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The Control Based on the Genetic Algorithm for Nonlinear SVC Systems

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Abstract— **This study presents a sliding mode control and genetic algorithm based sliding mode control of a system with two-bus. The proposed algorithm uses either the coefficients which have been calculated in terms of stability for sliding mode control or the coefficients in the genetic algorithm based sliding mode control which have been calculated by considering stability and optimization. In order to solve the chattering problem of the sliding mode, a solution was offered by obtaining the fast fourier transform of the switching signal and frequency spectrum distribution. Simulation results showed that sliding mode control based on genetic algorithm performs better response than sliding mode control in terms of accuracy.**

Index Terms— **Chattering, Genetic Algorithm, Fast Fourier Transform, Stability, Static Var Compensator.**

I. INTRODUCTION

The transmission lines including SVC (static var compensator), have a nonlinear behavior. However, the control of nonlinear systems is implemented by either linearizing nonlinear systems or using one of the nonlinear control techniques. Sliding mode control is one of the nonlinear control techniques which is used for the different systems. The main reason for this popularity is the attractive properties that sliding mode control (SMC) has, such as good control performance for nonlinear systems, applicability to multiple-input–multiple-output (MIMO) systems, and well-established design criteria for discrete-time systems [1]. Sliding mode control has been widely studied in recent years and has been playing an important role in the application of control theory to practical problems [2]. For example: Automotive, transmissions, engines, power systems [3], induction generators [4], robots [5]-[6], electric drives [7]-[8], multi machine power systems [9], and elevator velocity [10]-[11].

The SMC method has some advantages such as robustness to parameter uncertainty, insensitivity to bounded disturbances, fast dynamic response, a remarkable computational simplicity with respect to other robust control approaches, and easy implementation of the controller [12]-[15].

An ideal sliding mode controller has a discontinuous switching function and it is assumed that the control signal can be switched from one value to another infinitely fast [3, 16]. Due to imperfect switching in practice it raises the issue of chattering [11].

The chattering phenomenon is generally perceived as motion which oscillates about the sliding manifold. There are two possible mechanisms which produce such a motion. First, in the absence of switching non-idealities such as delays, i.e., the switching device is switching ideally at an infinite frequency; the presence of parasitic dynamics in series with the plant causes a small amplitude high-frequency oscillation to appear in the neighborhood of the sliding manifold. The interactions between the parasitic dynamics and VSC generate a non-decaying oscillatory component of finite amplitude and frequency, and this is generically referred to as chattering [17].

Instead of a discontinuous switching function, continuous functions have been used to avoid the chattering of the control and to achieve the exponential stability such as saturation functions, sigmoid functions, relay functions, hyperbolic functions, and hysteresis-saturation functions [11], [18-21]. Sliding mode has two phases as reachability and sliding phases. In order to perform these phases, a reachability function must be selected by considering Lyapunov rule and a sliding surface must be selected. The coefficients that will have been used in these phases, should be selected to provide stability and to get minimal error. The Lyapunov rule has been used for stability and genetic algorithm (GA) has been used for optimization.

As a different technique from analytic optimization technique; Genetic Algorithm, is an optimization technique which could be used to get the extremum points of cost function. The parameters of cost function are coded as binary strings and after that these binary strings are called chromosome. The chromosomes pass some genetic processes such as population, reproduction, selection, crossing-over and mutation. The chromosomes which pass these processes produce new chromosomes. Each chromosome has a fitness value according to cost function. All the GA processes run until it obtains an adequate fitness value. The chromosome which has the adequate fitness value, gets the optimum performance parameters.

In this study, a SMC and genetic algorithm based sliding mode control (GASMC) based controller design has been implemented for a nonlinear system included two-bus with SVC. Simulation results showed that GASMC method performs better results than SMC method in terms of accuracy.

II. SYSTEM MODEL

A. Plant model

We construct a model for the generator and an SVC system that can be described by a two-bus system, shown in Figure 1. This model can be considered as a generalized case where the SVC is located at the end-point of a transmission line. The control rules developed for SVC based on this system are valid for both single-machine power systems.

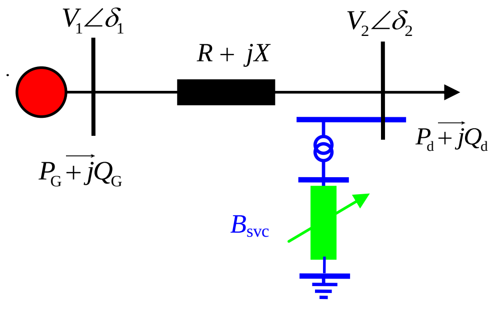


Fig.1 The two-bus SVC system [22]

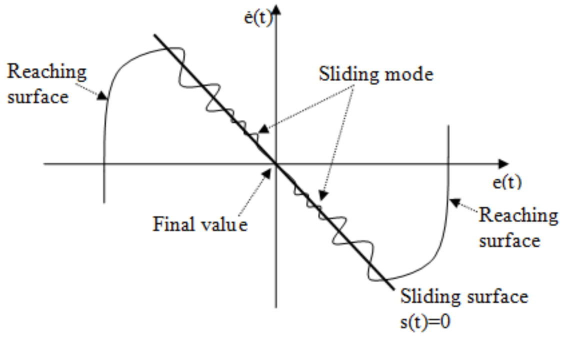


Fig. 2 Graphical illustration of sliding mode control

The system model for excitation control design and stability analysis is usually that of a single generator infinite-bus system. In this model, $\delta(t)$ is the power angle of the generator; $\omega(t)$ is the rotor speed of the generator; P_m, mechanical input power; $P_e(t)$, active electrical power delivered by the generator; D_G, damping constant; M, inertia constant; X, reactance of the transmission line constant, respectively.

