Minimization of THD and Transmission Losses Using GA SVC controller

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Abstract

Distribution systems are faced with power quality problems such as low power factor, harmonic distortion, losses and unreliability. Static var compensator (SVC) such as thyristor controlled reactor (TCR) is usually used for balancing reactive powers of all the three phases independently by controlling the firing angle of thyristors. TCRs that are installed in distribution lines compensate unbalanced reactive power but while doing so the TCR injects harmonic currents of odd order into the point of common coupling. This paper proposes a new procedure of controlling the injected harmonics of TCR to the power system by using genetic algorithm (GA). In addition three objective functions are defined in order to optimize the amount of SVC harmonic injection, PF and transmission losses simultaneously. In this paper a trade of between different aims of installing SVC is studied. The results of optimized thyristors firing angles are illustrated through the MATLAB software.

I. Introduction

The power quality improvement at low voltage distribution level is the topic of interest for a long time. There are various methods of improving the power quality at distribution transformer which are reported in the literature [1- 3]. Static compensators (STATCOMs) are ideally suited for distribution feeders where the loads are unbalanced and nonlinear. STATCOMs being ideal solutions for such systems, suffer from the limitations of higher losses, high cost and complex control strategy. TCR type of SVCs if used in the distribution systems, they can minimize cost in terms of cost of losses and initial costs, and can operate with moderately complex control strategy. The operation of TCRs at appropriate conduction angles can be used advantageously to meet the phasewise, unbalanced and variable reactive power demand. However operation of TCR at various triggering delay angles produces harmonic currents that get injected at the point of common coupling (PCC) causing

serious concern about the quality of power at PCC. In such cases it becomes necessary to provide external filters or filter the harmonics internally by choosing suitable switching angles of TCR. It is obvious that the first approach attracts additional investment [4].
Nowadays, the electrical energy demand increases continuously. This problem should be monitored and observed because it can affect the power flows in the system. If this is not controlled, this will lead to an augmented stress of the transmission lines and higher risks for faulted lines[5]. It means that the current situation is not satisfactory. But, building a new transmission line will not be an effective way to solve the problems because it is quite complicated due to the environmental and political reasons. Therefore, the only way to overcome this major problem is by utilizing one of Flexible AC Transmission Systems (FACTS) devices [6].

II. Reactive Power Compensation

The aim of reactive power is reaching to satisfactory operation of the transmission system in future years. That is, to ensure sufficient reactive power is going to be there if needed. The definition of satisfactory operation generally involves factors such as minimizing power losses [7], minimizing voltage deviations [8], ensuring load flow balance [9] and maximizing voltage collapse margins [10] (maximizing voltage stability). Compensation also requires the operational problem to be solved. This operational problem arises from the need to evaluate how well a power system can perform with each candidate VAr expansion scheme installed. This requires adjustment of certain parameters of the power system to attain optimal operational performance and maximum benefit from the newly installed devices. These parameters are the settings for any variable transformer taps operating in a preventive mode (that is, they do not respond dynamically) and the voltage set points of the controller characteristics of any dynamic compensation devices: SVCs or synchronous compensators, for example. This part of the compensating problem is called the operational problem and may be solved simultaneously with the planning problem or as a sub problem. Solving the optimization problem is not a trivial matter; the problem quickly becomes very complex as the size of the system increases. For a large system the problem space would be highly non-linear, multi-modal and discontinuous [11]. Much work has been carried out to develop optimization techniques that can operate in such an environment. Decomposition [12], Linear Programming [13] and Simulated Annealing [14, 15] remain popular choices [16]. The focus in this paper lies on the SVC. The SVC is a shunt-connected device and is already well established and widely used. Furthermore, SVC is one of controllers based on Power Electronics known as FACTS Controllers, which can control one or more variables in a power system. It also provides a fast variable source or sink of reactive power. Conceptually, it is a variable shunt reactance injecting or absorbing reactive power in order to control the voltage. It also decreases the losses and enhances the unstable capacity of existing transmission lines. SVC can permit to increase the system loadability [6].
It can also be used for balancing unsymmetrical loads. As shown in Fig 1, it is normally constituted by one TCR and a number of thyristor switched capacitor (TSC) branches. The value of the reactance of the inductor is changed continuously by controlling the firing angle of the thyristors, while each capacitor can only be switched on and off at the instants corresponding to the current zero crossings, in order to avoid inrush currents in the capacitors. With this arrangement, the SVC can generate continuously variable reactive power in a specified range, and the size of the TCR is limited to

