

October 2011

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V. Lakshmi Devi

Narayana Engineering College, Nellore, vldevi.eee@gmail.com

T. Phanindra

JNTU, Kakinada, phanindras.thota@gmail.com

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Devi, V. Lakshmi and Phanindra, T. (2011) "Novel Approach For Minimal Injected Harmonics At Distribution Level – Svc," *International Journal of Smart Sensor and Adhoc Network*: Vol. 1 : Iss. 2 , Article 4.

Available at: <https://www.interscience.in/ijssan/vol1/iss2/4>

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Novel Approach For Minimal Injected Harmonics At Distribution Level – Svc

V. Lakshmi Devi¹ and T.Phanindra²

¹ P.G.scholar, vldevi.eee@gmail.com, Narayana Engineering College, Nellore

² P.G.scholar, phanindras.thota@gmail.com, JNTU , Kakinada

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 are going to be used 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. Verification of the system and by using matlab/simulink with proper modeling.

1. 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. A variety of power factor improvement & harmonic minimization techniques are available ranging from various power factor-correcting devices to passive & active harmonic filters .

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

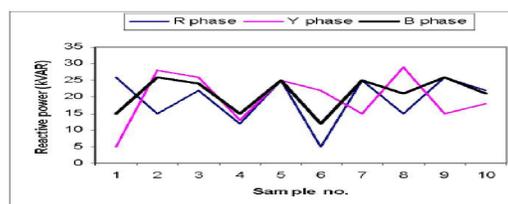


Fig.1. Reactive power profile of distribution substation

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.

The proposed solution is aimed at reducing the harmonic injections at the existing TSC-TCR installations so that a flexible scheme is available. Consumers can tune the controller so that they obtain a high value of power factor with little higher total harmonic distortion (THD) or less value of the power factor with low THD or a compromised value of power factor and THD at the point of common coupling (PCC).

II. COMPARISON WITH CURRENT TECHNOLOGY

The improvement of the power quality as delivered by the distribution transformer has been a topic of interest for a long time. Several methods are available for delivering quality output and operating the distribution transformer at unity power factor without much voltage distortion. The use of STATCOM at the PCC solves most of the problems of power quality (PQ). But the TSC-TCR used at the PCC can address current

balancing and reactive power control. It has low cost and a moderately complex control strategy. Table I shows the comparison between the STATCOM and TSC-TCR of similar ratings [7]. Though STATCOM is superior to TSC-TCR in terms of its capability, stability margin, and response time, it suffers from the disadvantage of high cost, high losses, and complex control strategy.

D. Thukaram *et al.* in [8] have analyzed a fixed capacitor thyristor-controlled reactor (FC-TCR) type of compensator for minimum harmonic injections in terms of . The authors have concluded that the compensator operation beyond a certain range of triggering delay angles may increase the harmonic components and, thus, the compensator capacitor and reactor size should be selected based on the overall requirement of meeting the loads.

The authors in [9] have reported a combined system consisting of classical SVC and active power filters which can eliminate harmonics produced by TCR and nonlinear loads. The proposed system corrects power factor and provides voltage stability but with the additional cost of an active filter.

R. Bayindir *et al.* in [10] have presented an ANN-controlled field excitation system of a synchronous motor which is used for dynamic power factor correction without harmonic injection. Despite the advantage of harmonic-free operation of the synchronous motor, the disadvantage of the system is that it is only attractive for the applications in industrial systems where the synchronous motor is already available. The authors in [11] have applied an ANN approach to minimize total demand distortion (TDD) at a high-voltage level of a 220/66-kV system with reactive power variation of 0–30MVAR per phase and presented the results with a minimum TDD and minimum approach.

This paper is applied to the 11-kV/400-V distribution transformer feeding linear fluctuating loads. The SVC used in the system has various sizes of TSC and a fixed size of TCR as given in Section VII. The system considers reactive power variation of 0–30 kVAR per phase. For given values of reactive powers of three phases; it calculates the optimum triggering delay angles for delta-connected TCR with flexible operation as explained in Section I. The system is applicable to low- voltage distribution systems. The harmonic injections at the PCC are minimized by Optimizing and internally without using any external filter.

III SYSTEM MODELING

The single-line diagram of the distribution substation under consideration is shown in Fig. 2. The compensator essentially functions as a thyristor-

switched capacitor and thyristor-controlled reactor (TSC-TCR).