The steady state load demand is modeled through the parameter P_d, under the assumption that reactive power load demand is directly proportional to the active power demand, i.e, $Q_d = kP_d$; this parameter is used here to carry out the voltage collapse studies. SVC operated capacitive mode figures out compensation effect for power system stability. In order to simplify the stability analysis, resistance and line susceptance are neglected (R=0, B_L=0), $P_m = P_d$ [22]. P_d is assumed to vary between 0.6 and 1.3 pu.

The model can be written as follows:

$$\left.\begin{aligned}
&\dot{\delta}(t) = \omega(t)\\
&\dot{\omega}(t) = \frac{1}{M}\left(P_m - \frac{V_1V_2\sin\delta}{X} - D_G\omega\right)\\
&\dot{V}_2 = \frac{1}{\tau}\left(-v_2^2\left(\frac{1}{X} - B_{svc}\right) + \frac{V_1V_2\cos\delta}{X} - kP_d\right)\\
&M = 1, X = 0.5, V_1 = 1, \tau = 8, k = 0.25, D_G = 0.1
\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}
&x_1 = \delta, x_2 = \omega, x_3 = V_2, B_{svc} = u,\\
&\dot{x}_1 = \omega = x_2,\ \dot{x}_2 = \dot{\omega},\ x_3 = V_2\\
&y(t) = V_2 = x_3
\end{aligned}\right\}$$

III. 3. Sliding Mode Control

The major steps in the design of a sliding mode controller are (i) to construct a switching surface that represents a desired system dynamics, and (ii) to develop a switching control law such that a sliding mode exists on every point of the switching surface, and any states outside the surface is driven to reach the surface in finite time [23]. The control laws of SMC consist of two separate parts. The first part is responsible for conducting the state trajectory to the sliding surface. The second part makes the system output convergent to the desirable output, based on the desired dynamics [24].

Therefore it is required that the sliding surface is stable, which means $\lim_{t\to\infty} e(t)=0$; then the error will die out asymptotically. This implies that the system dynamics will track the desired trajectory asymptotically [3].

The first step in designing the SMC is to define an appropriate sliding surface in the state space. This sliding surface, which is called the switching function, is considered as follows:

$$s(t) = \left(\lambda + \frac{d}{dt}\right)^{(n-1)} \tilde{x}(t) \quad (2)$$

where n is the order of uncontrolled system, $\tilde{x}(t)$ is the error state vector, and λ is a positive coefficient in real number cluster [24]. The second step is to determine the control law for conducting the system to the selected sliding surface. In this method, the control law always consists of two parts, the equivalent control u_{eq}(t) and switching control u_{sw}(t), shown in this equation:

$$u(t) = u_{eq}(t) + u_{sw}(t) \quad (3)$$

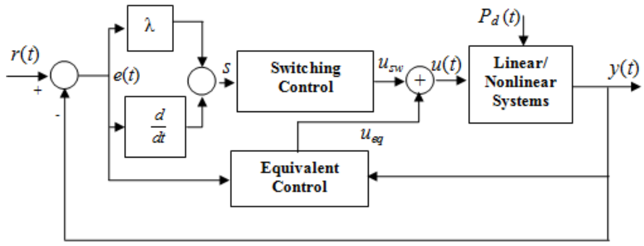


Fig. 3 Block diagram of sliding mode control

The error $e(t)$ can be defined in terms of physical plant parameters as,

$$e(t) = r(t) - y(t) = x_{3ref}(t) - x_3(t) \quad (4)$$

where x_{3ref}(t) is the reference signal and x_3(t) is the measured output signal.

It is known that the crucial and the most important step of SMC design is the construction of the sliding surface s(t) which is expected to response desired control specifications and performance. The trajectories are enforced to lie on the sliding surfaces [24]. If the Eq. (5) is selected, the Eq. (6) is obtained.