the rating of one TSC branch. Obviously, the size of the reactor limits the power that can be absorbed in the inductive range. The SVC can be found in applications such as power line compensation, compensation of railway feeding system, reducing disturbance from rolling mills and arc furnace compensation (both for reactive power supply and for flicker mitigation). The ability to absorb changes in reactive power makes to some extent the SVC suitable for flicker reduction. In this case, the SVC normally consists of a TCR branch with a filter (no TSC). An SVC installed together with an arc furnace not only reduces the flicker, but also, thanks to the stabilized AC voltage, increases the steel production and its quality. However, the ability of the SVC to mitigate flicker is limited by its low speed of response [17].

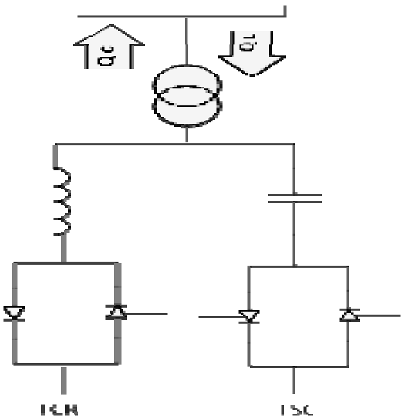

Fig1. A basic TSC-TCR type SVC

- **TCR**

TCR are used in industry for PF correction, correct phase imbalance, and terminal voltage stabilization of fluctuating and nonlinear loads. The fixed capacitor biases the reactive output of the compensator into the generating regime. The demand for reactive power is met by controlling the duration of the conducting interval in each half-period by gating pulses to the two oppositely poled thyristors. For a sinusoidal voltage, the TCR current is easily found and transformed to the frequency domain [18].

This technique is satisfactory in purely sinusoidal systems in which it is possible to completely compensate the reactive current and achieve a power factor very close to unity. However, performance as far as the optimization of the power factor is concerned, may be reduced above certain levels of harmonic distortion of the supply voltage waveform. One of the objectives of this paper is to arrive at a more general formulation to take the place of the former when the supply voltage contains a combination of significant harmonics. In such circumstances, as will be seen shortly, each voltage harmonic "generates" its own combination of harmonics of current in the compensator, as if the case were sinusoidal. This makes the situation much more complicated from a theoretical point of view, and the calculation of the firing angle is not simple. This difficulty is in part caused by imprecision in the moment when the thyristor fires due to the fact that the zero crossing of the voltage and current signals is influenced by the harmonic content. Furthermore, this makes the prediction of the duration of the conduction angle difficult [19]. Magnitude of the current in the reactor can be varied continuously by delay angle control from maximum *(*α = 0) to zero (α = 90), as illustrated in Fig 2, where the reactor current, together with its fundamental component, are shown at various delay angles, α . The adjustment of current in the reactor can take place only once in each half-cycle, in the zero to *T/2* interval ("gating" or "firing interval"). The amplitude *ILF(α)* of the fundamental reactor current *iLF(α)* can be expressed as a function of angle *α:*

$$I_{LF}(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

Where *V* is the amplitude of the applied AC voltage, *L* is the inductance of the TCR, and ω is the angular frequency of the voltage. The variation of the amplitude *ILF(α),* normalized to the maximum current ILFmax, (ILFmax = *V/ωL),* is shown plotted against delay angle α in Fig 2 [20].

