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Genetic Algorithm Based Optimization of Space Vector Modulation Employed in STATCOM to Reduce Harmonics in Power System

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Abstract: Existing of nonlinear loads and harmonic generation in electric power systems makes it prevalent to use harmonic filters. STATCOM plays an important role in eliminating harmonics and fixing the voltage using power electronics switches. Various control methods have been introduced for switching in a STATCOM. In this paper the Space Vector Modulation (SVM) is described and it is optimized by Genetic Algorithm (GA) to reduce the harmonic contents. At last, some simulations of power system with STATCOM have been done in MATLAB to prove the efficiency of the proposed switching method employed in a STATCOM. Results including voltage weighted THD show the proper performance of STATCOM using optimized SVM by GA.

Key words: FACTS, genetic algorithm, harmonic, STATCOM, SVM, WTHD

INTRODUCTION

Widely use of nonlinear loads that are mainly power electronics devices (e.g., Adjustable Speed Drive, rectifiers, uninterruptible power supply and switch mode power supply) make the power system faces serious problems (Peng, 2001). These loads not only increase the harmonic content of the network, but also increase the losses of lines and transformers, significantly as well as raising the amount of reactive power and resonance (Emadi *et al*., 2005; Mohan, 2003; Rashid, 2001).

In recent decades, employing FACTS controllers has been effective to overcome such problems (Tan and Wang, 2003). For instance, SVC is a static reactive power compensator, although, STATCOM is more potential in compensating reactive power than SVC due to usage of new converters. STATCOM is also used in load balancing, harmonic eliminating and voltage regulation (Singh *et al*., 2009). Figure 1 shows a STATCOM connected to the three phase power system containing a nonlinear load. It has been made of a three phase VSI with a DC link. STATCOM regulates the voltage at PCC and control the power factor by exchanging the reactive power with the main grid. It can fix the DC link voltage by exchanging active power, too (Singh *et al*., 2000).

Various switching techniques are used to control the STATCOM that have their own merits (Saeedifard *et al*., 2007; Bina and Bhat, 2008; Vahedi and Sheikholeslami, 2010) DC link voltage control leads to controlling the grid voltage at the PCC as well as managing the injected reactive power. Among different switching techniques, SVM is used in industrial implementation widely. The switching frequency is lower in this method results in lower switching losses. It works in a vast linear modulation area so utilize the DC voltage better (Garcia-Gonzalez and Garcia-Cerrada, 2000). In this method, a combination of switches are turned on to generate a voltage vector, therefore a switching table would be prepared according to the voltage vectors. This technique has high adaptability in blending with other switching methods as well as evolutionary algorithms for optimization (Mehrizi-Sani and Filizadeh, 2009).

In this study, GA based optimization of SVM has been introduced to employ in switching control of a STATCOM leads to decreasing harmonics in power system.

STATCOM STRUCTURE AND CONTROLLING PROCEDURE

As it is shown in Fig. 1, STATCOM consists of a three phase inverter with 6 power switches as well as a DC link. The voltage at the PCC can be controlled by supervising the exchanged active and reactive power between STATCOM and the network. Reactive power compensation and harmonics eliminating can also be done

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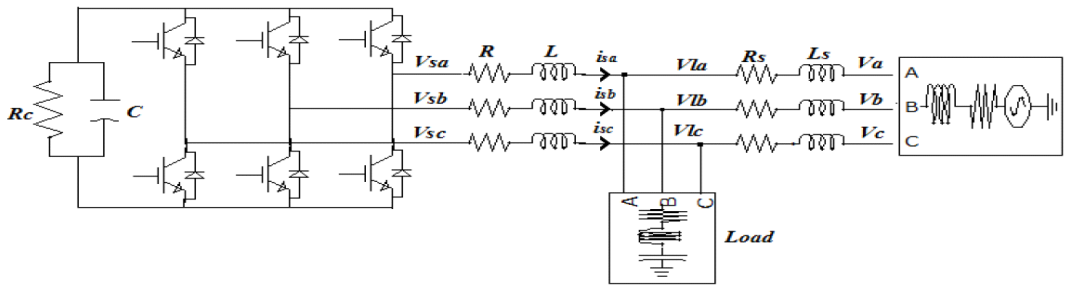

