

A SIMPLE STATE FEEDBACK LINEARIZATION CONTROL OF MULTILEVEL ASVC

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Abstract: This paper presents a modeling analysis of a nonlinear control strategy for a three-phase multilevel Advanced Static Compensator (ASVC). The nonlinear state-space model of the multilevel ASVC is obtained from the $DQ0$ reference frame. The input/output feedback linearization is then applied and the state feedback linearization control law is obtained. The model that was obtained was linearized and decoupled in two independent subsystems. The stabilizing controllers were designed based on the linear method. The simulation analysis was performed by MATLAB. The system performance was tested through a sudden change of the load from inductive to capacitive mode.

Key words: ASVC (Advanced Static Var Compensator), NPC (Neutral Point Clamping), Nonlinear Controller.

1. Introduction

Advanced Static Var Compensator (ASVC) is a 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 the inverter output voltage. The AC system is connected to a DC capacitor (energy storage device) through the inverter [1]. The basic function of the ASVC installed in a power system is for the line voltage control. To achieve smooth control of the proposed system, two controllers were implemented. The first one is an AC voltage controller which regulates the reactive power exchange between the ASVC and the power system. A second controller installed also in the ASVC is the DC voltage controller which regulates the DC voltage across the DC capacitor of the ASVC [2]. The multi-pulse converter topology was used thoroughly in the ASVC. Alternatively, multilevel converters can also be used to eliminate the complex transformer array needed to suppress the harmonics. In comparison with other converter topologies, the multilevel structure can reduce voltage stress across the switches and provide more available vectors. The

three-level neutral point clamped (abbreviated as NPC) inverter is the most popular topology. The use of the NPC inverter produces effective compensation[3]. There are many possible circuit configurations for Voltage Source Inverters (VSI) and consequently many different configurations of ASVC[4]. Various control strategies such as Proportional-Integral (PI) controller and nonlinear controller have been suggested to control the ASVC[5]. In nonlinear control, the Generalized Averaged Method has been used to determine the nonlinear time invariant continuous model of the system [6]. This model has been used to present a nonlinear control law based on the exact linearization via feedback of the ASVC. This method is particularly interesting because it transforms a nonlinear system into a linear one in terms of its input-output relationship.

2. Modelling and principle of operation

2. 1. Principle of operation of the ASVC

The static VAR compensator (ASVC) which uses a three-level converter of the voltage source type is shown in Figure 1.

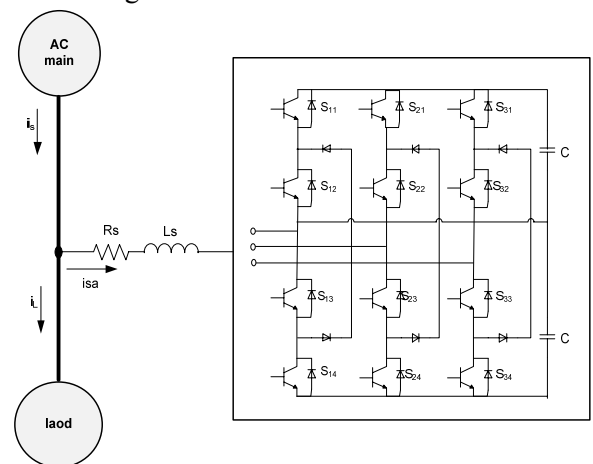


Fig.1. ASVC using three-level inverter

The main circuit configuration consists of a bridge inverter made up of twelve power GTO's with antiparallel diodes which is connected to the three-phase supply through an impedance Z_s of small value, comprising an inductance L_s , and a resistor R_s on the AC side. L_s represents the leakage inductance of the transformer, and R_s , represents the inverter and transformer conduction losses.