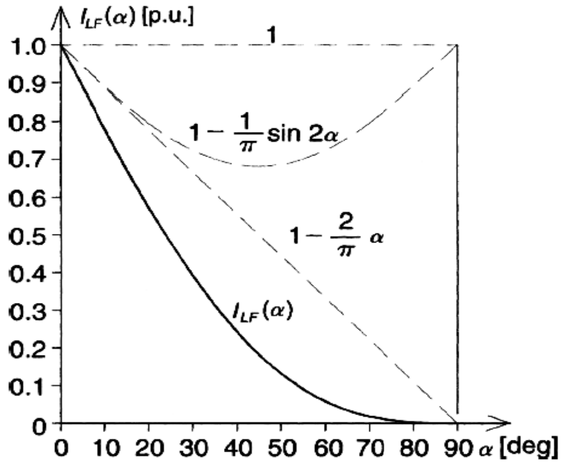

Fig.2 Normalized fundamental TCR current

III. Harmonics Generation

Both of the harmonics and reactive powers are serious problems associated with the grid. They are caused by nonlinear loads, including saturated transformers, arc furnaces, and semiconductor switches. The presence of harmonics and reactive power in the grid is harmful, because it will cause additional power losses and malfunctions of the grid components. To prevent the inflow of harmonic and reactive currents and to improve the operating ability of the transmission systems, a kind of FACTS has been proposed. The SVC is an important component of FACTS. It usually installs in power transmission systems and serves in various ways to improve the system performance. By the rapid control of their reactive power output, the SVCs regulate system voltages, improve transient stability, correct power factor, reduce temporary overvoltages, and damp subsynchronous resonances. Usually, an SVC is composed of a TCR and fixed capacitors (FCs). However, a TCR will introduce harmonic currents. Another problem is the harmonic amplification. The TCR introduces harmonic currents, and the FC amplifies the harmonic currents generated by the TCR [21].The SVC generates harmonics because of switching elements in the TCR. Several investigations have been done on harmonics reduction in SVCs. For example, using 12-pulse compensator is one of the solutions but due to a high cost, it is not practical. The common solution is to use filters with the SVC to reduce harmonics. It should be noted that if the SVC does not generate harmonics, it is possible to absorb more harmonics from the power system. In other words, since the current flowing through the filter reaches a certain value, by absorbing the compensator harmonics, some of its capacity to absorb the power system's reactive and harmonics currents is reduced. A comprehensive analysis of the compensator harmonics is presented. It is clear that the amount of harmonics increases by increasing firing angle. It can be seen that characteristic harmonics generated by the TCR are the 3rd, 5th, 7th, 11th, and 13th order harmonics. When the TCR is Δ-connected, the 3rd harmonics will be zero [22].

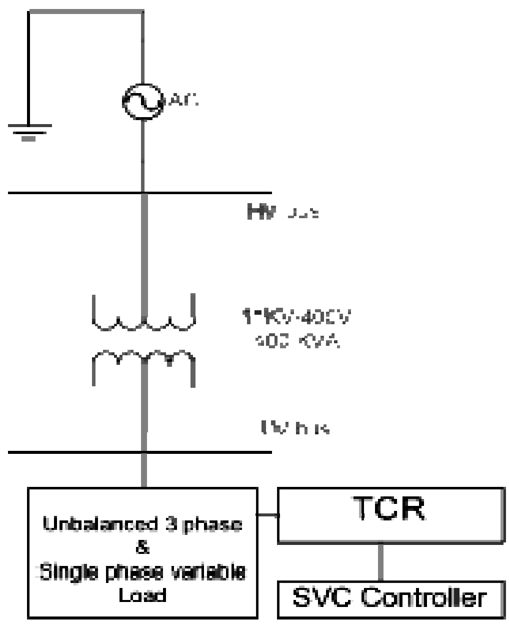

Fig 3. Single line diagram of the system

IV. SYSTEM MODELLING

The single line diagram of the distribution substation under consideration is shown in Fig 3.

A series of steady state loads at discrete time instants are recorded which represents 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.

In Table 1 all of the Nomenclature are listed.

The phase wise load demands are

PLa + jQLa, PLb + jQLb and PLc + jQLc

The phase wise loads that could be 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], Where VL=[VLa, VLb, VLc]T is the complex voltage vector at the load bus.