In the scheme, TSC and TCR are connected in star and delta, respectively. A series of steady state loads at discrete time instants is recorded which represent time-varying loads. The compensator requirement is to generate or absorb unbalanced reactive power which, when combined with the load demand, will represent balanced load to the supply system. The phase-wise load demands are $P_{La} + jQ_{La}$, $P_{Lb} + jQ_{Lb}$, and $P_{Lc} + jQ_{Lc}$ and the phase-wise load seen by the source after compensation is $P_{La} + jQ_{Sa}$, $P_{La} + jQ_{Sb}$ and $P_{La} + jQ_{Sc}$. Phase-wise complex voltages at the load bus are given by

$$[V_L] = [V_S] - [Z] [I_S] \text{ -----25}$$

Where $[V_L] = [V_{La}, V_{Lb}, V_{Lc}]^T$ is the complex voltages vector at the load bus. $[V_S]$ is the complex voltages vector at the source bus and $Z = \text{diagonal}[Z_a, Z_b, Z_c]$ is the line impedance matrix [11].

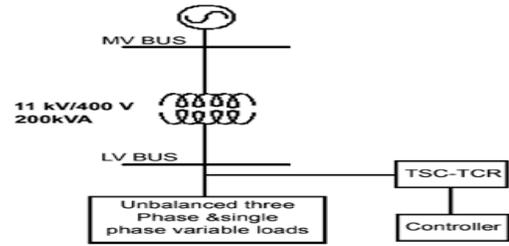


Fig. 3.5. Single line diagram of the system

The vector of currents in the lines between the source bus and the load bus $I_S = [I_{Sa}, I_{Sb}, I_{Sc}]^T$ is obtained from

$$\begin{aligned} I_{sc} &= \frac{(P_{La} - jQ_{sa})}{V_a} \\ I_{sb} &= \frac{(P_{Lb} - jQ_{sb})}{V_b} \\ I_{sc} &= \frac{(P_{Lc} - jQ_{sc})}{V_c}. \end{aligned} \text{ -----26}$$

The nonlinear complex set of equations given by 25 and 26 can be solved for load bus voltages. The reactive power balance equations at the load bus are

$$[Q_S] + [Q_C] = [Q_R] + [Q_L], \text{ -----27}$$

For a given reactive power demand $Q_L = [Q_{La}, Q_{Lb}, Q_{Lc}]^T$, setting balanced values for $Q_C = [Q_{Ca}, Q_{Cb}, Q_{Cc}]$ of the TSC and $Q_S = [Q_{Sa}, Q_{Sb}, Q_{Sc}]^T$ of the source, the unbalanced reactive power absorbed by the TCR, $Q_R = [Q_{Ra}, Q_{Rb}, Q_{Rc}]$ can be obtained from 27. Once the voltage vector at the load bus is determined, the values of delta-connected TCR reactance's X_{ab} , X_{bc} , and X_{ca} required to absorb the computed reactive power can be determined.

The variable reactances of the compensator are realized by delaying the closure of the appropriate thyristor switch by varying the TCR's firing delay angle $\alpha[0 - \pi/2]$. The unsymmetrical firing of TCR valves within the delta can be advantageously used to obtain the unsymmetrical delta-connected reactances. Considering only the fundamental component, the unsymmetrical firing delay angle α_1 , corresponding to the delta reactance X_{ab} , can be obtained by solving the following equation:

$$X_{ab} = \frac{X_{ab}^0}{1 - \frac{2\alpha_1}{\pi} - \frac{\sin 2\alpha_1}{\pi}} \text{-----28}$$

where is the reactance for full conduction of thyristors (corresponding to zero firing delay angles). Similar equations can be written for X_{bc} , and X_{ca} to obtain the values of α_2 and α_3 .

IV HARMONICS DUE TO SVC OPERATION

The PQ at the PCC is expressed in terms of various parameters. Total harmonic distortion (THD) or total demand distortion (TDD) at PCC is one of these parameters, which is commonly used in practice. The performance index THD and TDD is given by

$$\text{THD} = \frac{1}{I_f} \sqrt{\sum_{h=2}^m I_h^2} \text{ and } \text{TDD} = \frac{1}{I_d} \sqrt{\sum_{h=2}^m I_h^2} \text{-----29}$$

Where,
 I_f = fundamental current;
 I_d = demand current;
 I_h = harmonic line current;
 m = maximum order of harmonics considered.