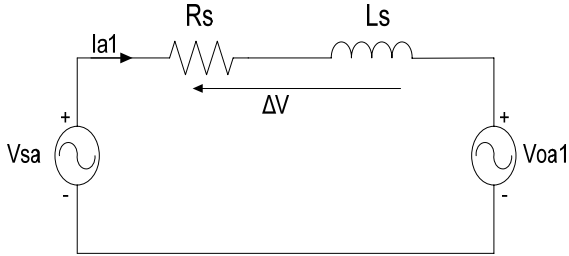


Fig.2. Per-phase fundamental equivalent circuit

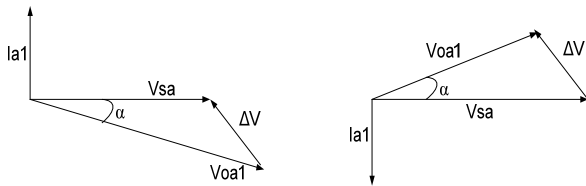


Fig.3. Phasor diagram for leading and lagging mode

Two capacitors are connected to the dc side of the converter. The structure of one leg of the inverter itself is made up of four pairs of diode-GTO forming a switch and two diodes allowing to have the zero level point of the inverter output voltage. The operation principles of the system can be explained by considering the per-phase fundamental equivalent circuit of the ASVC system as shown in Figure 2. In this figure, v_{sa} is the ac mains voltage source. i_{a1} and v_{oa} are the fundamentals components of current and output voltage of the inverter supply respectively.

2. 2. Modelling of the system

The main circuit of the ASVC shown in Figure 1 is modeled in this section. The equivalent circuit is obtained by performing a circuit dq transformation method with the following assumptions:

- The source voltages are balanced,
- Line impedance and total loss of the inverter is represented by lumped resistor R_s ,
- Harmonic components generated by switching action are negligible.

Figure 4 shows a simplified equivalent circuit of the ASVC. Using matrix form, the mathematical model is given by:

$$L_s \frac{d}{dt} \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} -R_s & 0 & 0 \\ 0 & -R_s & 0 \\ 0 & 0 & -R_s \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} v_{sa} - v_{oa} \\ v_{sb} - v_{ob} \\ v_{sc} - v_{oc} \end{pmatrix} \quad (1)$$

$$K = \frac{2}{3} \begin{pmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin \omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$K^{-1} = K^T \quad (2)$$

$$X_{dq0} = K X_{abc}, \quad X_{abc} = K^{-1} X_{dq0} \quad (3)$$

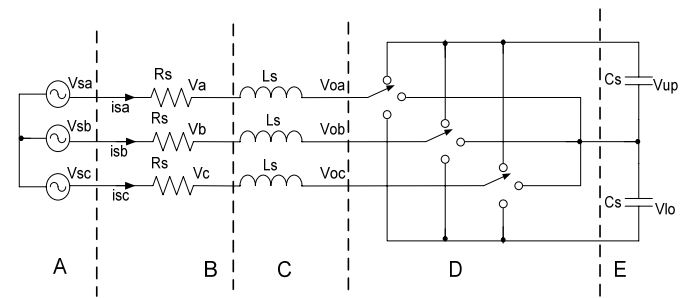


Fig.4. Equivalent Circuit of the Static Var Compensator

2. 2.1. Transform of Part A, B

The voltage and current relation about resistor R_s is:

$$v_{s,dq0} = R_s i_{s,abc} + v_{dq0} \quad (4)$$

DQ transforms of (4) becomes:

$$v_{s,dq0} = R_s i_{s,abc} + v_{dq0} \quad (5)$$

Where

$$v_{s,dq0} = K v_{s,abc} = \begin{pmatrix} V_s \\ 0 \\ 0 \end{pmatrix} \quad (6)$$

Where v_s is the rms line voltage.