VS= [Vsa, Vsb, Vsc]T is the complex voltage vector at the source bus and

Z = diagonal [Za., Zb , Zc] is the line impedance matrix. The vector of currents in the lines between the source bus and the load bus, Is = [Isa, Isb, Isc]T is obtained from

$$Is_a = \frac{(PL_a - jQs_a)}{V_a} \tag{1a}$$

$$Is_b = \frac{(PL_b - jQs_b)}{V_b} \tag{1b}$$

$$Is_c = \frac{(PL_c - jQs_c)}{V_c} \tag{1c}$$

This non-linear complex set of equations can be solved for load bus voltages. For a given reactive demand $QL = [QL_a, QL_b, QL_c]T$, and $Qs = [Qs_a, Qs_b, Qs_c]T$ of the source, the unbalanced reactive power absorbed by the TCR, $QR = [QR_a, QR_b, QR_c]T$ can be obtained from reactive power balance equations at the load bus $[Qs] = [QR] + [QL]$.

Table 1. Nomenclature

Parameters	Description
PL + jQL	Phase wise load demand
PL + jQS	Phase wise load seen by the source after compensation
VS	Complex voltage vector at source bus
VL	Complex voltage vector at the load bus
Z	Line impedance matrix.
Is	Line current between source bus & load bus
L	Per phase inductance of TCR
Xab0	Reactance per phase of TCR under full conducting state
Xab	Reactance per phase when the triggering delay angle is α1
If	RMS value of fundamental line current
Ih	RMS component of h(th) order harmonic current
ω	Fundamental frequency in rad/sec
Vm	Peak value of line voltage
Φ	Phase difference between line voltages
θh	Phase difference between harmonic voltage & current
θf	Phase difference between fundamental voltage &current
α1, α2, α3	Triggering delay angles for three branches of TCR

Once the voltage vector at the load bus is determined, the values of delta connected TCR 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 TCR's firing delay angle 0< α <90.
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 α1 corresponding to the delta reactance xab can be obtained by solving the following equation:

$$X_{ab} = \frac{x_{ab}^{0}}{1 - \frac{2\alpha_1}{\pi} - \frac{\sin 2\alpha_1}{\pi}} \qquad (2)$$

Where xab^0 is the reactance for full conduction of thyristors, corresponding to zero firing delay angles. Similar equations can be written for xbc & xca, to obtain the values of α2 and α3.

- **Harmonic due to SVC operation**

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

$$THD = \frac{1}{I_f}\sqrt{\sum_{h=2}^{m} I_h^{\,2}} \qquad (3)$$

Where I_f is the fundamental current, I_h is the harmonic line current for h_{th} harmonic and m is the 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:

$$I_f = \frac{V_m}{2\pi\omega L}\sqrt{G_f^{\,2} + H_f^{\,2}}\,\sin(\omega t - \varphi - \theta_f) \qquad (4)$$

$$I_h = \frac{V_m}{2\pi\omega L}\sqrt{G_h^{\,2} + H_h^{\,2}}\,\sin(h(\omega t - \varphi) - \theta_h) \qquad (5)$$

$$G_f = (3\pi - 4\gamma - 2\sin 2\gamma - 2\beta - 2\sin 2\beta) \qquad (6)$$

$$H_f = \sqrt{3}(\pi - 2\beta - 2\sin 2\beta) \qquad (7)$$

$$G_h = \left(\frac{\sin(h+1)\gamma}{(h+1)} - \frac{\sin(h-1)\gamma}{(h-1)} - \frac{2\sin\gamma\cosh\gamma}{h}\right) + \frac{1}{2}\left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\beta}{h}\right) \qquad (8)$$

$$H_h = \pm\sqrt{\frac{3}{2}}\left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\beta}{h}\right) \qquad (9)$$

$$\theta_f = \tan^{-1}\left(\frac{H_f}{G_f}\right) \;\&\; \theta_h \approx \tan^{-1}\left(\frac{H_h}{G_h}\right) \qquad (10)$$

$\varphi = 0, \gamma = \alpha_1, \beta = \alpha_3$ for phase A

$\varphi = \frac{2\pi}{3}, \gamma = \alpha_2, \beta = \alpha_1$ for phase B

$\varphi = \frac{4\pi}{3}, \gamma = \alpha_3, \beta = \alpha_2$ for phase C

For line currents $I_a, I_b \,\&\, I_c$ respectively,
h=harmonic order, $(6k \pm 1)$ $k = 1,2,3...$
+ Sign for harmonics of order $(6k+1)$ and
-Sign for harmonics of order $(6k-1)$.
For triple harmonics $(3^{rd}, 9th)$

$$G_h = \left(\frac{\sin(h+1)\gamma}{(h+1)} - \frac{\sin(h-1)\gamma}{(h-1)} - \frac{2\sin\gamma\cosh\gamma}{h}\right) + \frac{1}{2}\left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta\cosh\beta}{h}\right) \qquad (11)$$

$$H_h = 0$$

A program in MATLAB is written to get the above values and is used for calculating the various parameters.

