt reactor in installed in the line for excess VARs in line. The value of reactance required is evaluated as shown below:

$X_L = \frac{Sin\ \beta l}{(1-Cos\beta l)} * Z_{C,}$ β=2*π*f$\sqrt{L * C}$; Thus inductive reactance required for compensation under no load is 59.69Ω. Therefore L= 0.19H and value of Capacitance is chosen based on required leading VAr = 6 μf. The firing angle control of SVC is designed and the firing angles are varied manually for various loading conditions to make the receiving end voltage equal to sending end voltage. All the results thus obtained in open loop as well as in closed loop with PI controller are shown in Table II. Based on observed results, fuzzy logic controller is designed to achieve the firing angles for SVC such that it maintains a flat voltage profile at the receiving end.

4.1 Firing scheme

The firing of SCRs with PI or Fuzzy logic controller is carried out by single chip control circuit TCA 785 a sixteen pin IC as shown in Fig 9(a). For three phase line three such ICs are used. This IC has output current rating of 250 mA. It has four outputs viz. Q_1, Q_2, $\overline{Q_1}$, $\overline{Q_2}$ and it internally generates a ramp signal which is synchronized with ac mains and is compared with the variable DC control voltage (obtained from PI or Fuzzy logic control), in order to vary the firing angle between 0^0 to 90^0. A fuzzy logic trainer kit (TQ) is used which has two analog inputs with one defuzzified output and having five linguistic variables hence, 5 by 5 rules can be generated using this kit. The output of fuzzy logic varies from DC -5V to +5V is given to IC 785 controller pin 11, which controls the comparator voltage VC , and the firing angle α for one cycle and (180+α) during negative cycle shown in Fig.8(b).



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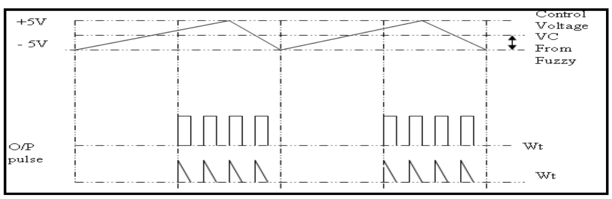


(b)

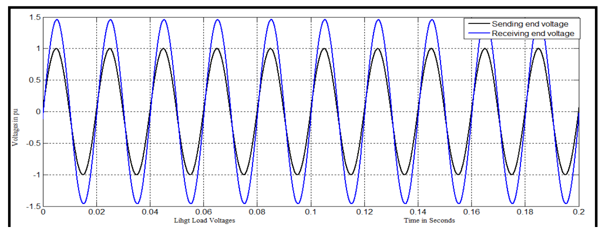
Fig. 8 (a) Firing Scheme with TCA 785 IC. (b) Generation of wave forms of TCA 785 IC.

5. Test Results

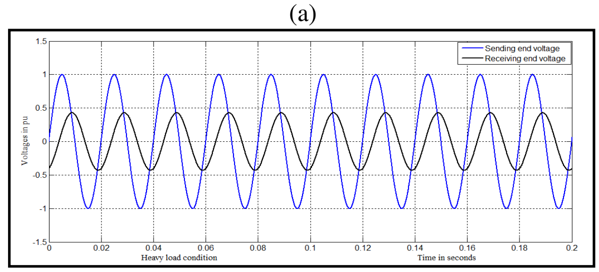
The transmission line without any compensation was not satisfying the essential condition of maintaining the voltage within the reasonable limits. The effect of increasing load was to reduce the voltage level at the load end. At light loads, the load voltage is greater than the sending end voltage as the reactive power generated is greater than that of absorbed. At higher loads the load voltage drops, as the reactive power absorbed is greater than generated as shown in Fig.(9). Fig. 10(a) clearly shows the firing angle and inductor current of SVC. Compensated instantaneous and rms voltage waveforms with PI controller are shown in Fig.10(b) and Fig.10(c) which shows slow settling time response which is about 6-7 cycles, whereas fuzzy controller is fast taking about 1 to 2 cycles as shown in Fig.10(d) and Fig.10(e) respectively. Compensated voltage for both light and heavy load with fuzzy logic controller shown in Fig.10 (f).Odd current harmonics generated by SVC shown in Fig.10.

Table II. Load voltage before and after compensation.

Load R Ω	Before compensation [For Vs=230(p-p)]			After compensation	
	Qs(VAr) generated by line	$V_{s(rms)}$	V_R	V_R	Firing Angle
1000	-1200	162.6	400	162.4	2
500	-1000	162.6	350	162.3	6
200	-700	162.6	300	162.5	15
100	-400	162.6	275	162.8	30
50	-300	162.6	230	162.7	60
30	+100	162.6	150	162.6	66
20	+400	162.6	140	159.2	75
10	+700	162.6	110	158.6	85

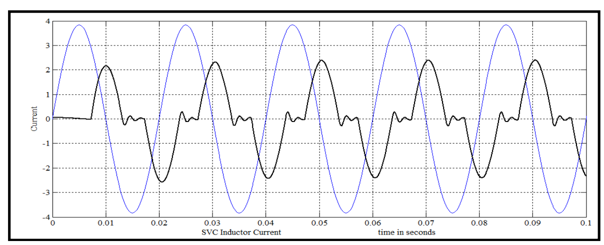


(a)



(b)

Fig.9.(a) For light load $V_R>V_S$ (b) For heavy load $V_R<V_S$.



