



GA For Optimal PI in DC Voltage Regulation of D-STATCOM

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Abstract

The performance of DSTATCOM depends on a DC capacitor voltage regulation. The regulation of DC capacitor voltage based on optimal PI coefficients. The conventional method to determine PI coefficients is trial and error method. In this paper Genetic Alogorithem is applied for exact calculation of optimized PI coefficients can carried out to reduce disturbances in DC link voltage. Optimizations and simulations are worked out in MATLAB environment.

Keywords: DSTATCOM, Nonlinear controller, optimized PI coefficients, Genetic Algorithm (GA)

1. Introduction

Static Compensators (STATCOMs) are based on shunt Flexible AC Transmission System (FACTS) devices that can regulate line voltage at the Point of Common Coupling (PCC), balance loads or compensate load reactive power by producing the desired amplitude and phase of inverter output voltage which is connected to a DC capacitor [1]. Generally, a transformer leakage reactance is located between STATCOM and transmission network. The STATCOM connected in distributed system is called as DSTATCOM. There are many possible configurations of Voltage Source Inverters (VSI) and consequently many different configurations of DSTATCOM [2-3]. Many different strategies such as Proportional-Integral controller, sliding mode controller [4] and nonlinear controller have been suggested to control DSTATCOM. Because of nonlinear operation of DSTATCOM, nonlinear controller is preferred in comparison with linear method [5]. Moreover, four chosen sets of PI parameters may not be suitable for all ranges of operating points and finding these values are very time consuming and complex. Vector-controlled techniques are used to control the converters currents leading to fast reactive current control [6-7]. In nonlinear controller, the Generalized Averaged Method [8] has been used to determine the nonlinear time invariant continuous model of the system [9-11]. This model has been applied to implement a nonlinear control law based on exact linearization via feedback for STATCOM [12]. This technique is particularly interesting because it transforms a nonlinear system into a linear one in terms of its input-output relationship. In the literature [9-10], only q axis current was regulated, but it should be noted that unlike other shunt compensators, large energy storage device that have almost constant voltage, makes DSTATCOM more robust and it also enhances the response speed. Therefore, there are two control objectives implemented in DSTATCOM. First is q-axes current and the second is capacitor voltage in DC link [13]. Fortunately, q-axes current tracks its corresponding reference value perfectly, but capacitor voltage is not fixed on reference ideally because of presence of a proportional-integral controller between the reference of the d-axis current and DC link voltage error. In other words, the performance indices (settling time, rise time and over shoot) have notable values. Thus, the optimized and exact determination of PI gains can lead to reduction in disturbances of system responses.

In this Paper, one of the powerful and famous optimization algorithms (e.g. Genetic Algorithm [14-15]) is applied to find optimized values of PI gains. Two objective functions are defined. The new PI coefficients, calculated in these ways, are implemented in controller to demonstrate the improvement of convergence speed, reduction of error, the overshoot in capacitor voltage and other circuit parameters. The results are compared with trial and error method.

2. Configuration of DSTATCOM

In this paper, a simplified DSTATCOM configuration is considered. It is shown in Fig. (1). It consists of a voltage inverter, a capacitor C and an inductance L and a resistor R_s on the AC side, L represents the leakage inductance of the transformer and the line, R_s represents the inverter and transformer conduction losses. The line voltages are called V_a, V_b, V_c , E_a, E_b, E_c are the inverter output voltages and V_{dc} is the DC voltage. The angular velocity of the AC voltage and current vectors is equal to ω .