$$s = \dot{e} + \lambda e \quad (5)$$

$$\left.\begin{aligned} e &= x_{3ref} - x_3, \\ \dot{e} &= \dot{x}_{3ref} - \dot{x}_3, \\ e &= \ddot{x}_{3ref} - \ddot{x}_3, \\ x_{3ref} &= \text{constant},, \\ \dot{x}_{3ref} &= \ddot{x}_{3ref} = 0 \end{aligned}\right\} \tag{6}$$

$$\dot{s} = -\rho\, sign(s) - K\, s \tag{7}$$

When the fixed-proportional varying is selected, the following equations is obtained:

$$\left.\begin{aligned} &\dot{s} = \ddot{e} + \lambda\dot{e} = \\ &\ddot{x}_{3ref} - \ddot{x}_3 + \lambda(\dot{x}_{3ref} - \dot{x}_3) = -\rho\, sign(s) - K\, s \end{aligned}\right\} \tag{8}$$

$$\dot{x}_3 = 0.25x_3\cos x_1 - 0.25x_3^2 + 0.125x_3^2u - 0.03125P_d$$

Here, the derivative of disturbance and control signal is considered as zero. The changing of the derivate of disturbance and the changing of the control signal were assumed to be slowly. That's why the derivatives of them were assumed to be zero. Because of the fact that x_2 is closed to zero, the following equations can be written for $u(t)$:

$$u(t) = \frac{(0.25x_3\cos x_1 + \lambda)(x_3^2 - x_3\cos x_1 + 0.125P_d)}{x_3 + (0.25\cos x_1 + \lambda)\, 0.5\, x_3^2} + \frac{\rho\, sign(s) + K\, s}{x_3 + (0.25\cos x_1 + \lambda)\, 0.5\, x_3^2} \tag{9}$$

Lyapunov stability analysis is the most popular approach to prove and to evaluate the stable convergence property of nonlinear controllers, e.g., sliding mode control [18]. The following equations can be written for stability analysis.

$$s\,\dot{s} = s(-\rho\, sign(s) - K\, s) < 0$$

$$\rho > K\left(\frac{-(0.25x_3\cos x_1 - 0.25x_3^2 + 0.125x_3^2u)}{sign(s)} + \frac{(-0.03125P_d + \lambda(x_{3ref} - x_3))}{sign(s)}\right) \tag{10}$$

IV. Genetic Algorithm

Genetic Algorithms (GA's) are global search method which imitates the evolution of the nature or natural selection [25]. Its mechanism is neither governed by the using of differential equations nor does it behave like a continuous function. It has the ability to search and optimize a solution for a complex problem where other mathematical techniques may be unsuccessful [26]. A GA begins without any knowledge of the solution and the correct solution is relevant to responses its environment and GA operators.

All living organisms consist of cells. Each cell contains chromosomes. A chromosome can be examined as combined structure of some genes each of which encodes a trait of organism. Each gene is located as a part of a chromosome and each chromosome consist of nucleotides. In genetic algorithms, the term chromosomes refer to candidate solutions to a problem and consist of binary strings. The genes are either single bits or short blocks of adjacent bits which encode a particular element of the candidate solution [27]. The encoded particular elements are concatenated in order to compose a large string. The final string consist of *n* concatenated substring, which is one member of a population and it is given as follow:

1 0 1 1 1 0 0 0 | 0 1 0 1 1 0 1 0 | 1 1 0 1 0 1 0 0
parameter 1 parameter 2 parameter 3

Genetic algorithms involves three basic operations: selection, crossover, mutation. These operators provide the GA with powerful searching ability. The general concept of GA is that a collection of potential solutions to a problem is created by taking random numbers from a chosen distribution and then using operators to produce new potential solutions. Some basic concepts of GA are as following [28]-[30]:

Search space: The term search space refers to some collection of candidate solutions to a optimization problem and some assumption of distance among candidate solutions.

Population size: This is the free parameter which determines the individual number of the population.

Selection: Selection operator selects individuals from the current population to generate mating pool. GA use principle of natural selection, survival of the fittest in order to select individuals. Selection compares the fitness of one individual in relation to other individuals and decides which individual live on the next population. The selected chromosomes are parents. Selection operator also chooses the chromosomes which will be eliminated from the current population in order to replace new offsprings instead of eliminated chromosomes. There are several types of selection, including random, best, roulette, tournament and top percent. Roulette wheel mechanism is the most usable selection technique.

Crossover: Crossover operation is the most important feature in evolutionary computation because of its all ability to reproduce new offsprings for the next generation. It provides to generate new phenotypes around between the values of the parents' phenotypes by exchanging parts of their genetic material between individuals of a population. Two individuals are selected and crossed. The resulting offspring replaces the parents in the new population. The most popular crossover operation types are one-point, two-point, blending and uniform.

Parent 101|00110011|000011010111010000111

Parent 101011111111|10001000|010111110010

Child 1 10110001000000011010111010000111

Child 2 10101111111100110011010111110010

Mutation: For the mutation operation, an arbitrary bit in a genetic sequence is changed with a mutation probability. The mutation process effects a random variation upon the gene of an individual. A mutation is occurred with the mutation-probability Pm, which is defined before the optimization. Mutation operator alters the chromosome structure and physical properties.

Chromosome
10110001000000011010111010000011

Mutant chromosome
101**011101111**000011010111010000111

Mutation prevents the algorithm to be snared in a local minima and keep diversity in the population.

Cost function: This is the main evolution function based on which the fitness of each individual of the new generation is determined. The individuals which are identified as "fit" survive, put into a mating pool and reproduce a new generation.

The cost function of the system with sliding mode controller is made of error function. In order to solve the sliding mode controller design problem, the cost function is provided to be minimized. When it is minimized, the parameters converges the optimum.