Assuming balanced three-phase voltages at the load bus, the fundamental and harmonic components of the line currents can be obtained by using the following equations 29, as shown in (30)-(31) at bottom .

$$I_f = \frac{V_m}{2\pi\omega L} \sqrt{G_f^2 + H_f^2} \sin(\omega t - \phi - \theta_f)$$

$$I_h = \frac{V_m}{2\pi\omega L} \sqrt{G_h^2 + H_h^2} \sin(h(\omega t - \phi) - \theta_h) \text{---- 30}$$

$$G_f = (3\pi - 4\gamma - 2\sin 2\gamma - 2\beta - 2\sin 2\beta)$$

$$H_f = \sqrt{3}(\pi - 2\beta - 2\sin 2\beta)$$

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

$$+ \frac{1}{2} \left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\gamma}{h} \right)$$

$$H_h = \pm \sqrt{3} \left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\gamma}{h} \right) \text{---31}$$

A program in MATLAB is written to obtain the aforementioned values and is used in the fuzzy logic toolbox.

V MINIMIZATION OF HARMONICS

For a given load reactive power demand Q_L , minimizing the value of Q_s is required. By setting balanced values for Q_C and Q_S , the unbalanced reactive

power absorptions of TCR can be obtained by using the procedure described above. Now, the unsymmetrical reactances required absorbing Q_R and the corresponding unsymmetrical firing angles can be computed from Eqn28. 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. Thukaram *et al.* have shown in [11] that different combinations of firing angles lead to various harmonic levels, as indicated by the value of the 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 a low harmonic level. It has been further shown that there are several combinations of firing angles which lead to a 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 Q_s and THD satisfactorily low.

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 Q_s and THD is not straightforward. In this paper, fuzzy logic and the ANN controller are used to obtain the triggering delay angles α_1 , α_2 , and α_3 for the TCR. These triggering delay angles correspond to minimum THD values and acceptable compromised reactive power Q_s .

A. SVC Control With Fuzzy Ranking System

It is reported in the literature that Mamdani-type fuzzy controllers give better performance for reactive power control of TSC-TCR circuits. 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 determines the step size of TSC and the unsymmetrical firing angles of the TCR as outputs.

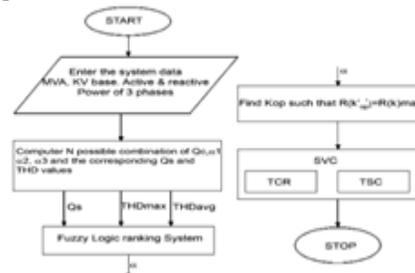


Fig. 3. Flowchart of the fuzzy controller.

The first block computes a set of feasible combinations (say, N different combinations) of firing angles α_1 , α_2 , α_3 and the corresponding Q_s 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 N th combination depending on the corresponding $Q_{S(K)}$ and $THD_{(K)}$ values. In the case of three-phase unbalanced loads, three different THD values resulting from the

B. ANN Approach

The relationships between the inputs to the controller , namely, phase-wise active , reactive power demands, and the outputs, namely, 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 the ANN controller that is used is shown in Fig. 4. It was observed that the dependency of the outputs on the real power demands is minimal. It reflects only in the calculation of the load-bus phase voltages. A small change in load-bus voltages does not really

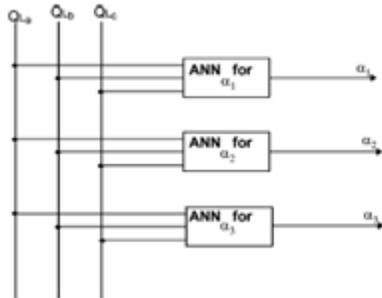


Fig.4 ANN architecture

affect the amount of reactive power that is absorbed or supplied by the TCR and TSC, respectively. In order to reduce the complexity of the neural network, only reactive power demands are used as inputs to the controller. The neuralnetwork controller contains a three-layer feedforward 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 angles α_1 , α_2 , α_3 , and corresponding to the delta reactances X_{ab} , X_{bc} , and X_{ca} , respectively. The ANNs are trained by using the data generated by the fuzzy-logic-based controller with arbitrary load profiles. These load profiles are carefully generated so that data cover all expected regions of operations.

