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Ann Based SVC Switching At Distribution Level for Minimal Injected Harmonics

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Abstract*—*Electrical distribution system suffers from various problems like reactive power burden, unbalanced loading, voltage regulation and harmonic distortion. Though DSTATCOMS are ideal solutions for such systems, they are not popular because of the cost and complexity of control involved. Phase wise balanced reactive power compensations are required for fast changing loads needing dynamic power factor correcting devices leading to terminal voltage stabilization. Static Var Compensators (SVCs) remain ideal choice for such loads in practice due to low cost and simple control strategy. These SVCs, while correcting power factor, inject harmonics into the lines causing serious concerns about quality of the distribution line supplies at PCC. This paper proposes to minimize the harmonics injected into the distribution systems by the operation of TSC-TCR type SVC used in conjunction with fast changing loads at LV distribution level. Fuzzy logic system and ANN is used to solve this nonlinear problem, giving optimum triggering delay angles used to trigger switches in TCR. The scheme with Artificial Neural Network (ANN) is attractive and can be used at distribution level where load harmonics are within limits.

Index Terms* - *ANN, Fuzzy logic control, Harmonic distortion, Reactive power, Static Var Compensators.

I. INTRODUCTION

The Indian power distribution systems are facing a variety of problems due to proliferation of nonlinear loads in the last decade. In addition to poor voltage profile, the power factor and harmonics of the system are the major concerns of the utility [1]. A variety of power factor improvement & harmonic minimization techniques are available ranging from various power factor-correcting devices to passive & active harmonic filters [2]-[5]. Thyristor controlled Static Var Compensators (SVCs) are popularly used in modern power supply systems for compensating loads. A Static Var Compensator generally consists of a Thyristor Controlled Reactor (TCR) & a Thyristor Switched Capacitor (TSC) and compensates loads through generation or absorption of reactive power. The operation of Thyristor Controlled Reactors at appropriate conduction angles can be used advantageously to meet the phase-wise unbalanced and varying load reactive power demand in a system [6]. However, such an operation pollutes the power supply in another form by introducing harmonic currents into the power supply system. In such cases, it becomes necessary either to minimize harmonic generation internally or provide external harmonics filters. It is obvious that the latter approach is associated with additional investment. This paper deals with minimizing harmonic generation internally by using optimized switching determined by using ANN toolbox in MATLAB 7.0.

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An observed reactive power profile of an 1 lkV/400V, 100kVA distribution substation, shown in Fig. 1 illustrates the extent of fluctuations & imbalance.

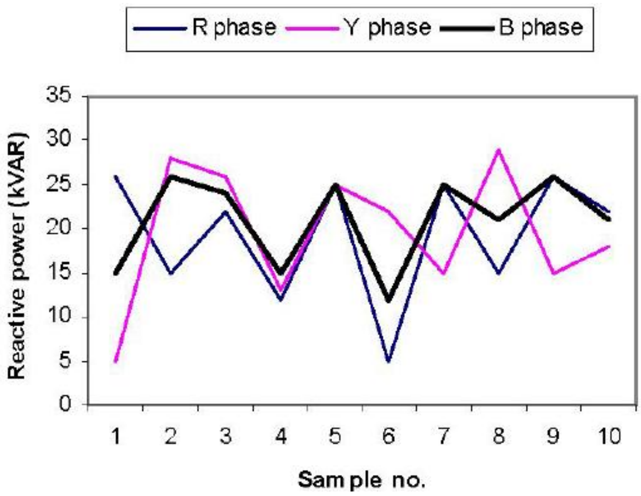

Fig. 1. Reactive power profile of distribution substation.

An algorithm is proposed for on-line control of SVCs compensating varying unbalanced load by incorporating ANN to choose the optimum combination of firing angles of TCR. The resulting controller is expected to control the SVC so that it balances the reactive power drawn by the supply, minimize the reactive power drawn from the supply and minimize the harmonics injected into the system in an acceptable time.

II. SYSTEM MODELLING

The single line diagram of the distribution substation under consideration is shown in Fig. 2. The compensator essentially functions as a Thyristor Switched Capacitor & Thyristor Controlled Reactor (TSC-TCR).