Fitness value: In GA, each member of population represents a point in the GA search space. In each generation, relatively good members reproduce, while relatively bad members don't survive. The fitness of a member serves to distinguish between relatively good and bad members. The members which will be kept their existence in the population are determined by fitness value. Fitness function is a standard used to evaluate the performance of each chromosome.

Stop criterion: The stop criterion may be set as the maximum number of generations fixed by user, or maximum time to be expended for algorithm and etc. simply by trial and error method based on approaching of process of sliding mode parameters. The stop criterion brings on the GA process termination and the obtaining of optimum parameters according to population size.

A. How to GA works

In the beginning, GA generates an initial, random population of members for a predefined size. Some parameters are supposed to be fixed just like population size M, genetic evolution generation N, cross-probability P_c and mutation-probability P_m in initializing. Each chromosome is a candidate solution to the problem. The fitness value of each individual is calculated via through the fitness function. The stop criterion is checked whether it is happened or not. If not, based on the fitness of each individual, a group of the fittest chromosomes is selected via the selection mechanism. Then, the genetic operators, crossover and mutation, are implemented to this surviving population in order to promote the next generation solution. The process keeps going on till the cost function converges minimum or another stop criterion is happened [31].

B. Optimization of the SMC parameter

A genetic algorithm has been used in this study so that the sliding mode parameters in the control input, λ, ρ and K could be adjusted optimally. The block diagram of the sliding mode control system is shown in Figure 5. Before initiate genetic algorithm to the sliding mode control system, the cost function has to be formulated. The cost function is as below:

$$J(\lambda,\rho,K)=\sum_{k=0}^{W}\left[e(k)\right]^2=\sum_{k=0}^{W}\left[I(k)-O(k)\right]^2 \qquad (11)$$

Where $I(k)$ and $O(k)$ are the digitized reference input and output values of the system with controller, respectively. The objective is to minimize Eq. (11). It may be stressed that this cost model introduces a multimodel error surface which is assumed impossible for the application of traditional gradient methods. In the error search space, where the cost function is minimum the SMC parameters are optimum. GA guarantees that cost function is globally optimized in spite of its complexity. It allows to find the optimum point in the search space [32].

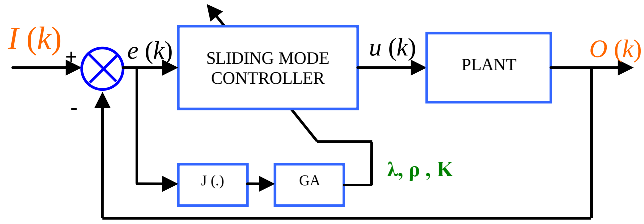
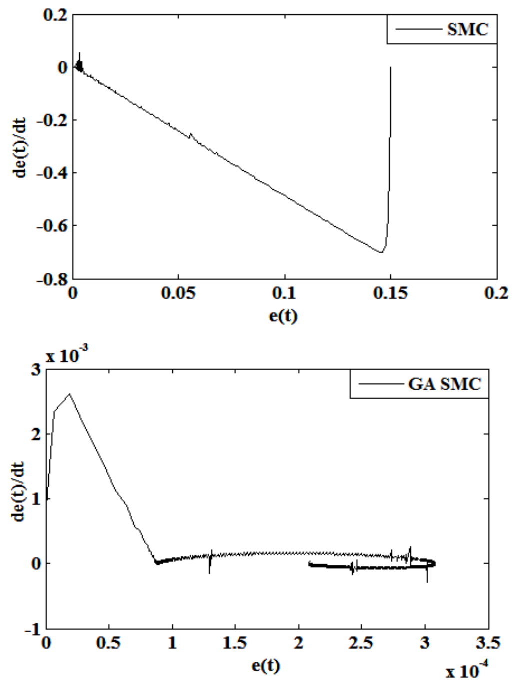


Fig. 4 SMC parameter optimization diagram [33]

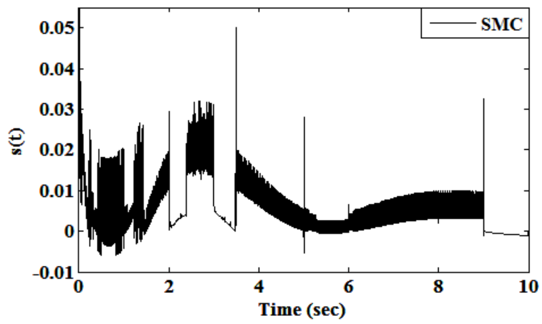
The parameters about GA are: Population size is 50, genetic evolutional generation is 200, crossover function is scattered and mutation function is gauss. The initial values of parameters (lambda, rho and K) were assumed to be [0, 0, 0]. And the limit of the parameters (lambda, rho and K) were assumed to be as [0 100], [0 100] and [0 100], respectively. The parameters has been obtained as $\lambda = 34$, $\rho = 12$ and $K = 61$ by using these GA parameters [33].