Fig. 1: Three phase power system with STATCOM

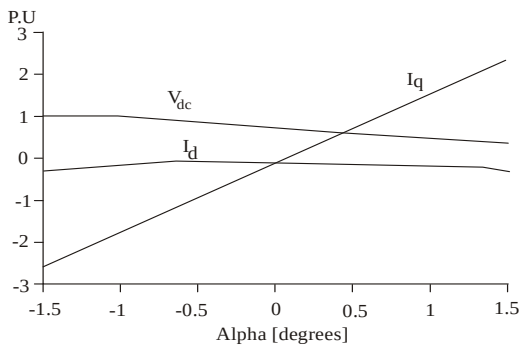

Fig. 2: Steady state operation of STATCOM in terms of α

by injecting the harmonic current components to the grid. In this study, the dq method has been used in extracting the reference current. Thus, the load voltage has been measured and transformed into dq coordinate by Eq. (1) to to produce the reference current (Singh *et al*., 2000; Singh *et al*., 2009; Saeedifard *et al*., 2007):

$$\begin{bmatrix} i_{ds}^{*} \\ i_{qs}^{*} \end{bmatrix} = \frac{1}{v_{dl}^{2} + v_{ql}^{2}} \begin{bmatrix} v_{dl} & -v_{ql} \\ v_{ql} & v_{dl} \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \quad (1)$$

where P_{ref} and Q_{ref} are the planed active and reactive power at the PCC, respectively. The angle difference between output voltage of converter and the system voltage called α is calculated as follows:

$$\alpha = tg^{-1} \frac{v_{qs}}{v_{ds}} \quad (2)$$

Figure 2 shows the steady state operation of STATCOM in terms of α. i_d, i_q and V_{dc} are active current, reactive current and DC voltage, respectively. The negative values of α indicates that the STATCOM is working in capacitor mode and the positive one stands for inductive mode.

Space Vector Modulation (SVM): Recently, SVM method has been noted in VSIs considerably. This technique is based on presenting the ac side voltages in a space vector which is used widely due its simplicity (Saeedifard *et al*., 2007; Mehrizi-Sani and Filizadeh 2009).

In a system with balanced sinusoidal voltage, the concept of space vector comes from transforming three phase voltages to $\alpha\beta$ coordinate. The three phase voltage can be written as:

$$V = \frac{3}{2}(V_m \cos\omega t + jV_m \sin\omega t) = \frac{3}{2} V_m e^{j\omega t} \quad (3)$$

which describes the circular path with radius of $3/2V_m$. So, controlling the frequency and amplitude of the output voltage can be converted into a voltage vector turning around with angular speed of ω and amplitude of $3/2V_m$. To produce the mentioned voltage vector, a number of switching states are used to apply ratio of V_{dc} at output. To apply the expected voltage at inverter output, various voltage states should be considered. There are six switches in a three phase inverter that each pair of them are in one leg. Due to short circuit they cannot turn on or off simultaneously in one leg. Therefore, eight switching states would be considered. V_0 and V_7 are the zero vectors and they are located at the center of coordinates in Fig. 3. V_1 to V_6 are active voltage vectors that make the hexagon and six switching area.

The space vector is based on six non-zero vectors which are placed on coordinates with angle of 60º symmetrically. To describe this method assume that a reference voltage (V_r) has been sampled in a ideal point with frequency of f_s which is shown in Fig. 4. This vector would be in one of the six areas. Assume V_x and V_y as the active vector in sides of the V_r in an area.