In the scheme, TSC is connected in star whereas TCR in delta .A series of steady state loads at discrete time instants are recorded which represent time varying loads. The compensator requirement is to generate/absorb unbalanced reactive power which when combined with the load demand, will represent balanced load to the supply system. The phase wise load demand are PLa + jQLa, PLb + jQLb and PLC + jQLc and the phase wise load seen by the source after compensation are PLa + jQSa, PLb + jQsb and PLc + jQsc.

Phase wise complex voltages at the load bus are given by

$$[VL]= [VS]-[z]*[Is] \qquad (1)$$

Where,

$VL=[VLa,VLb,VLc]^T$ is the complex voltage vector at the load bus.

$Vs= [Vsa, Vsb,Vs,]^T$ is the complex voltages vector at the source bus and

Z = diagonall [Za., Zb , Zc] is the line impedance matrix [7].

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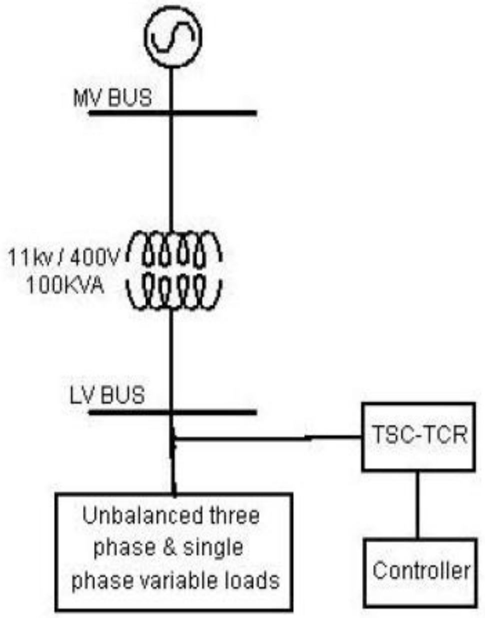

Fig. 2. Single line diagram of the system.

The vector of currents in the lines between the source bus and the load bus, Is= [Isa,Isb,Isc]^T is obtained from.

Isa = (PLa - jQsa) / Va
Isb = (PLb - jQsb) / Vb
Is c= (PLc - jQsc) / Vc (2)

The non-linear complex set of equations given by (1) and (2) can be solved for load bus voltages. The reactive power balance equations at the load bus are

[Qs]+[QC]=[QR]+[QL] (3)

For a given reactive power demand QL=[QLa, QLb, QLc]^T, setting balanced values for QC=[QCa, QCb,QCC]^T of the TSC and Qs=[QsaQsb,Qsc]T of the source, the unbalanced reactive power absorbed by the TCR, QR=[QRa,QRb,QRc]^T can be obtained from (3). Once the voltage vector at the load bus is determined, the values of delta connected compensator reactances, Xab, Xbc, Xca, required to absorb the computed reactive power can be determined.

The variable reactances of the compensators are realized by delaying the closure of the appropriate thyistor switch by varying its firing delay angle α[0 - π / 2]. The unsymmetrical firing of thyristors can be advantageously used to obtain the unsymmetrical delta connected reactances [8]. considering only the fundamental component, the unsymmetrical firing delay angle a, corresponding to the delta reactance Xab can be obtained by solving the following equation.

$$X_{ab} = \frac{x^0_{ab}}{1 - 2\alpha 1/\pi - \sin 2\alpha 1/\pi} \quad (4)$$

Where Xab is the reactance for full conduction of thyristors (Corresponding to zero firing angles). Similar equations can be written for Xbc & Xca, to obtain the values of α2 & α3.

III. HARMONICS DUE TO SVC OPERATION

The power quality at the point of common coupling (PCC) is expressed in terms of various parameters. Total Harmonic Distortion (THD) at PCC is one of these parameters, which is commonly used in practice. The performance index THD is given by

$$\text{THD} = \frac{1}{I_f}\sqrt{\sum_{h=2}^{m} I_h^{\,2}} \quad (5)$$

where If is the fundamental current, Ih is the harmonic line current for hth harmonic and m is the maximum order of harmonics considered. Assuming balanced three-phase voltage at the load bus. The fundamental and harmonic components of the line currents can be obtained by using the following equations [5]

$$I_f = \frac{Vm}{2\pi\omega L}\sqrt{G_f^2 + H_f^2}\,\sin(\omega t - \phi - \theta)$$
$$I_h = \frac{Vm}{2\pi\omega L}\sqrt{G_h^2 + H_h^2}\,\sin(h(\omega t - \phi) - \theta_h) \quad (6)$$