ANN training is highly sensitive to the number of neurons used in the hidden layer. However, the number of hidden layer neurons required for successfulANNtraining is problem dependent and is

three phases exist. After various considerations, the highest THD value among the three phases $THD_{MAX(K)}$ and the average THD of the three phases 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.

usually determined by a trial-and-error procedure. The number of hidden neurons depends on input vector size and the number of input classifications. It is known that too few neurons can lead to underfitting whereas too many neurons can contribute to overfitting. Further, it is also reported that prolonged training beyond certain epochs, the ANN has the tendency to memorize the input–output pattern which results in poor generalization ability. Thus, in the present investigation, 1500 epochs and a mean squared error of 0.001 were set as a goal of ANN training.

VI. SIMULATION RESULTS

An 11-kV/400-V, 200-kVA distribution substation feeding a fluctuating load is taken for simulation as shown in Fig. 2. The load consists of single-phase and three-phase motors, laboratory equipment, and switched-mode power supplies. The static VAR compensator was considered consisting of a TSC that can vary through four steps; 0, 10, 20, and 30 kVAR per phase and a thyristor-controlled reactor (TCR) of capacity of 10 kVAR per phase under full conduction. The parameters of the line between the source bus and load bus are taken as 0.02 ohms/phase and 0.07 ohms/phase. The simulated results using ANN in the MATLAB 7.0 environment for ten samples at two seconds each are shown in table below

Sample number	Load (P+jQ) kVA			% THD _{avg}	
	R	Y	B	Unoptimized (Q=0)	Optimized (Q not zero)
1	14+j26	27+j5	30+j15	18.65	8.70
2	24+j15	17+j28	15+j26	37.29	13.13
3	13+j22	17+j26	17+j24	16.15	8.30
4	20+j12	25+j13	30+j15	8.74	5.41
5	25+j25	25+j25	25+j25	13.35	11.53
6	10+j05	15+j22	25+j12	2.55	1.47
7	14+j25	15+j15	10+j25	13.55	6.96
8	12+j15	30+j29	17+j21	24.41	12.79
9	14+j26	12+j15	19+j26	22.39	11.01
10	19+j22	30+j18	19+j21	15.66	8.70

For each load data, Avg. shows the reactive power drawn from the source for optimized. The percentage average THD for unoptimized (Q=0) operation shows the percentage average THD when SVC perfectly balances the reactive power whereas for optimized (Q not zero) operation indicates the percentage average THD when SVC is compromised with power factor for minimal THD. Fig. 5 shows a reduction in THD using fuzzy and ANN structures compared to operation,

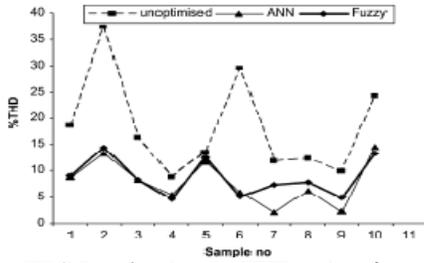


FIG.5 reduction in THD using fuzzy and ann

clearly showing that the ANN controller follows the trend. The THD profile of one of the phases using the ANN controller shown in Fig. 6 depicts the

VII. CONCLUSION

SVCs are preferred for varying loads due to low cost and simple control strategy. DSTATCOM, as the ideal solution, suffers from serious limitations of high cost, high losses, and complex control strategy. The SVCs, while correcting power factor, inject harmonics in distribution lines. The operation of thyristor controlled compensators (TSC-TCR) at various conduction angles can be used to advantageously 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 scheme can be effectively used at SVC installations in distribution feeders that cater to linear loads to minimize harmonic injections. The proposed controller can be tuned to provide flexible operation; the limitation is the inability to filter load harmonics.

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minimization of harmonics compared to unoptimized operation.

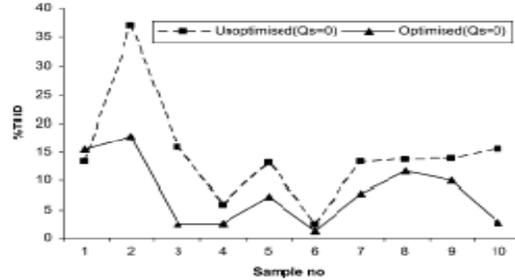


FIG: 6 THD for phase-B after ANN optimization

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