- **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 Q_S, the unbalanced reactive power absorptions of TCR can be obtained. Now the unsymmetrical reactances required absorbing QR and the corresponding unsymmetrical firing angles can be computed from equation 2. 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 IV. Thukaram et al. have shown 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. However, the task of selecting the particular combination of firing angles from a set of all plausible combinations of firing angles to achieve optimum values of Qs and THD 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 genetic algorithm controller is used to get the triggering delay angles α1, α2 and α3 for the TCR. These triggering delay angles correspond to minimum THD_{avg} values and an acceptable compromised reactive power Qs in terms of power factor [4]. A growing trend over recent years has been the application of genetic algorithm based techniques to the compensating problem. GAs have been shown to be powerful optimization techniques which, theoretically, converge to the global optimum with a probability of one [16].

V. The Genetic Algorithm

Genetic Algorithms are a family of computational models inspired by evolution. These algorithms encode a potential solution to a specific problem on a simple chromosome like data structure and apply recombination operators to these structures as to preserve critical information. Genetic algorithms are often viewed as function optimizer, although the range of problems to which genetic algorithms have been applied are quite broad. An implementation of genetic algorithm begins with a population of (typically random) chromosomes. One then evaluates these structures and allocated reproductive opportunities in such a way that these chromosomes which represent a better solution to the target problem are given more chances to 'reproduce' than those chromosomes which are poorer solutions. The 'goodness' of a solution is typically defined with respect to the current population. The particular extensions implemented in this work are discussed in the next section.

The features that set GAs apart from other optimization techniques are,

- GAs perform a parallel search: the GA uses a population of independent points, not a single point. This population can move over hills and valleys, allowing global optimisation.

- GAs use payoff information (fitness or objective functions) directly for the search direction, not derivatives or other auxiliary knowledge. GAs can therefore deal with non-smooth, discontinuous and non-differentiable functions. This property relives GAs of approximation assumptions that are often required for other optimization methods.
- GAs use probabilistic transition rules, not deterministic rules, to select the next generation. This enables them to search complicated and uncertain areas to find the global optimum, thus making them more flexible and robust than conventional methods.

These features make GAs robust, parallel algorithms to adaptively search for the global optimal point [16].

- **SVC Control With GA**

The genetic algorithm is a method for solving optimization problems based on natural selection, the process that drives biological evolution. In nature, the individual that has better survival traits will survive for a longer period of time. This in turn provides it a better chance to produce offspring with its genetic material. Therefore, after a long period of time, the entire population will consist of lots of genes from the superior individuals and less from the inferior individuals. In a sense, the fittest survived and the unfit died out. This force of nature is called natural selection. Genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce off springs for the next generation. Over successive generations, the population evolves towards an optimal solution. The genetic algorithm uses three main types of rules namely selection rules, crossover rules and mutation rules to create the next generation from the current population. Selection rules select the individuals called parents that contribute to the population at the next generation whereas crossover rules combine two parents to form off springs for the next generation. The mutation rules apply random changes to individual parents to form optimized off springs [4]. The optimized triggering delay angles of TCR are calculated using genetic algorithm in MATLAB 7.0 environment. The objective function for the problem is formulated as

$$F_1(\alpha) = THD_{avg} + THD_{\max} \quad (12)$$

$$F_2(\alpha) = F_1(\alpha) + \frac{1}{P.F} \quad (13)$$

$$F_3(\alpha) = F_2(\alpha) + [R]*[Ave(I_s)]^2 \quad (14)$$

Where THD_{avg} is the average value of THD of all the three phases, $THD_{\max}$ is the maximum value amongst all THD values of three phases and P.F is the average power factor of all the three phases, for a load sample. The objective function is calculated in terms of α1, α2 and α3 as shown in Section III and IV. Flowchart of the genetic algorithm used for the proposed solution is shown in Fig 4. The system data in terms of MVA, kV base, active and reactive power of the three phases are entered. The program computes α1, α2, α3, THD_{max} , $\%THD_{avg}$ and PF.