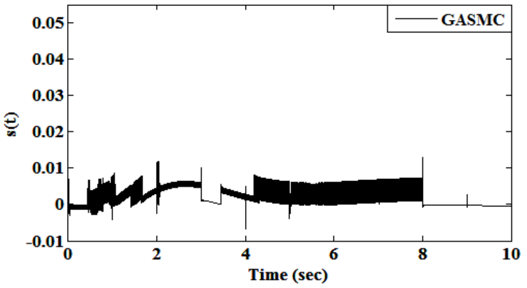
V. Simulation Results

SMC and GASMC simulation results have been obtained by using the Matlab/Simulink.



(a)





(b)

Fig. 5 Phase plane and variation of the sliding surface s(t) during the control of SMC and GASMC. (a) Phase plane (b) Variation of the sliding surface s(t)

From the phase plane of SMC and GASMC in the Figure 5.(a), it is obvious that GASMC has got reach the sliding phase with faster and small amplitude. From Figure 5(b)., it is obvious that the amplitude of the vibration of the sliding surface which has been obtained for SMC method, is bigger than GASMC's.

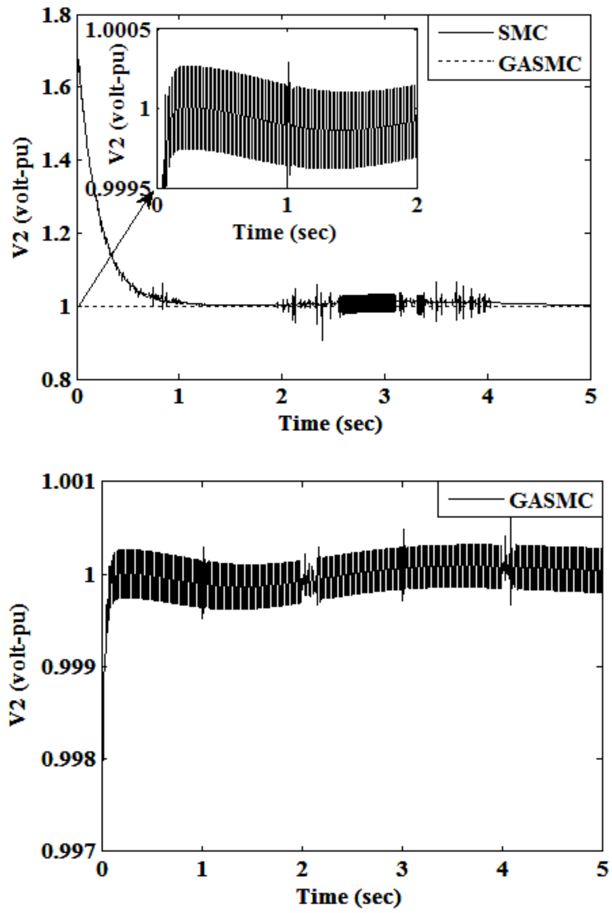
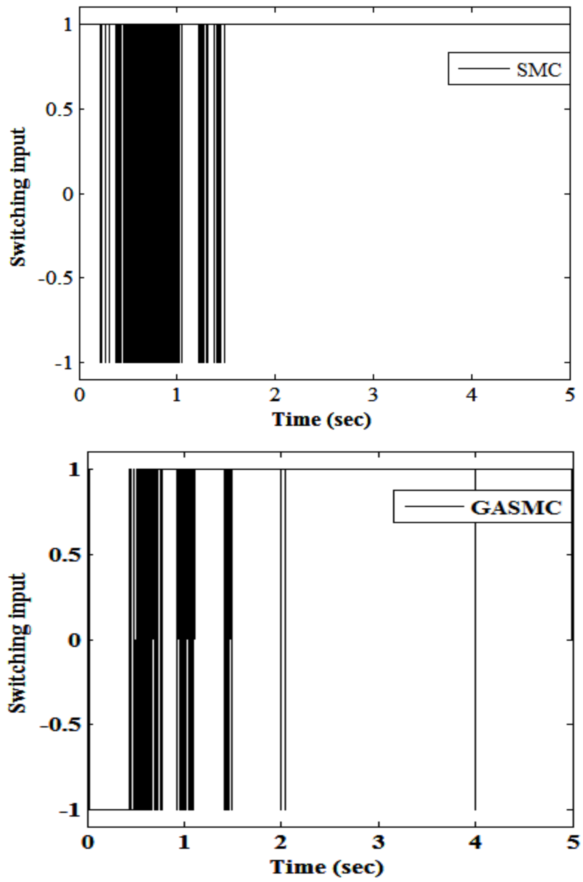
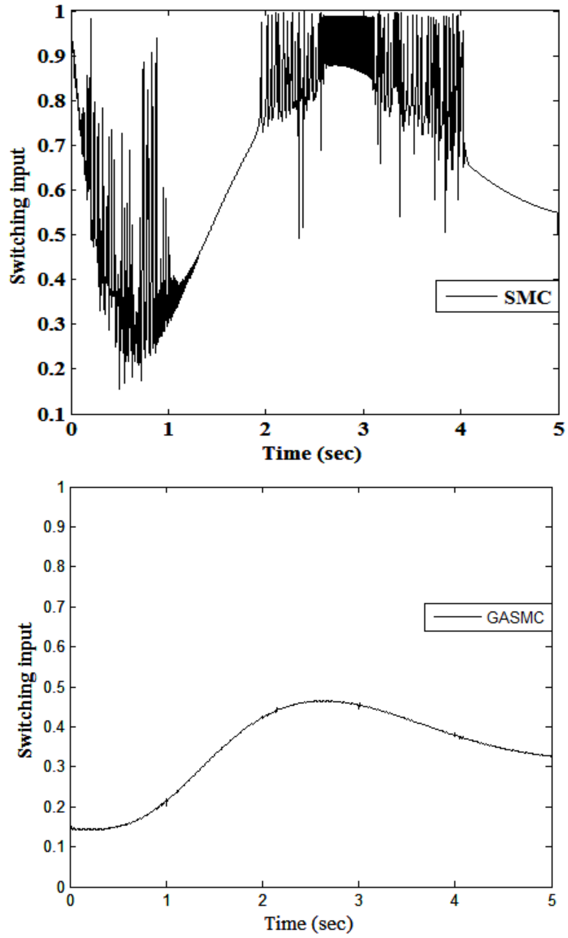