Let us consider a system of reference (d, q) rotating at the same speed, and let us note α is the angle between d axis and line voltage vector E. The system equations are [9],

$$\begin{bmatrix} \frac{dI_d}{dt} \\ \frac{dI_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & -\omega \\ \omega & -\frac{R_S}{L_S} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \frac{1}{L_S} (V_{dq} - E_{dq}) \quad (1)$$

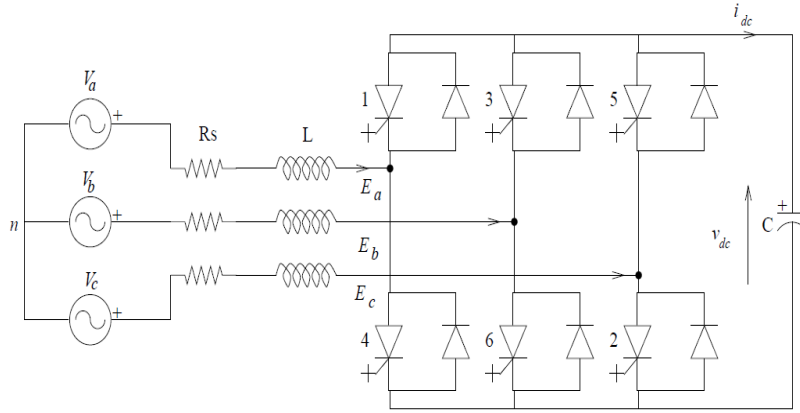


Fig (1): The representation of DSTATCOM

The model of the AC side in this system of reference is given by equation (1),
The powers are expressed by equation (2)

$$P = \frac{3}{2}(E_d I_d + E_q I_q), \quad Q = \frac{3}{2}(E_d I_q - E_q I_d) \quad (2)$$

If α is chosen by zero, the E_q voltage is equal to zero and the reactive power becomes proportional to $E_d I_q$. To control the reactive power Q , it is sufficient to control I_q

$$E_q = 0, Q = \frac{3}{2} E_d I_q \quad (3)$$

By writing the equation (2) for capacitor voltage and substituting equation (4) in it third equation is added to equation (1)

$$P = V_{dc} C \frac{dv_{dc}}{dt} \quad (4)$$

By applying the average model used for control only fundamental harmonic of inverter output voltage is considered. The influence of all other harmonics is ignored. The control variable is δ the firing angle with reference to the network voltage E_j zero crossing. In this case, this model is used for simulation purpose, but not to choose and tune the controller. A generalized Averaging method [8] is used to get a continuous time invariant model of the converter.

The averaged equations are:

$$\frac{d}{dt} \begin{bmatrix} I_d \\ I_q \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & \omega & -\frac{M \cos \delta}{L_S} \\ -\omega & -\frac{R_S}{L_S} & \frac{M \sin \delta}{L_S} \\ \frac{M \cos \delta}{C} & \frac{M \sin \delta}{C} & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ V_{dc} \end{bmatrix} + \frac{1}{L_S} \begin{bmatrix} V_S \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

3. Non linear control scheme for DSTATCOM

The nonlinear control law is based on the theory of exact linearization via feedback [12]. The system has to be described by equations (6 & 7). It is relative degree 'r' if equations (9 & 10) are verified for all X and all $K < (r-1)$. $L_f h(x)$ is called $h(x)$ derivative along 'f'; it is defined by (8).

$$\dot{x} = f(x) + \sum_{i=1}^m g_i(x) u_i \quad (6)$$

$$y_i = h_i(x) \quad (7)$$

$$L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) \quad (8)$$

$$[L_{g_1} L_f^k h_1(x) \quad L_{g_2} L_f^k h_1(x) \quad \dots \quad L_{g_m} L_f^k h_1(x)] = 0 \quad (9)$$

$$L_{g_j} L_f^{r-1} h_j(x) \neq 0 \quad (10)$$

For at least one $1 \leq j \leq m$

In DSTATCOM system, because of compensating the reactive power and eliminating the undesired internal dynamic, Q and Vdc are chosen as output control variables. Consequently, the modulation index (m) and δ are chosen as two control inputs variables. A MIMO system is obtained as follows:

$$\begin{aligned} \dot{X} &= f(x) + g_1(x)u_1 + g_2(x)u_2 = \\ &\begin{bmatrix} -\frac{R_S}{L_S}x_1 & \omega x_2 & \frac{V_S}{L_S} \\ -\omega x_1 & -\frac{R_S}{L_S}x_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} -\frac{x_2}{L_S} \\ 0 \\ -\frac{x_1}{c} \end{bmatrix} u_1 + \begin{bmatrix} 0 \\ -\frac{x_2}{L_S} \\ -\frac{x_2}{c} \end{bmatrix} u_2 \quad (11) \end{aligned}$$

$$Y = \begin{bmatrix} h_1(X) \\ h_2(X) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (12)$$

Where

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \\ V_{dc} \end{bmatrix} \quad \text{is the state vector}$$

$$U = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} M \cos \delta \\ M \sin \delta \end{bmatrix} \quad \text{is the control vector}$$

The system described by (11)-(12) has a relative degree of $r = \{1, 1\}$, and a fairly standard form. By solving the problem of reproducing a reference output, the following control law can be obtained:

$$U(t) = \begin{bmatrix} -\frac{L_S}{x_3} & 0 \\ 0 & -\frac{L_S}{x_3} \end{bmatrix} \left(\begin{bmatrix} -\frac{R_S}{L_S}x_1 + \omega x_2 + \frac{V_S}{L_S} \\ -\omega x_1 - \frac{R_S}{L_S}x_2 \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \right) = \begin{bmatrix} -\frac{L_S}{x_3} (v_1 + \frac{R_S}{L_S}x_1 + \omega x_2 - \frac{V_S}{L_S}) \\ -\frac{L_S}{x_3} (v_2 + \omega x_1 + \frac{R_S}{L_S}x_2) \end{bmatrix} \quad (13)$$

Where V_1 and V_2 are output reference. V_1, V_2 are the new inputs and Y_1, Y_2 are their corresponding outputs. Two proportional controllers are chosen to construct the new inputs (V_1 and V_2) and an external PI controller is chosen to regulate dc link voltage (All details are shown in Fig. (2)), thus the system with nonlinear control law and three controllers is described. Considering the I_q channel, the equivalent closed loop transfer function can be expressed as

$$\frac{I_q}{I_q^*} = \frac{1}{1+s/\lambda} \quad (14)$$

Where λ determines the response speed of reactive current. By substituting Eq.(13) in Eq.(11) and considering Eq.(14), the following Eq. is given

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \lambda_1(x_1^* - x_1) \\ \lambda_2(x_2^* - x_2) \end{bmatrix} \quad (15)$$

By solving this differential equation, x_i tends to its reference (x_i^*).

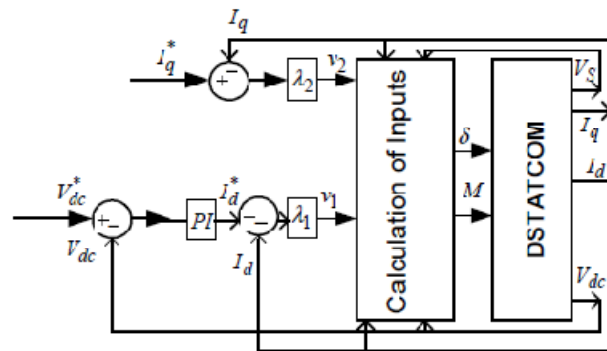


Fig (2). The detail structure of DSTATCOM controller

4. Genetic Algorithm

A genetic algorithm (GA) is a learning algorithm that imitates the evolution of organisms. In the natural evolution process of organisms, the reproduction of a set of individuals that forms a certain generation (i.e., the population) is such that those individuals with fitness to environmental adaptation survive with high probability. Reproduction that is based on the degree of conformity of an individual in a GA as an artificial model that imitates the evolution process of such an organism is performed, and the next-generation population is generated through crossover and mutation. The process is carried out by repeating such genetic operations, and if the individual of the last generation that fulfills end conditions can be found, the semi-optimal solution in question may be determined. The flow of the basic operation of the GA shown in Fig. (3) is explained below.