I. SIMULATION RESULTS

An 11kV/400V, 400kVA distribution substation feeding a fluctuating load is taken for simulation as shown in Fig 5 and both active and reactive power for ten samples are shown in Table 2.

Load consists of single phase and three phase motors, laboratory equipments and switched mode power supplies. A SVC considered consists of a 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 and X= 0.07 ohms per phase. Simulated results using GA toolbox in the MATLAB 7.0

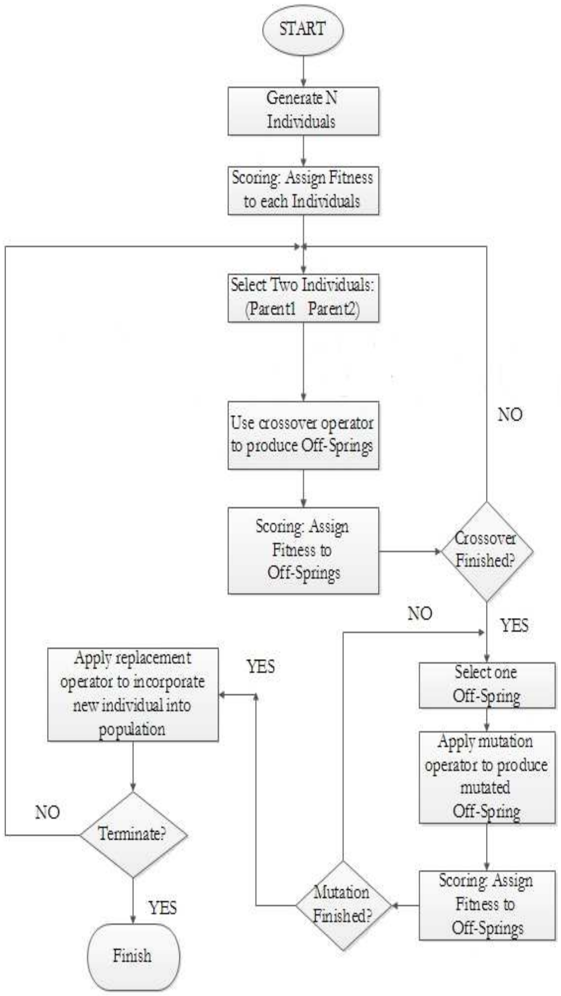

Fig 4. Flowchart of the GA used for the proposed solution

environment for ten samples at two seconds each are shown in Table 3. For each load data, optimized average power factor shows the average power factor of all the three phases at the source and the computational time for optimized α1, α2 and α3. The percentage average THD (% THD_{avg}) for optimized (Qs not zero) operation indicates the percentage average THD when SVC is compromising with power factor for minimal THD. A programme in MATLAB is written to minimize the objective function given in equations 12, 13, 14. Number of trials were carried out by taking a range of generations and it is shown in figures 6, 7, 8 that the objective function given in equations 12, 13, 14 respectively converged for a population of 37, 28 and 37. Convergence of the objective function with number of populations used in genetic algorithm is shown in Fig 6, 7, 8.

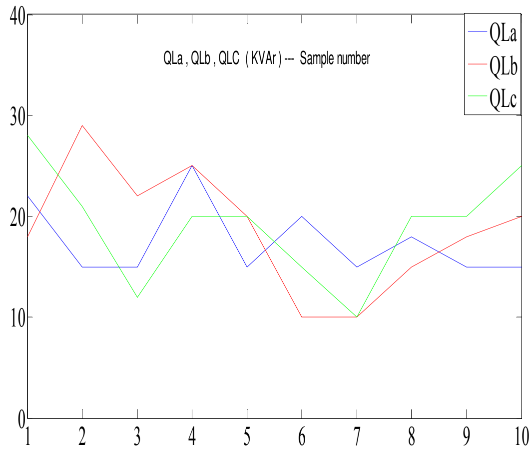

Fig 5. Reactive power of distribution substation

Table 2. Active and Reactive Powers

Sample Number	Phase A	Phase B	Phase C
1	19+j22	30+j18	19+j28
2	12+j15	30+j29	17+j21
3	10+j15	15+j22	25+j12
4	10+j25	12+j25	15+j20
5	8+j15	10+j20	25+j20
6	30+j20	22+j10	20+j15
7	10+j15	10+j10	10+j10
8	15+j18	20+j15	15+j20
9	20+j15	20+j18	20+j20
10	30+j15	30+j20	25+j25