Fig. 6 Output voltage of SMC and GASMC

In the Figure 6, the simulation results is given for the reference point of the V_2 output voltage. In the SMC method, V_2 voltage caught 1.0 pu in 1 second from 1.7 pu and a response curve with vibration and with high error, has been obtained. In the GASMC method, a response curve with low error and with minimum vibration (%0.01), has been obtained. From the Figure 7., it shows that vibration amplitude of the sliding phase in the SMC method, is higher than GASMC's.



(a)

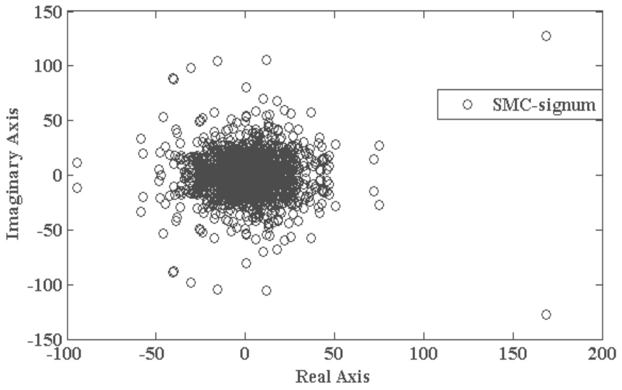


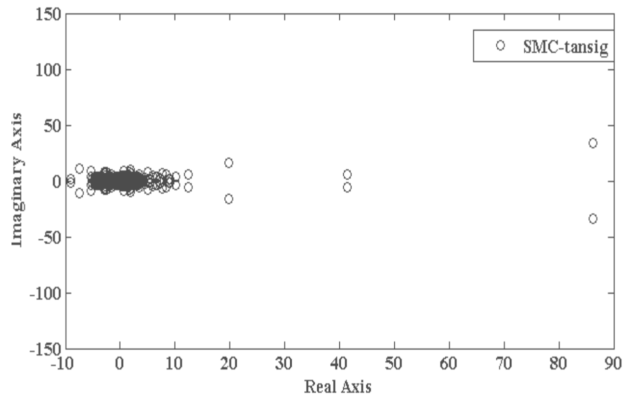
(b)

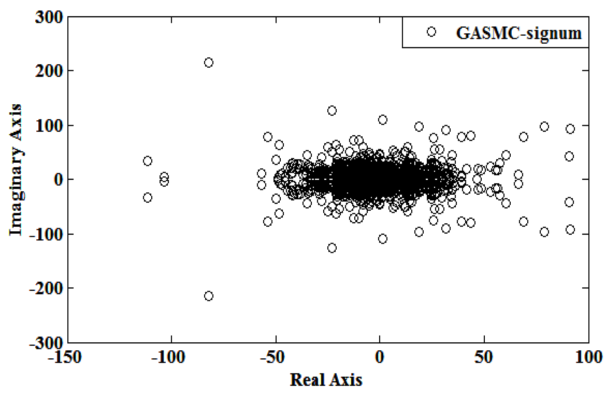
Fig. 7 Switching input $u_{sw}(t)$ of the SMC and GASMC systems. (a) for sign(.) function, (b) for Tansig(.) function

In the Figure (7)., for the SMC and GASMC methods, the Usw(f) switching input curves for sign(.) and tansign(.) functions, is given separately. The same optimization was used for tansig and sign functions. It is obvious that usage of tansig(.) function decreases the amplitude and the frequency of the input signal. The fast fourier transform (FFT) of the signal is obtained in order to examine this improvement in the frequency plane. The Fourier coefficients which are obtained for SMC and GASMC methods, are given in Figure (8) and the frequency response is given in Figure (9).