Where,
If = RMS value of fundamental line current
Ih= RMS value of harmonic line current of hth order
Co =Fundamental frequency
L= Inductance of each delta connected inductance

$$G_f = (3\pi - 4\gamma - 2\sin 2\gamma - 2\beta - 2\sin 2\beta)$$
$$H_f = \sqrt{3}(\pi - 2\beta - 2\sin 2\beta) \quad (7)$$
$$G_h = \left(\frac{\sin(h+1)\gamma}{(h+1)} - \frac{\sin(h-1)\gamma}{(h-1)} - \frac{2\sin\gamma\cosh\gamma}{h}\right) + 1/2\left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\beta}{h}\right)$$
$$H_h = \pm\sqrt{\frac{3}{2}}\left(\frac{\sin(h+1)\beta}{h+1} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\beta}{h}\right)$$
$$\&\ \theta f = \tan^{-1}\left(\frac{Hf}{Gf}\right) \&\ \theta h \approx \tan^{-1}\left(\frac{Hh}{Gh}\right) \quad (8)$$
$$\Phi = 0, \gamma = \alpha_1, \beta = \alpha 3; \phi = \frac{2\pi}{3}, \gamma = \alpha_2, \beta = \alpha_1;$$
$$\phi = \frac{4\pi}{3}, \gamma = \alpha_3, \beta = \alpha_2$$

For line currents an, lb & IC respectively.
H=harmonic order, (6k ± 1) , k=1, 2, 3....
+ Sign for harmonics of order (6k+1)
- Sign for harmonics of order (6k-1).
For triplen harmonics (3rd, 9th,),

$$G_h = \left(\frac{\sin(h+1)\gamma}{(h+1)} - \frac{\sin(h-1)\gamma}{(h-1)} - \frac{2\sin\gamma\cosh\gamma}{h}\right) + \left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\beta}{h}\right)$$
$$H_h = 0 \quad (9)$$

A program in MATLAB is written to get the above values and is used in the fuzzy logic toolbox.

IV. MINIMIZATION OF HARMONICS

For a given load reactive power demand, QL, it is required to minimize the reactive power drawn from the source, Qs. By setting balanced values for Qc and Qs, the unbalanced reactive power absorptions of TCR, Q, can be obtained using the procedure described in Section II. Then the unsymmetrical reactances required absorbing QR, and the corresponding unsymmetrical firing angles can be computed from (4). Knowing the voltages at the compensator node and the firing angles of the TCR, harmonic analysis can be carried out and the performance index, THD, can be evaluated as explained in Section II. Thukaram et al. Have shown in [6] that different combinations of firing angles lead to various harmonic levels, as indicated by the value of performance index. In order to minimize the harmonics generated due to SVC operation, the TCR should be operated at a combination of firing angles which results in low harmonic level.

It has been further shown that there are several combinations of firing angles which leads to lower level of harmonic generation. The combination of firing angles that corresponds to the minimum THD value usually conflicts with the objective of minimizing the reactive power drawn from the source. Therefore it is necessary to find a combination of firing angles, which can simultaneously keep both Qs and THD satisfactorily low.

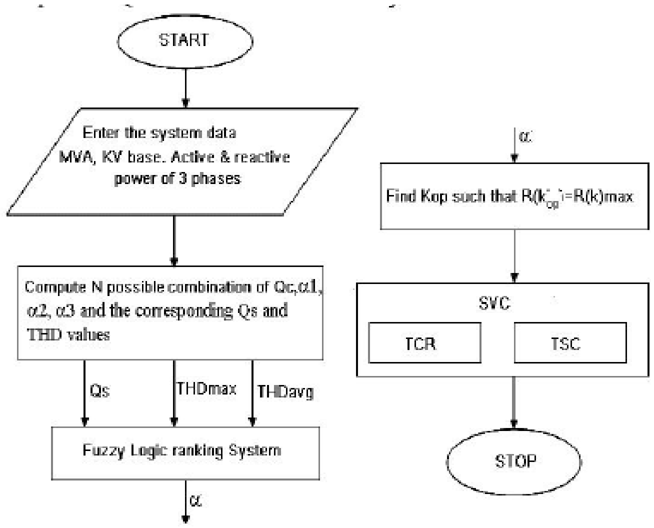

Fig. 3. Flowchart of the fuzzy controller.

