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Simulated Annealing Based Voltage Source Inverter Design For Harmonic Mitigation

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***Abstract:** In this paper, a Simulated Annealing (SA) Algorithm for a three-phase three-wire Shunt Active Power Filter (SAPF) under ideal sinusoidal conditions is proposed to derive the optimal control. The optimal control is obtained by optimizing the values of proportional gain (k_p), integral gain (k_i) of Proportional Integral (PI) controller. The PI controller is employed in the SAPF to regulate the DC bus voltage of the Voltage source inverter (VSI). To evaluate the performance of the proposed optimal control, the time domain specifications are analyzed under closed loop, during steady state and in transient state. The proposed tuning strategy improves the performance of SAPF through optimal gain parameters of the PI controller and suppresses the harmonics well below the IEEE-519 standard and achieves the better regulation of DC bus voltage under transient conditions.*

***Keywords:** SAPF, VSI, SA, PI controller.*

I. INTRODUCTION

The increased applications of solid-state electronics-based Non-Linear Loads (NLLs) in industries as well as in home appliances cause several power quality problems. The distributed presence of dynamically changing NLLs in the power grid gives rise to the additional problem of current harmonics. The cumulative effects of the above on power grid results in increased current distortions, very low power factor, high loses, and hence reduces the overall efficiency of operation. The elimination of harmonics is necessary task as the harmonics are structured noise that is persistent throughout the period of operation of NLLs [2]. The SAPF also known as converters are employed for the elimination task of harmonics than the traditional LC filter [5].These SAPF generate harmonic currents in opposite phase and that is injected at Point of Common Coupling (PCC) [1]. There is a strong relationship between the voltage of DC bus and THD minimization effort made by SAPF. Optimal voltage on DC bus can also contribute to the maximum compensation [3]. Maintaining the DC bus voltage to a constant value is also greatly contributes to the improvement in compensation effort of the SAPF. Because of the advancements in machine learning and neural networks, to regulate the DC bus voltage one can get wide number of controllers such as Model Predictive Controller (MPC), Fuzzy Logic Controller (FLC), Support Vector Machine (SVM) based adaptive control and Adaptive Neuro Fuzzy Inference System (AN-FIS) based control schemes. But PID controllers are the most widely implemented in industries because of their very simple structure and ease implementation [6]. The regulator of DC bus of VSI is a PI controller. It is obvious that the state of art methods of PI tuning methods in SAPF will not provide a good regulatory action on the DC bus voltage because of non-linearity of the plant[14]. To minimize the problems caused by non linearity, Evolutionary computation techniques can be imposed to SAPF for the task of determining optimal k_P and k_i.

The goal of optimization is to seek better solution of the PI controller parameters. Evolutionary Algorithms (EA's),

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searches the potential solution in a sub-space of total search space [4]. Compared to other optimization algorithms, SA algorithm has less number of parameters to be assigned in order to make algorithm to run. In genetic algorithm the quality of the solution is depends on the crossover fraction, mutation fractions and elite count. In particle swarm optimization the values of social attraction factor and cognitive attraction factor has impact on the quality of solution. But in simulated annealing only less number of parameters has to be specified. Hence the dependency of user supplied parameters on quality of solution in simulated annealing optimization algorithm is very less and converging rate of algorithm is also good [8].The purpose of studying SA techniques is to compare the performance of this algorithms in this particular application in determination of optimal PI parameters. SA is trajectory-based optimization method since it determines a new single current solution at each iteration [13].

The main contribution of the paper is as follows: firstly the well known optimization algorithm SA is developed to the optimization of k_p and k_i of SAPF. Secondly the performance improvement of SAPF by the proposed optimal control is evaluated in time domain specifications.

The paper has been organised as follows: In section II, a brief overview of SAPF is given. Optimization of PI controller parameter using SA is described in section III. Simulation results, performance analysis are given in section I V. The paper ends with a brief conclusion in Section V.

II. SHUNT ACTIVE POWER FILTER

The series combination of active filter needs to bear full load current of the Non Linear Loads (NLLs). Hence the practical implementation of series active filter will bear high expense for compensation effort as the rating of the switches has to be chosen as large enough to handle load current[12]. In Fig. 1 configuration of SAPF shows that the generated negative magnitude current harmonics (i_{fa}, i_{fb}, i_{fc}) injected at the PCC. Hence the harmonics are neutralized and thus THD is reduced. The main components of the SAPF are discussed in following section.