From Figure (8), because of the fact that the imaginer root distribution of the Fourier coefficients which is obtained for signum(.), is high, the vibrations are with noise and the Fourier coefficients which are obtained by harmonics for tansig(.), bunches along with in the left s semi-plane. When the tansig(.) function is used in the structure of the SMC and the GASMC, the signal which has the effective frequency around 250 Hz which its noise harmonics are pressed, has been obtained in the Figure (9). When the amplitude of the signals is 10^4 in the SMC method, it's $2x10^2$ in the GASMC method.







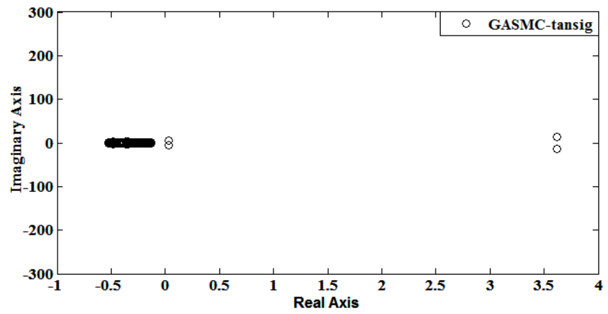
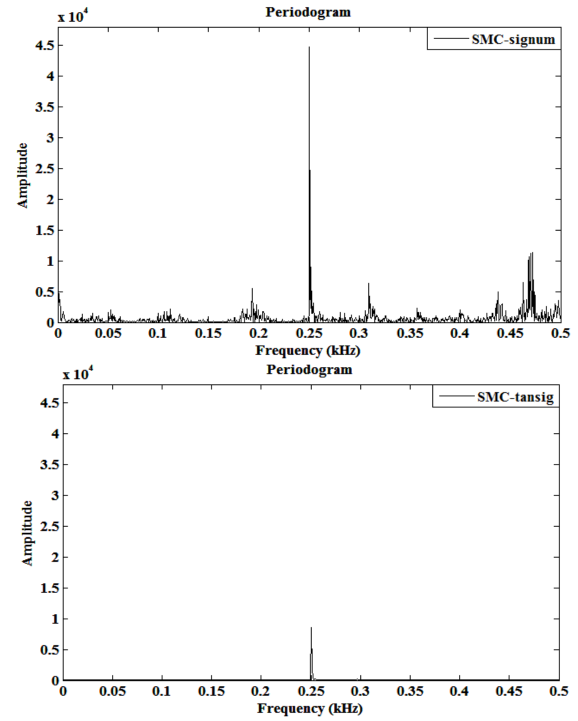
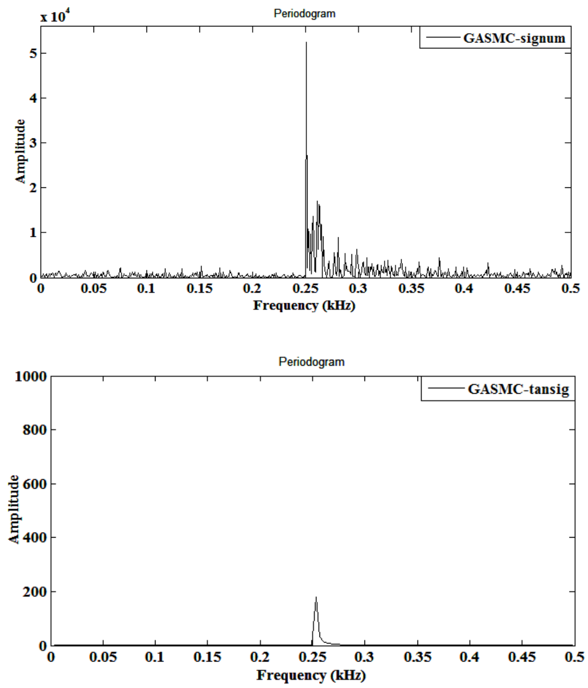


Fig. 8 Fourier coefficients in complex plane for SMC and GASMC control



(a)



(b)

Fig. 9 Frequency domain display for SMC and GASMC control (a) SMC control (b) GASMC control

From the curves in the Figure (10), it is obvious, the V_2 output voltage obtained by GASMC method, follows the reference input with the less error and without vibration according to SMC method.