However, the task of selecting the particular combination firing angles from a set of all (or many) plausible combinations of firing angles to achieve optimum values of

Qs and TDD is not straight forward.

For a given load reactive power demand, QL, the best combination of firing angles are intuitively selected and the method can be adopted for controlling SVC used for compensating a constant or cyclic load with several known load steps. However if the load is continuously varying, the SVC controller needs to be capable of selecting the appropriate set of firing angles without human intervention.

In this paper fuzzy logic and ANN controller is used to get the triggering delay angles al, a2 and a3 for the TCR. These triggering delay angles correspond to minimum THD values and an acceptable compromised reactive power Qs.

A. SVC control with Fuzzy Ranking System

A Mamdani type fuzzy logic system was designed for ranking the combinations of TSC step size and three firing angles. The schematic diagram of the SVC control algorithm shown in Fig. 3, takes phase wise active and reactive power demands of the load as inputs and determine the step size of TSC and the unsymmetrical firing angles of the TCR as outputs. The first block computes a set of feasible combinations (say N different combinations), firing angles a], a2, a3 and the corresponding Qs and THD values.

The second block is the ranking of each feasible TSC step size-firing angles combination using the fuzzy logic ranking system. The fuzzy logic ranking system assigns a ranking score, R (k) for the kth combination depending on the corresponding Qs (k) and THD (k) values. In the case of three phase unbalanced loads, three different THD values resulting for the three phases exist. After various considerations, both the highest THD value amongst the three phases, THDmax (k) and the average THD of the three phases, THDaV (k), are used for ranking a particular firing angle combination. In the last step, the TCR step size firing angles combination that has the highest-ranking score is selected as the desired TSC and TCR operating points [9]-[10].

The three input variables to fuzzy system are the normalized phase wise reactive power drawn from the source [Qsn], the normalized average harmonic performance index THDavg and maximum harmonic performance index THDmaX . The output of the fuzzy system is the ranking score for each possible combination of firing angles. The firing angles and reactive power values corresponding to highest ranking score are selected as final values as shown in Fig 4 [11].

Table I.Fuzzy Rule Base Of The Ranking System

Qs	THDmax	THD avg			
		S	M	L	VL
S	S	VG	VG	OK	VB
	M	G	G	B	
	L	OK	OK	B	
	VL	VB			
M	S	G	G	OK	VB
	M	OK	OK	B	
	L	B	B	B	
	VL	VB			
L	S	OK	OK	VB	VB
	M	B	VB	VB	
	L	VB	VB	VB	
	VL	VB			
VL	S	VB			
	M				
	L				
	VL				

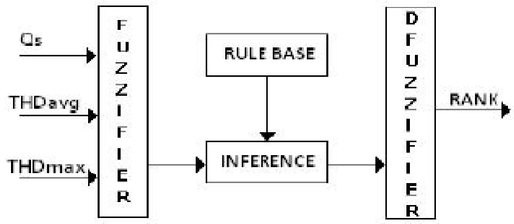

Fig. 4. Block diagram of fuzzy controller.

The universe of discourse of each input variable is partitioned into four fuzzy subsets namely; Small (S), Medium (M), Large (L) and Very Large (VL). The space of the output variable is partitioned into five fuzzy subsets namely; Very Good (VG), Good (G), Fair (OK), Bad (B) and Very Bad (VB) [8].The fuzzy decision rules can be formulated using the fuzzy subsets in the following way.

If Qs is Small and THDmax is Medium and THDavg is Small, then R (ranking score) is Good. The complete rule base of the fuzzy ranking system consists of many rules as given in Table I. The output R is a scalar in the range [0-1] with higher values indicating better combinations of TSC step size and firing angles.

B. ANN Approach

The relationships between the inputs to the controller, i.e., phase wise active and reactive power demands and the outputs , i.e., the firing angles and the TSC step size are quite complex and it is difficult for a single neural network to approximate such a complex relationship. The proposed algorithm can be used for real time control of SVCs which are used to compensate unbalanced fluctuating loads. The neural network is trained to approximate the function of the fuzzy logic based SVC control algorithm in order to reduce the computational time. The structure of ANN controller used is shown in Fig. 5.