- 1) Initialization: individuals with random chromosomes are generated that set up the initial population.
- 2) Reproduction: the degree of conformity of each object is calculated and an individual is reproduced under a fixed Rule depending on the degree of conformity. Here, some individuals with a low degree of conformity will be screened, while individuals with a high degree of conformity will increase.
- 3) Crossover: new individuals are generated by the method of intersection that has been set up.
- 4) Mutation: this is performed by an operation determined by the installed mutation probability or mutation, and a new individual is generated.
- 5) End judging: if end conditions are fulfilled, the best individual thus obtained is the semi-optimal solution in question .Otherwise, return to 2) [17].

A. Objective Function

ITAE criterion, i.e. integral time absolute error is widely adopted to evaluate the dynamic performance of the control System [16]. The index ITAE is expressed in (16),

$$J_{ITAE} = \int_0^T t e(t) \quad (16)$$

Where the upper limit T is a finite time chosen so that the integral approaches a steady-state value and is usually chosen as the setting time T_s . For the DSTATCOM system, the adopted objective function is:

$$Q_f(Z) = \sum_i m_i f_i(Z) \quad (17)$$

where

$$f_i(Z) = \sum_j \omega_j \int_0^T t |e_j(t)| \quad (18)$$

f_i is a performance index corresponding to the No. i objective. m_i is a weighted factor corresponding to the objective. $E_j(t)$ is the error between the real value of the No. j controlled variable and its desired value. w_j is the weighted factor corresponding to the No. j controlled variable. Vector $z=[z_1, z_2, \dots, z_n]$ is the control system parameters, i.e. PI parameters. For the DSTATCOM objective function, the objective function deduced by (16) is expressed in:

$$Q_f(Z) = 1000 \left(\int_0^T t |V_{dc}(t) - V_{dcREF}| + t |I_d(t)| \right) \quad (19)$$