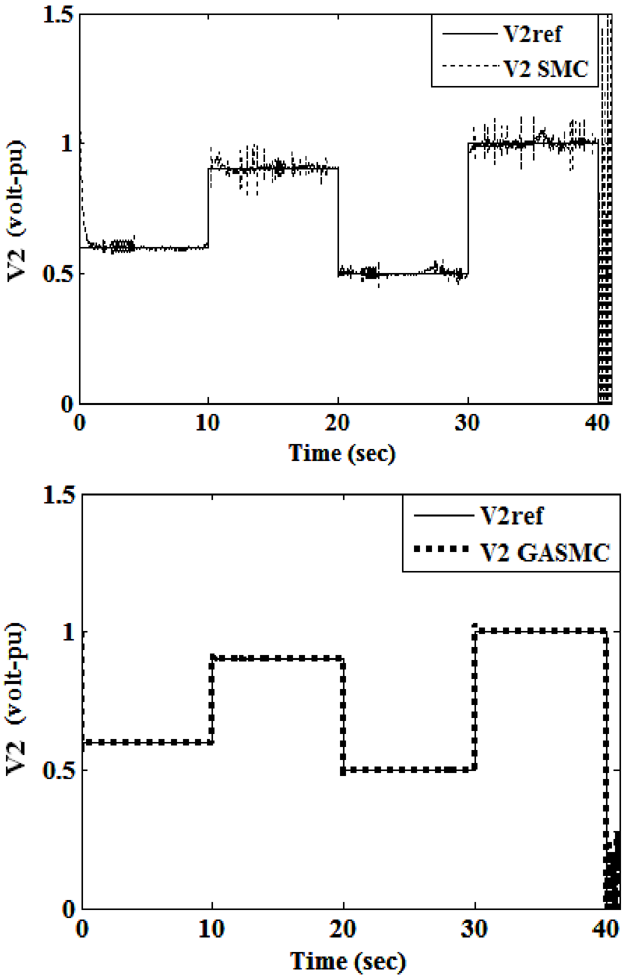
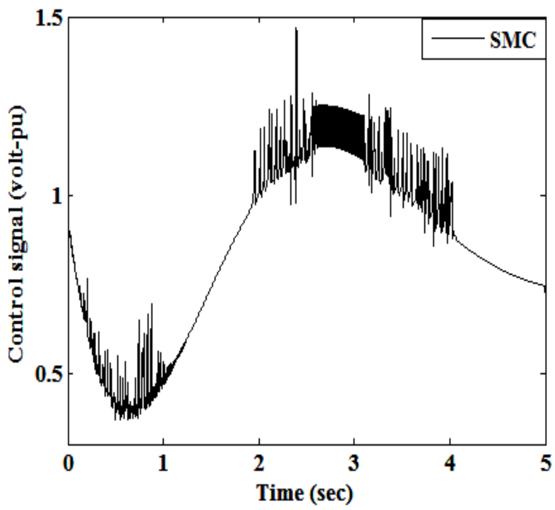
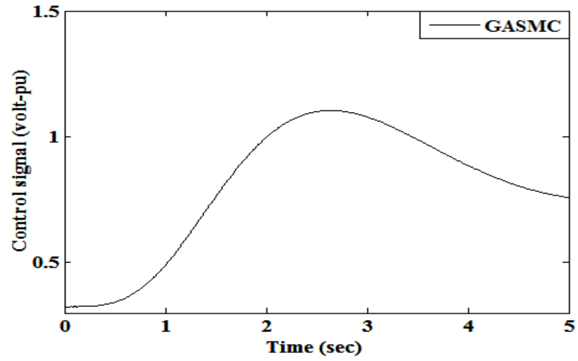


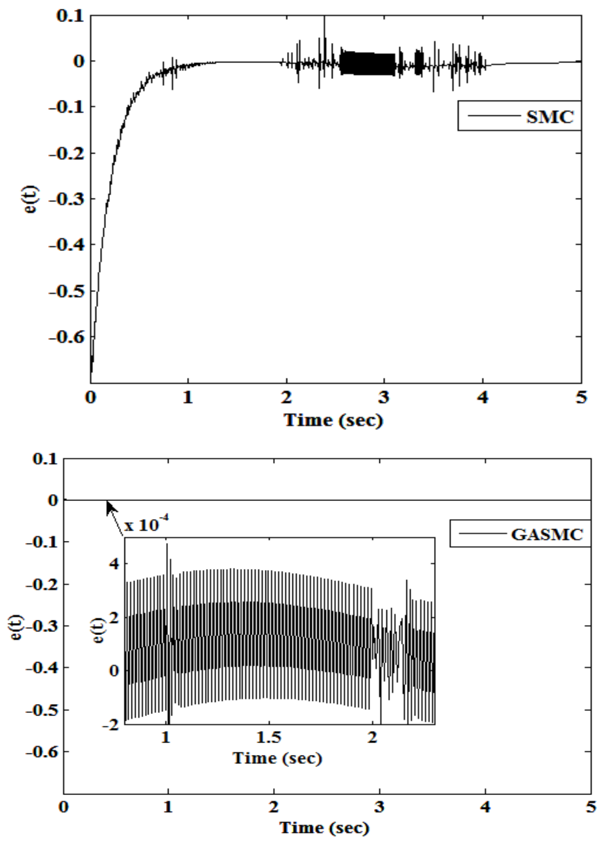
Fig. 10 Reference tracking with SMC and GASMC controller

According to time variation, curves of the control and error signal for the SMC and GASMC are given in Figure (11). It is shown from figures, the control signal of the GASMC has rather narrow variation distance.





(a)



(b)

Fig. 11 Control effort and Voltage error for SMC and GASMC (a) Control effort, (b) Voltage error

VI. Conclusion

In this study, the sliding mode control of a nonlinear system with SVC which its parameters are optimized by GA, has been implemented. It is shown in the simulation results that the output follows the input with a demanded error. Besides, the sliding surface variation has a rather narrow distance. The proposed GA based sliding mode control technique performed that it can carry the output voltage to a demanded reference level. The usage of the tansig function instead of signum function shows good performance at eliminating chattering problem and noise.

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