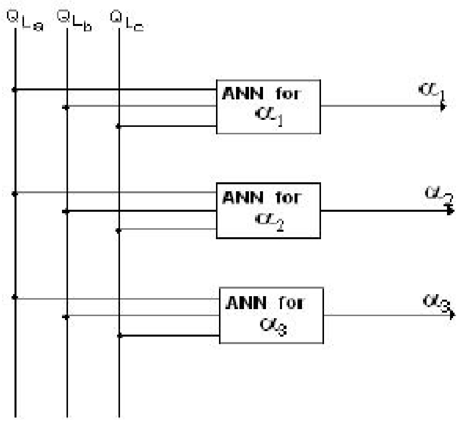

Fig. 5. Schematic diagram of the ANN controller.

It was observed that the dependency of the outputs on the real power demands is minimal. It reflects only in calculation of the load bus phase voltages. Small change in load bus voltages doesn't much affect on the amount of reactive power absorbed or supplied by the TCR and TSC respectively. In order to reduce the complexity of neural network only reactive power demands are used as inputs to the controller. The neural network controller used contains a three layer feed forward neural network each of which takes load reactive power demands in each of the three phases as inputs. Each layer generates the optimum triggering delay angle al, a2 or a3 corresponding to the delta reactances Xab,Xbc and Xca respectively. The ANNs are trained using the data generated by the fuzzy logic based controller with arbitrary load profiles. These load profiles are carefully generated so that data covers all expected regions of operations [12]. Target outputs required for training were obtained using the control algorithm with fuzzy logic ranking system described in Section IVA . Due to the complexity of the functions to be approximated, hidden layers ranging from 10 to 50 neurons were required to achieve a sufficient accuracy. Neural network toolbox in M\ATLAB 7.0 version was used for training and simulating ANNs.

V. SIMULATION RESULTS

An 11 kV/400V, 1OOkVA distribution substation feeding a fluctuating load is taken for simulation as shown in Fig. 2.

The load consists of single phase & three phase motors, laboratory equipments and SMPSs. The static VAR compensator was considered consisting of a TSC that can vary through four steps; 0, 10, 20 & 30 kVAR per phase and a Thyristor Controlled Reactor (TCR) of capacity of 30 kVAR per phase under full conduction. The parameters of the line between the source bus and load bus are taken as R=0.02 ohms per phase, X= 0.07 ohms per phase.

The simulated results using ANN in the MATLAB 7.0 environment for ten samples at 2 seconds each are shown in Table II. For each load data, Qs Avg. shows the reactive power drawn from the source and the computational time for optimized al, a2 and a3. The percentage average THD for unoptimised (Qs=0) operation shows the percentage average THD when SVC is perfectly balancing the reactive power whereas avg. THD for optimized (Qs not zero) operation indicates the percentage average THD when SVC is compromising with p.f. for minimal THD.

Fig. 6 shows reduction in THD using Fuzzy and ANN structures compared to unoptimised operation clearly showing that ANN controller follows the trend. The comparison of computational time using Fuzzy and ANN structures shown in Fig.7 clearly indicates that ANN structure gives fast results with an average computational time of 0.125 seconds. The computational time in case of

Fuzzy system depends upon the processor speed and number of iterations which change as per the reactive power demand. The THD profile of one of the phases using ANN controller shown in Fig.8 depicts the minimization of harmonics compared to unoptimised operation.

Sample NO.	LOAD (P+jQ) kVA			Qs kVAR Avg.	% Avg THD		Computational time Seconds
	R	Y	B		Unoptimized (Qs=0)	Optimi-zed (Qs not zero)	
1	14+j26	27+j5	30+j15	2.945	18.65	8.70	0.1250
2	24+j15	17+j28	15+j26	5.438	37.29	13.13	0.1250
3	13+j22	17+j26	17+j24	2.124	16.15	8.30	0.1250
4	20+j12	25+j13	30+j15	0.161	8.74	5.41	0.1410
5	25+j25	25+j25	25+j25	4.55	13.35	11.53	0.1250
6	10+j05	15+j22	25+j12	6.422	2.55	1.47	0.1250
7	14+j25	15+j15	10+j25	1.643	13.55	6.96	0.1250
8	12+j15	30+j29	17+j21	5.195	24.41	12.79	0.1400
9	14+j26	12+j15	19+j26	4.305	22.39	11.01	0.1250
10	19+j22	30+j18	19+j21	2.426	15.66	8.70	0.1250