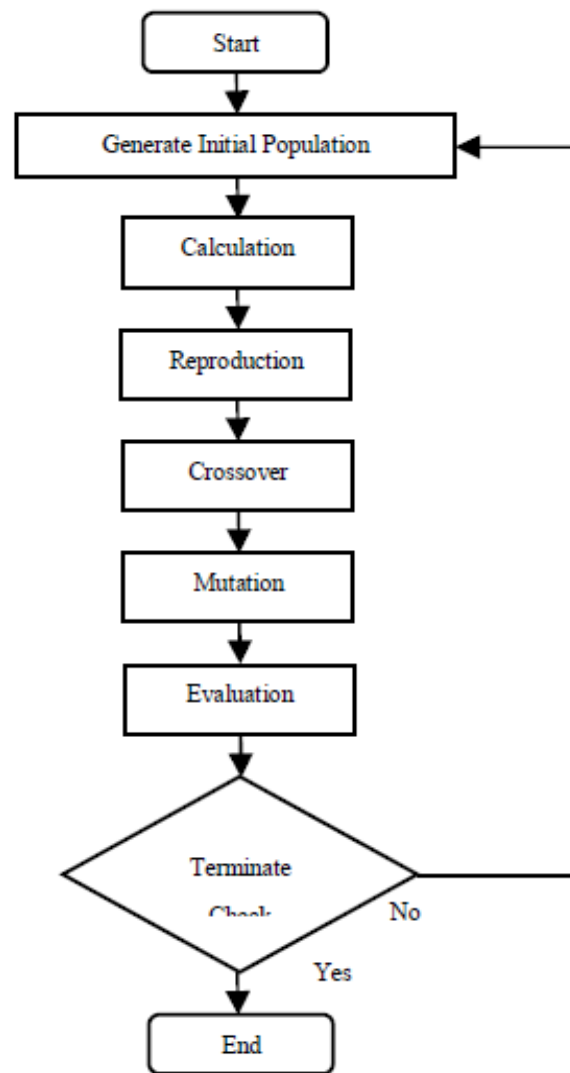


Fig (3). Flowchart of algorithm

$$Q_f(Z) = f(Z) = 1000 \int_0^T t |V_{dc}(t) - V_{dcREF}| \quad (20)$$

$$Z = [K_P \quad K_I]$$

The Eq. (19) is used when the goal is controlling the V_{dc} and I_d . Instead, the Eq. (20) is used when V_{dc} is individually regulated.

5. Simulation Results

The case study parameters of distribution system and DSTATCOM are as follows: $C=4900$ (μF), $F=50$ Hz, $R_s=.28$ (Ω), $L= 0.0013$ (H), $V_a=110_{\text{rms}}$ (L-L) (V), $V_{dc}=200$ (V), Initial voltage= 200v the reference I_q has a step change from zero to 15A at $t=0.02\text{s}$. λ_1 and λ_2 are selected equal to 1000. First of all, the effect of PI gains on voltage regulation is shown in following figures by offering unsuitable PI gains. Then PI gains, computed through trial and error method, are compared with ones computed by GA to study the operation of DSTATCOM. Randomly, zero and ten are selected for K_p and K_I , respectively.

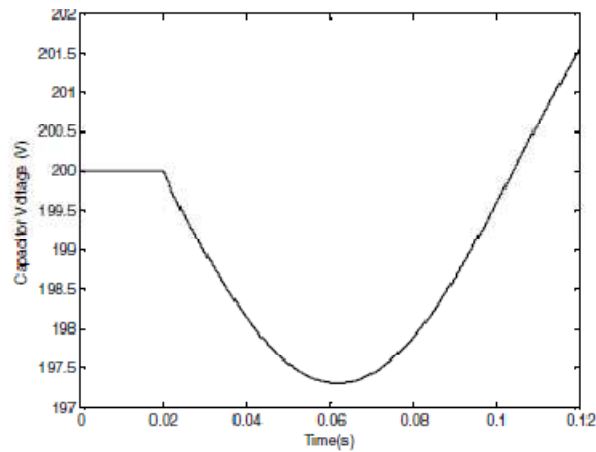


Fig.(4). shows the voltage response of capacitor.

These values cause divergence of DC voltage from steady state quantity. Fig. 5 shows the I_d response.