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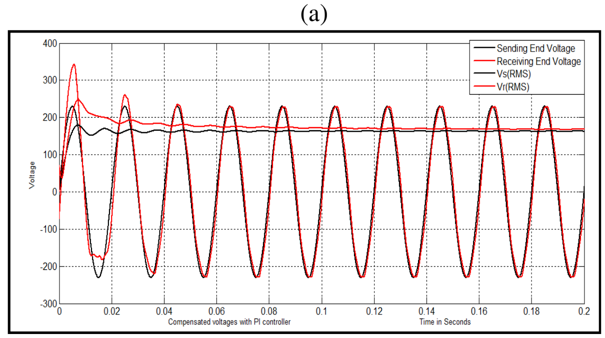

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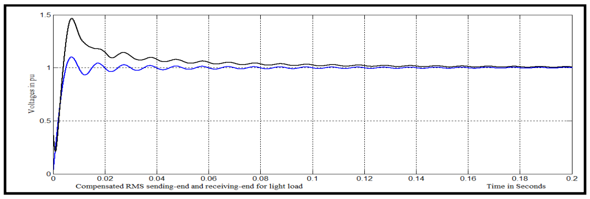

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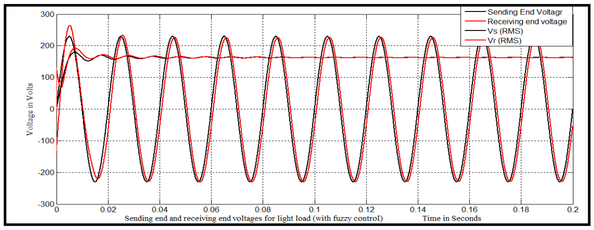

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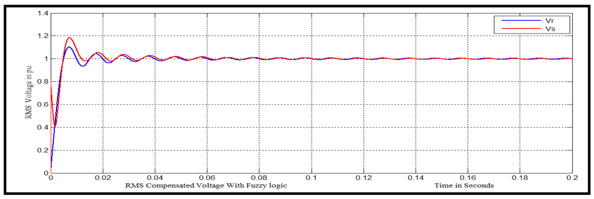

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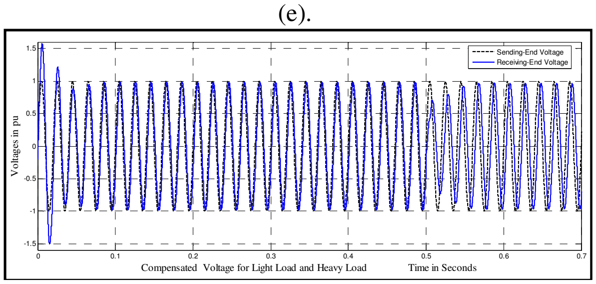

(f)

Fig.10. (a) SVC indictor current for α=60^0.
(b) Compensated V_S and V_R voltage waveforms with PI controller for light load condition. (c) Compensated rms voltage with PI control. (d) Compensated voltage with fuzzy logic. (e) Compensated rms voltages with fuzzy logic controller. (f) Compensated voltages for both light/heavy load conditions with fuzzy logic controller.

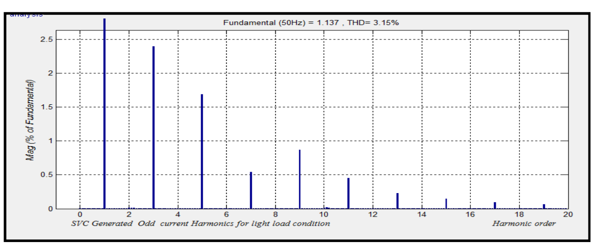

Fig.11.Odd current harmonics in line current

6. Conclusion

This paper presents different techniques of online control of SVC including the Fuzzy control scheme. It can be concluded that the use of fuzzy controlled SVC compensating device with the firing angle control is continuous, effective and it is a simplest way of controlling the reactive power of transmission line. The use of fuzzy logic has facilitated the close-loop control of system, by designing a set of rules, which decides the firing angles to be given to SVC in order to attain the required flat voltage profile at the receiving end. With MATLAB simulations and actual testing it is verified that the Fuzzy logic closed-loop control of SVC provides fast and effective way of reactive power control irrespective of load variations in comparison with PI control.

7. References

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