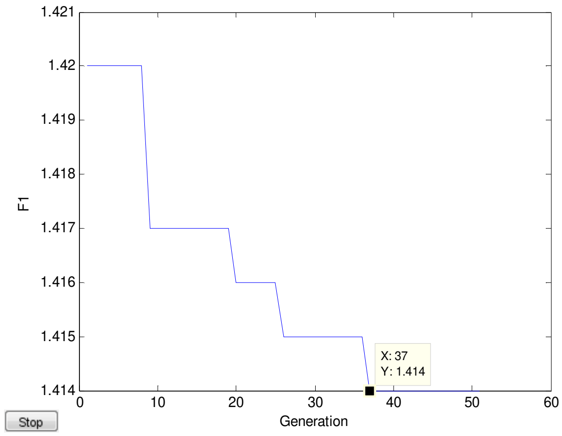

Fig 6. Convergence of F_1 with generations

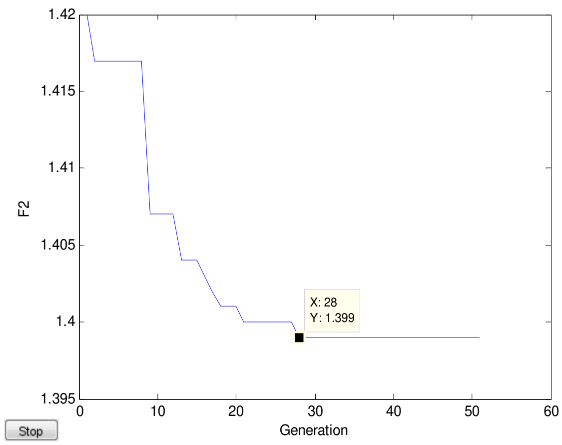

Fig 7. Convergence of F_2 with generations

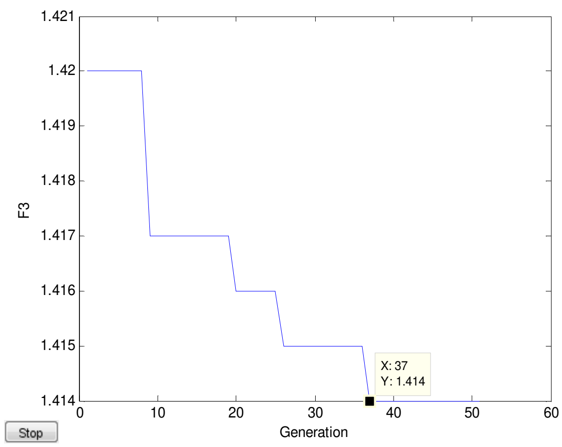

Fig 8. Convergence of F_3 with generations

Table 3. Simulated results using GA

	F_1	F_2	F_3
α_1	0.028489	0.005030	0.001926
α_2	0.003733	0.001923	0.001127
α_3	0.0000297	0.003131	0.000489
$P.F$	0.7151	0.7263	0.7267
THD_{ave}	0.0001311	0.0002565	0.0000451
THD_{max}	0.0000863	0.0001552	0.0000534

I. CONCLUSION

TCR type of SVC can be used for fluctuating loads due to low cost, low losses and moderately complex control strategy. STATCOM being ideal solution suffers from serious limitation of high cost, high losses and complex control strategy. The SVCs, while correcting power factor, inject harmonics in distribution lines. The operation of TCR at various conduction angles can be used advantageously to meet the unbalanced reactive power demands in a fluctuating load environment. The proposed GA 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. Through the use of different objective functions, based on various aims, firing angles could be determined. Hence we did not find another results for firing angles with other ways used for controlling the TCR, it is not possible to have a comparison between GA and another control scheme. But in the future it could be possible to have a comparison between different ways of TCR firing angle control.

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