It is clear that the inverter can generate just one of the voltage states (V_0 to V_7) and the reference vector is not equal to the instantaneous phase voltages. The V_r can be achieved by dividing the time of applying V_x and V_y. Thus, the corresponding time of V_x and V_y are T_x and T_y in a period of T. The difference of T and T_x+T_y is set to the

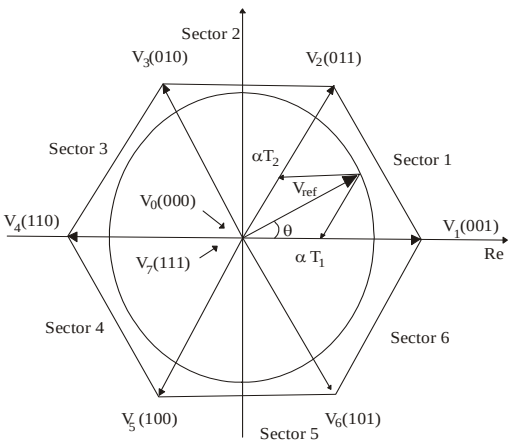

Fig. 3: Voltage vectors in SVM

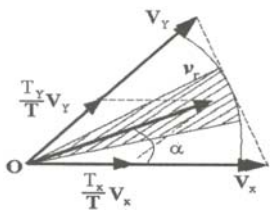

Fig. 4: SVM method to generate the voltage vector

zero vectors (V_0 or V_7) named T_0. In this case, it is expected that the below equations can calculate the times of active and zero vectors:

$$\begin{cases} \dfrac{T_x}{T} = Mk_v \sin(\dfrac{\pi}{3} - \alpha) \\ \dfrac{T_y}{T} = M \sin\alpha \\ \dfrac{T_0}{T} = 1 - \dfrac{T_x}{T} - \dfrac{T_y}{T} \end{cases} \quad (4)$$

where M is a ratio factor and k_v is the gain related to the output DC voltage of inverter. Equation (4) gives the times of each voltage vector (V_x and V_y and V_0 or V_7) to produce the reference voltage vector (V_r). m is the modulation index which is calculated as follows:

$$m = \frac{V_r}{V_{dc}} \quad (5)$$

It should be noted that the SVM only assigns the time division of each border but it doesn't specify their sequence. For instance, if Vr is in first area, after indicating their own time, the conventional sequence of them is $V_0V_1V_2V_7$ and the times of V_0 and V_7 would be $T_0/2$.

SVM optimization base on Genetic Algorithm (GA): As explained in previous section, in SVM switching method, only the time of each active vector and total time of zero vectors are calculated, but these vectors' sequences and also the way of T_0 division between zero vectors of V_0 or V_1 are not specified. And also in f_s specifying sampling frequency the balance between the THD and switching losses should be observed. High frequency not only makes the Harmonics and THD reduced but also increases the switching losses and vice versa. Thus using evolutionary algorithms leads to an optimized mixture of voltage vectors in order to make optimum SVM switching. Genetic algorithm is one of the natural evolutionary techniques which is looking for maximizing health of a population or minimizing the cost function (Mehrizi-Sani and Filizadeh, 2009). An important feature of GA is its ability to work with real and integer (binary codes) optimization variables simultaneously. This feature is used in optimizing harmonic spectrums in SVM including both these parameters (real and binary).

Answer space is specified by chromosomes, in GA. Each chromosome consists of a number of genes showing the possible amount of optimizing parameters. Calculating objective function for a chromosome in each generation, in SVM, includes:

- Making a waveform using SVM considering sequences in chromosome
- Harmonic spectrums calculating
- Objective function valuation. Each chromosome must completely explain the sequence of SVM

That should have some information about space vector sequence (two active vectors and two zero vectors) and also time division between two zero vectors. Objective function is the amount of harmonics which should be minimized. The maximum amount of total harmonic is 5 and 3% for each component in IEEE STD 519 standard. So to reduce the harmonic component weighed THD objective function can be used. In this function, amount of each harmonics is divided to its harmonic number. Thus high harmonic has less effect on function. And amount of harmonics has been selected 50 as maximum. (n = 50):

$$WTHD = \frac{\sqrt{\sum_{h=2}^{n} \left(\frac{V_h}{h}\right)^2}}{V_1}$$
$$WTHD_{total} \le 5\%$$
$$WTHD_{induvidual} \le 3\% \quad (6)$$