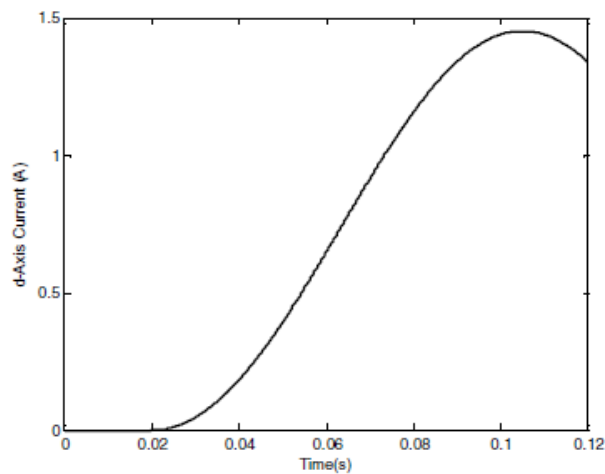


Fig (5). The d-axis current response to first random PI gains

It is obvious that these values are improper for controlling the DSTATCOM and consequently, PI coefficients cannot be determined randomly. The normal solution for determination of PI gains is trial and error method. Many pairs should be tested. Best of them are selected. Some benchmarks such as Steady state error and fluctuations are effective in choosing PI gains. Every one may select a unit pair and there is no guaranty for them. Here, a set of forty pairs are studied and finally PI gains are given as $K_p=1$ and $K_I=70$. Due to being certain of optimized PI gains, GA as a powerful, famous and applicable method is applied. The numbers of generation and iteration are 1000 and 500 respectively. The objective function is defined as two types. The first one focuses on capacitor voltage to regulate it independently and the second type according to the fluctuations of I_d and M attempts to insert I_d into objective function. So, both I_d and V_{dc} are regulated in a same weighted factor. The run time in a normal personal computer is about ten minutes. Since, the calculations are offline, the time of run is not important. The first type of objective function leads to $K_p=617.9668$ and $K_I=39.1076$ and the second type of objective function leads to $K_p=1.7748$ and $K_I=150$. The above three obtained PI coefficients are implemented to DSTATCOM. The corresponding time domain simulation plots for some variables including V_{dc} , I_d , M and δ are compared in figures (6-9). As it is shown in Fig. 6, the best regulation of V_{dc} is carried out by GA with double-objective function. The overshoot is very small and voltage is fixed on 200v. The presence of high frequency fluctuations causes M and I_d to reach to their corresponding nominal values with high frequency fluctuations (the red color of Figs. 7 and 9). Thus, if the objective is controlling the V_{dc} only, this method is very effective and should be chosen, but if the objective is to reduce oscillations in addition to voltage regulation, the double-objective function has to be chosen. The results of implementing double-objective function are shown with black color in Figs. (6-9). It completely removes high frequency oscillations from I_d and M responses but as it is predicted, the dynamic characteristics of V_{dc} become poorer than single-objective function status. However, double-objective function technique is the preferred option rather than trial and error method because the overshoot and rise time of the system decrease. All methods have a nearly same δ and I_q responses (Figs. 8 and 10).