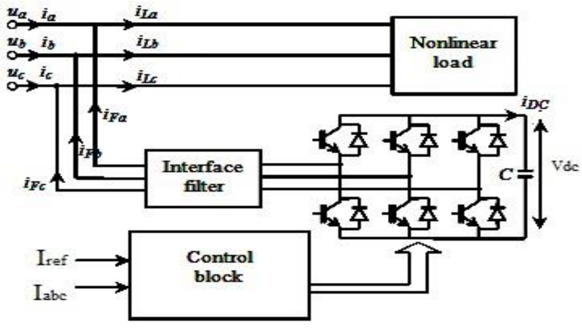

Figure 1: Shunt Active poer Filter Configuration

A. VOLTAGE SOURCE INVERTER

In VSI, DC bus voltage is always tried be maintain at constant value [6]. Because of economic consideration and performance VSI's are chosen over current source inverter (CSI). Since the Current of DC bus flows in either direction, the switches of VSI should be of bidirectional type. On the DC bus side, voltage is provided by capacitor. The capacitor value is selected as large enough value that can handle a sustained charge or discharge current that accompanies the switching sequence of the inverter switches and phase angle of the switches are shifted without injecting more disturbance to the dc bus voltage.

B. PI CONTROLLER

It is well known that the 90% of the controllers employed in the industry to manipulate the process variable is PID.PID controllers are universal because of their ease of implementation [6]. They will outperform all other controllers if the values of gain values are selected appropriately. This selection of gain is called as tuning. However with the increased degree of non linearity the state of art tuning methods will not provide sufficient control action. The proportional gain decides the rise time; overshoot etc where the integral gain eliminates the steady state error.

C. CURRENT CONTROLLER

Current controller is mainly used to provide the switching pulse to the VSI. There are many techniques used for giving the switching signals to VSI such as sinusoidal PWM, triangular PWM, hysteresis current controller, adaptive hysteresis current controller, space vector modulation and space vector with hysteresis current controller etc. out of these hysteresis current Controller is imposed in our design because of the ease of implementation and involves less complexity in real world implementation [6]. The three leg configuration VSI is adapted to supply three phase compensation harmonic currents. The magnitude of hysteresis band width also has its own impact on the generation of switching signals. Poor choice of band will lead to the less effort on compensation task. Based on the knowledge of the process we choose the band width as 0.2.

III. SIMULTED ANNEALING

The SA was introduced in 1983 by Kirkpatrick. This SA optimization algorithm is derived from the process of annealing of solids. This algorithm can transforms poor solution into a highly acceptable optimized solution. This approach is similar to hill climbing approach the only difference is that the simulated annealing doesn't rejects the poor points but it accepts with probability [11]. The detailed approach of the algorithm is shown in following section and the flow chart of the algorithm is shown in fig.2. unlike the other optimization algorithms the SA offers a re-annealing strategy to escape from local minimum of the function [9]. After some iteration we re-anneal (increase the heat to a specified value) the optimization task and again cool it down under controlled situations. This provides more quality of search of global optimum in the search space. The following section explains about the SA approach to arrive PI controller parameters.

- *THE MINIMIZATION FUNCTION:* the energy equation in thermodynamics is same like the objective function of Simulated Annealing algorithm. Objective function is a function of performance index. One can have more number choices such as settling time, rise time, peak overshoot, steady state error, integral absolute error(IAE), integral square error(ISE), integral time squared error(ITSE), integral time absolute error(ITAE) etc as performance index criteria. The time weighted error criteria such as ITAE and ITSE will stress on the steady state error rather than the initial error values. In this work authors use ITSE as objective function to compare with the existing optimized settings [6].
- *INITIAL STARTING POINT:* The start point (T_0) of search of optimal point is set to have very high value [8] and temperature in order to avoid that algorithm is being trapped in local minimum.
- *ACCEPTANCE METHOD:* the generated new points are made to involve in acceptance function [8]. If the generated new point is better than the previous point (if the energy is lesser than previous value) we accept the solution without altering probability of it. Otherwise accepted with probability $p^{'}$ as per equation (1).

$$p^{'} > \frac{1}{1+e^{\frac{\Delta s}{u}}} \quad (1)$$

Where
$p^{'}$ is the random probability,
Δs is the energy change,
u is the temperature.
- *TEMPERATURE UPDATE:* In each iteration the temperature is determined by using the exponential function of the form that decreases the temperature with respect to the increase in the iteration. Initially we allowing the algorithm to increase temperature to maximum value to make the algorithm to inspect the global search space (more random search). After the iteration increases we stress to the local search to avoid more random search [11]. The determination of temperature found by using the equation (2).

$$T_i = a^i \quad (2)$$

Where
T_i is the temperature adjustment belongs to i^{th} iteration,
a is temperature adjustment co efficient,
i is iteration count.
- *STOPPING CRITERIA:* The termination of algorithm in searching for new solution is based on the stopping criterion that is specified. We select 1000 iterations as maximum iteration count. If the iteration count reaches the maximum value then the algorithm is terminated and the best value of controller parameter that minimizes the objective function is displayed.