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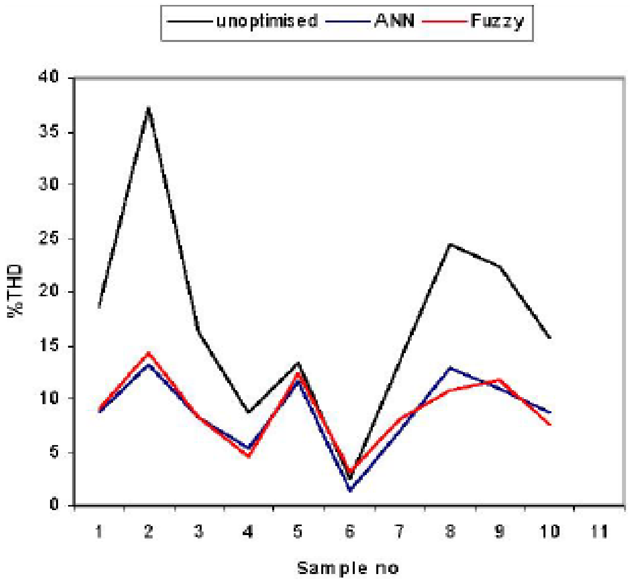

Fig. 6. Reduction in THD using Fuzzy and ANN structures.

VI. CONCLUSION

Static Var Compensators (SVCs) remain ideal choice for fast changing loads due to low cost and simple control strategy. DSTATCOM being ideal solution suffers from serious limitation of high cost and complex control strategy. The SVCs, while correcting power factor, inject harmonics in distribution lines. The operation of thyristor- controlled compensators at various conduction angles can be used advantageously to meet the unbalanced reactive power demands in a fluctuating load environment. The proposed ANN based approach can be effectively used to reduce and balance the reactive power drawn from the source under unbalanced loadings while keeping the harmonic injection into the power system low. The case study proves that the percentage THD under optimized condition is much less than the percentage THD under unity power factor condition (unoptimised). The computational time required was found to be satisfactory for the system considered. The scheme can be effectively used at distribution level where the load harmonics is not a major problem.

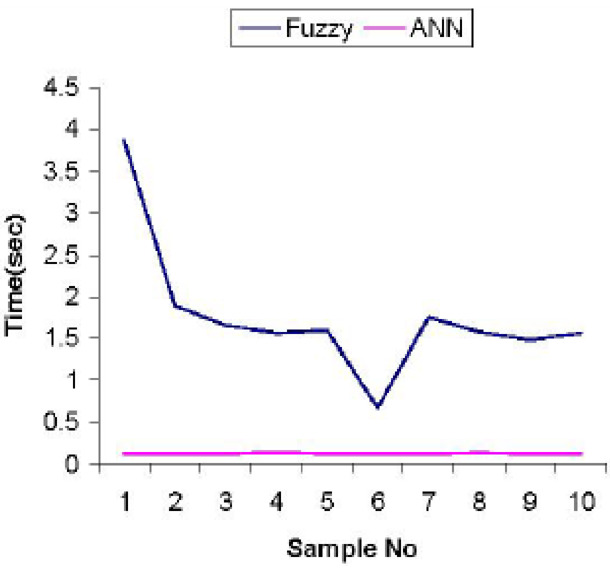

Fig. 7. Computational time using Fuzzy and ANN structures.

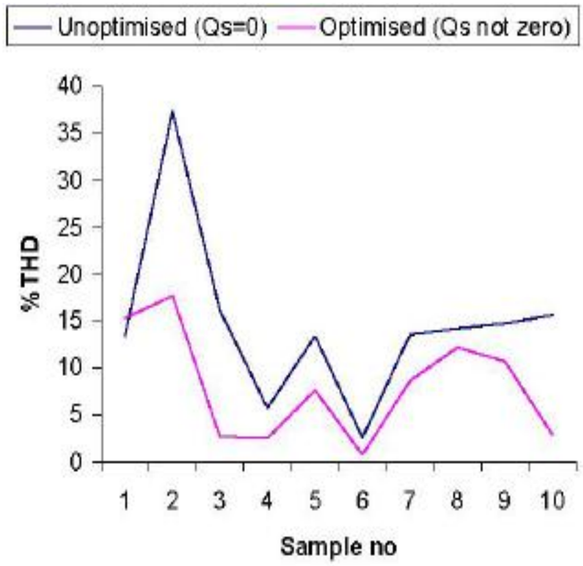

Fig. 8. THD for phase B after ANN optimization.

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