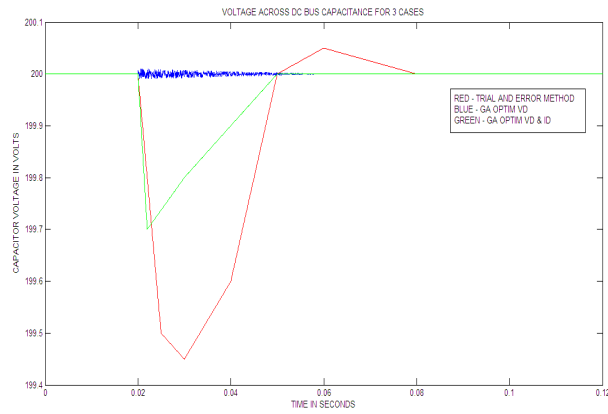


Fig (6). The capacitor voltage responses to three pairs of PI gains

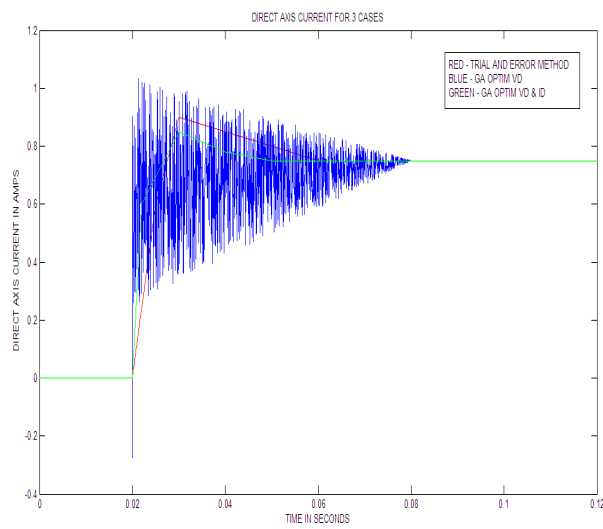


Fig (7). The d-axis current responses to three pairs of PI gains

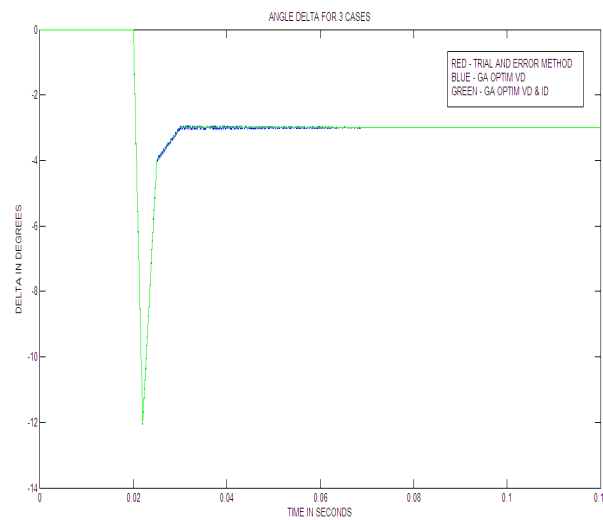


Fig (8). The phase difference responses to three pairs of PI gains

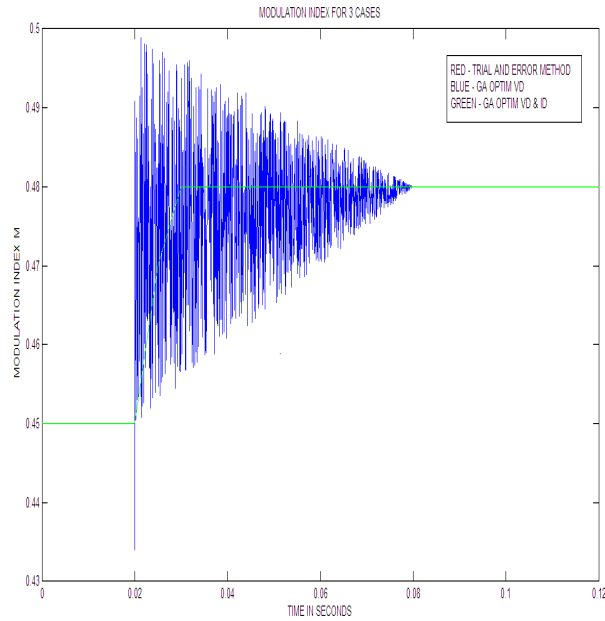


Fig (9). The Modulation Index responses to three pairs of PI gains

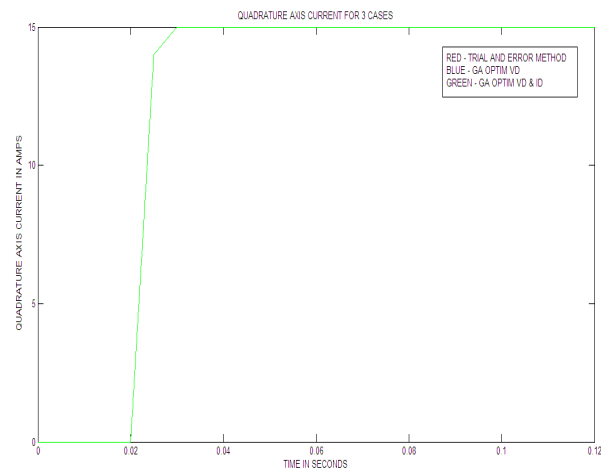


Fig (10). The q-axis current responses to three pairs of PI gains

6. Conclusions

The nonlinear control method of the DSTATCOM which is based on the exact linearization via feedback uses one proportional–integral controller. The PI values have a remarkable influence on responses of system variables such as line current, Modulation Index and DC link voltage. Normal way to calculate these coefficients is using trial and error method. In this paper, Genetic Algorithm with two types of objective function is suggested. This method leads to a better regulation of DC link voltage, d and q axis currents and other circuit parameters. Actually, the time of reaching to steady state value, the fluctuations and overshoot decrease.

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