The main drawback of optimization algorithms is that the lack of result reproducibility. The results that are obtained from first run of the algorithm may not be obtained during the next run of the optimization. Hence it is always preferred to have more number of optimization run to ensure the quality of the solution [11].

The flow of the algorithm during the optimization is explained in the following fig.2. It is clear that the SA will search in trajectories of previous solution that found in previous iterations. The initial solution is accessed as the first step of optimization and its cost function is estimated. And if it is not satisfies the acceptance criteria a new solution is created. This is continued till the maximum iteration count reaches. The temperature update is made at appropriate iteration to make the optimization to search to search for the global optimal solution.

The quality of global optimum solution depends on the quality in which the search is accessed for the potential solution. The search space must be accessed in a fashion that produces the global optimum solution. The cost function is defined as shown in equation (3).

$$J = ITSE = \int t.e(t)^2 \, dt \quad (3)$$

The SA algorithm aims to minimize the equation (3) by optimizing the k_p and k_i.

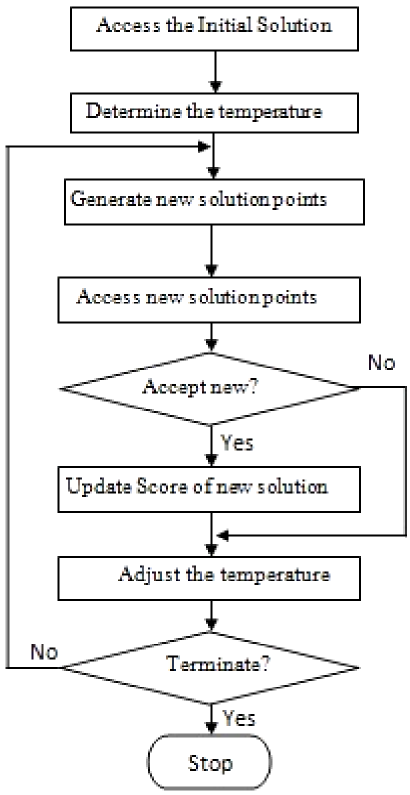

Figure 2: Flow chart of Simulted Annealing

IV. RESULTS AND DISCUSSIONS

The proposed simulated annealing is applied to SAPF which has the parameters as shown in Table.2.the parameters that are chosen for optimization algorithm is shown in Table.1

Parameter	***values***
Upper bound Kp	1.0
Upper bound Ki	300
lower bound Kp	0.1
Lower bound Ki	1.0
Number of iterations	1000
Initial temperature	[1 300]

Temperaturecooling Fraction(α)	0.95

Table 1: SA Parameters

System Parameter	***values***
Supply Voltage	100 V (peak)
Fundamental frequency	50 Hz
Source resistance	0.1 ohm
Source inductance	0.15 mH
Filter resistance	0.1 ohm
Filter inductance	0.66 mH
Load resistance	6.7 ohm
Load inductance	20 mH
DC bus voltage	220 V

Table 2: Shunt Converter Parameters

Parameter	***Conventional***	***Proposed SA based PI***
Proportional Gain Kp	0.57	1
Integral Gain Ki	10.3	259.6912
ISE	58.08	3.464
IAE	2.183	0.1398
ITAE	0.08023	0.001327
ITSE	1.6	0.003871
% of THD	0.0214	0.01865

Table 3: Perfomance Comparision

From Table III it can be seen that the proposed SA-PI controller performs improves the quality of control action.

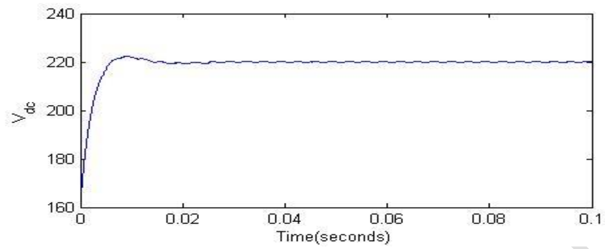

Figure 3: DC bus regulation of VSI in SAPF by SA-PI.

The Dc bus voltage under the steady state of SAPF using proposed simulated annealing based PI is shown in above fig.3. It is obvious that the proposed SA based PI achieves quicker settling time and also shown cosiderable improvement on performance(Refer Table III).