To optimize SVM, by GA, the best sequence of zero and active vectors should be chosen to make a reference

Table 1: System parameters

Supply voltage	1000 V
System frequency	60 Hz
STATCOM resistor	1 Ω
STATCOM inductance	1 mH
Switching frequency	2 KHz
Modulation index	0.8
Load power	1 KW

Table 2: WTHD optimization results

Rank	1	2	3	4	5
Sequence	$A_1V_7A_2V_0$	$A_1V_0A_2V_7$	$V_7A_1V_0A_2$	$V_7A_2V_0A_1$	$A_2V_7A_1V_0$
Z-Share	0.4429	0.6543	0.3931	0.9896	0.4321
WTHD	0.0330	0.0333	0.0331	0.0410	0.0376

Table 3: WTHD optimization results with various α

Optimization	Sequence	Z-Share	WTHD
α = 1°	$A_1V_7A_2V_0$	0.4427	0.0330
α = 0°	$A_1V_7A_2V_0$	0.4427	0.0330
α = -1°	$A_1V_7A_2V_0$	0.4427	0.0330

vector. As an example, if it is supposed that V_{ref} is located in area 1 (between V_1 and V_2), the sequences of $V_0V_1V_2V_7$, $V_1V_0V_2V_7$ and $V_2V_7V_1V_0$ can be applied. To choose the best sequence, these five questions should be answered. (It should be mentioned that A_1 and A_2 are the first and second active vectors in a sequence or chromosome).

- Has A_1 appeared in the step before A_2?
- Has V_0 appeared in the step before V_7?
- Is the first vector of the step one of active vectors?
- Is the second vector of the step one of active vectors?
- Is the third vector of the step one of active vectors?

Answers to these questions specify 5 genes in each chromosome (vectors' sequence). For example, for the $V_0V_1V_2V_7$, they can be answered as:

- V_1 appeared before V_2. (1)
- V_0 appeared before V_7. (1)
- First vector is not active. (0)
- Second vector is active. (1)
- Third vector is active. (1)

The expected code is 11011. As another example, the code 10101 belongs to $V_1V_7V_2V_0$. So for each binary code there would be 5 bit. Considering objective function and its criteria leads to best sequence to produce the voltage vector in each section of the hexagon to minimize the WTHD.

SIMULATION AND RESULTS

In this section a power system simulation with STATCOM using optimized SVM has been done. Note that, parameters of mentioned power system have been shown in Table 1. Results containing WTHD of voltage waveforms and time division of vectors are given and discussed. Some simulations for different values of α have been performed to validate the efficiency of proposed method in various modes (Capacitive and inductive) of STATCOM.

The aim of harmonic optimization is to find the active and zero vectors sequence as well as time division of zero vectors (z-share) leads to lower voltage WTHD finally. The results of simulation and optimization are gathered in Table 2. As it is seen, the sequence of $A_1V_7A_2V_0$ has the lowest WTHD. The lower harmonic contents, the lesser and cheaper filtering equipments. The other four sequences that have lower WTHD after first one are calculated in Table 2. Some simulations have been done with various α with the sequence of $A_1V_7A_2V_0$.

Table 3 shows that change in α don't have any influence on STATCOM with the proposed sequence. According to the SVM optimization results, due to freedom in applying active and zero vectors and their corresponding intervals, the harmonic components diminished significantly in network which proves the efficiency of the optimization of SVM employed in STATCOM. This method can be used in multilevel converters also.

CONCLUSION

STATCOM is one of important equipments in power systems to compensate the reactive power and eliminating harmonics and fixing voltage at the PCC. Proper switching of inverters leads to better performance of a STATCOM. Thus, SVM has been used in this paper due to its widely usage in industry. Since SVM has the ability to be optimized with evolutionary algorithms, GA-based optimization has been described in this paper and the results including voltage WTHD have been achieved. The results proves the fact that employing GA-based optimization of SVM in STATCOM leads to lower WTHD as well as balancing between switching frequency and system losses and WTHD.

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