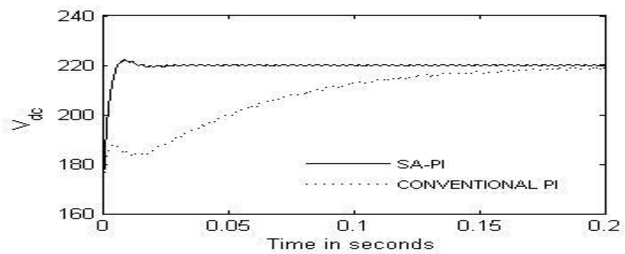

Figure 4: Comparision of DC bus regulation of VSI.

The above fig.4 shows the performance comprision of proposed SA based PI with conventional PI controller parametrers [6].

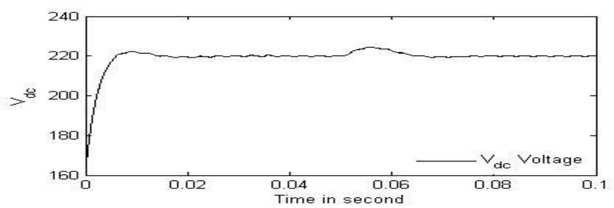

Figure 5: DC bus regulation of VSI in SAPF

In the Fig.5 the regulatory action of PI during the load change is presented. Fig.6 shows the harmonic spectrum analysis of the source current using SA based PI controler. and the Fig.7 shows the conventional PI controller based SAPF's harmonic mitigation effort. from the results it is observed that the harmonics are reduced from 2.14% to 1.86% by using SA based tuning stratergy.

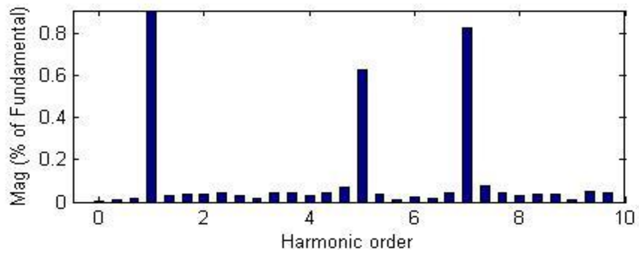

Figure 6: Harmonic Spectrum of source current using SA based PI

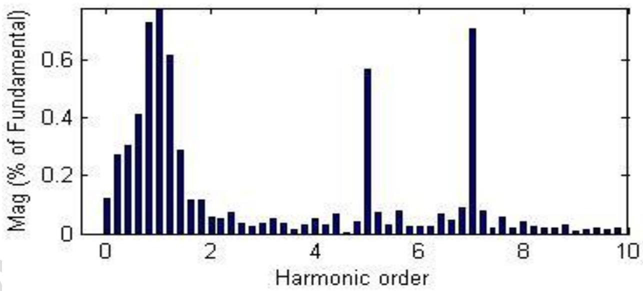

Figure 7: Harmonic Spectrum of source current using conventional PI

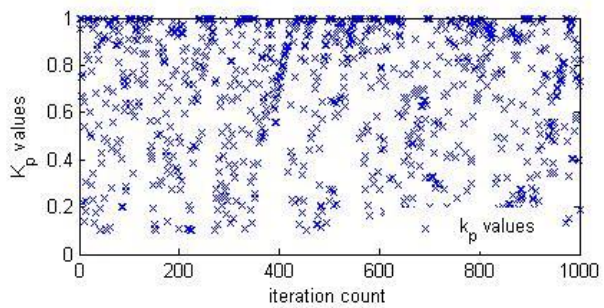

Figure 8: Search space accessed by SA for obtaining opttimal k_p

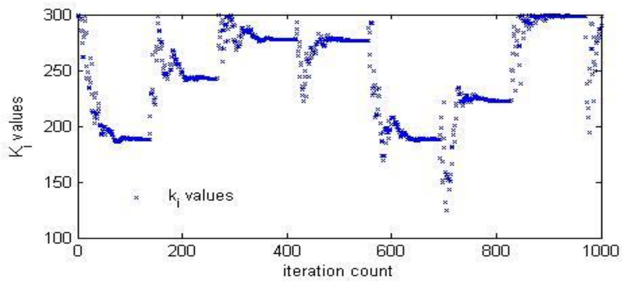

Figure 9: Search space accessed by SA for obtaining opttimal k_i

V. CONCLUSION

From the simulation results it is shown that the THD minimization effort of the shunt active filter after optimization

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is found to better than conventional methods. As power system is highly dynamic system where the load change is very frequent, the proposed SA based PI can be employed to achieve better compensation and regulation DC bus of VSI. The proposed SA-PI improves compensation effort of SAPF by 13%.

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