2. 2.2. Transform of Part C

The voltage and current relation with inductor L_s is:

$$L_s \dot{i}_{s,abc} = v_{abc} - v_{o,abc} \quad (7)$$

And the circuit dq transform becomes:

$$L_s \frac{d}{dt} i_{s,dq0} = L_s \frac{d}{dt} (K) K^{-1} i_{dq0} + v_{abc} - v_{o,abc} \quad (8)$$

That is:

$$L_s \frac{d}{dt} \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} = \begin{pmatrix} -R_s & \omega L_s \\ -\omega L_s & -R_s \end{pmatrix} \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} + \begin{pmatrix} v_{sd} - v_{od} \\ v_{sq} - v_{od} \end{pmatrix} \quad (9)$$

2. 2.3. Transform of Part D, E

The commutation function is defined by equation (10):

$$S = \begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} = \sqrt{\frac{2}{3}} m \begin{pmatrix} \sin(\omega t + \alpha) \\ \sin(\omega t - \frac{2\pi}{3} + \alpha) \\ \sin(\omega t + \frac{2\pi}{3} + \alpha) \end{pmatrix} \quad (10)$$

m is the modulation index in the Park axis.

α is the Phase angle between source voltage and switching function.

$$m = \frac{\sqrt{v_{od}^2 + v_{oq}^2}}{v_{dc}/2}, \quad \alpha = \tan^{-1} \left(\frac{v_{oq}}{v_{od}} \right) \quad (11)$$

Note that modulation index is given by

$$IM = v_{o,crête} / v_{dc} = \sqrt{\frac{2}{3}} m \quad (12)$$

The DC current and voltage is given by equation (13) and (14)

$$2i_{dc} = S^T K^{-1} i_{s,dq0} = m(1 \ 0 \ 0) \begin{pmatrix} i_{sd} \\ i_{sq} \\ i_{s0} \end{pmatrix} \quad (13)$$

$$v_{dc} = \frac{1}{C} \int i_{dc} dt \quad (14)$$

2. 2.4. Active and reactive power

Both powers are expressed by equation (15)

$$\begin{cases} p_c = \frac{3}{2} [v_{sd} i_{sd} + v_{sq} i_{sq}] \\ Q_c = \frac{3}{2} [v_{sq} i_{sd} - v_{sd} i_{sq}] \end{cases} \quad (15)$$

If α is chosen equal to zero, the v_{sq} , voltage is equal to zero and the reactive power becomes proportional to $v_{sd} i_{sq}$. To control the reactive power Q_c , it may be sufficient to control i_{sq} , (equation 16).

$$Q_c = -\frac{3}{2} v_{sd} i_{sq} \quad (16)$$

The average rate of change of energy associated with the AC link and DC link is given by

$$p = \frac{3}{2} [v_{sd} i_{sd} + v_{sq} i_{sq}] = C v_{dc} \frac{dv_{dc}}{dt} \quad (17)$$

From (14) and (17),

$$\frac{dv_{dc}}{dt} = \frac{\frac{3}{2} [v_{sd} i_{sd} + v_{sq} i_{sq}]}{C v_{dc}} \quad (18)$$

Equation (18) leads to nonlinear system with regard to v_{dc} . Combination of equation (9) and (18) describes a nonlinear model as:

$$\frac{d}{dt} \begin{pmatrix} i_{sd} \\ i_{sq} \\ v_{dc} \end{pmatrix} = \begin{pmatrix} \frac{-R_s}{L_s} i_{sd} + \omega i_{sq} \\ -\omega i_{sd} - \frac{R_s}{L_s} i_{sq} \\ \frac{3}{2C v_{dc}} (v_{sd} i_{sd} + v_{sq} i_{sq}) \end{pmatrix} + \begin{pmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_{sd} - v_{od} \\ v_{sq} - v_{oq} \end{pmatrix} \quad (19)$$

This system is of the third order with two control inputs.

3. Application of the input/output linearization to the ASVC

The feedback linearization is a method that eliminates the non-linearity of the system so that the closed-loop system dynamics are reduced to a linear form. Thus, the controller for the linearized system can be designed with the well-known linear control theory [8]-[9]

For feedback linearization process, at first, a multi-input multi-output (MIMO) [10], system is expressed from equation (19) as

$$\begin{cases} \dot{x} = f(x) + \sum_{i=1}^n g_i(x) u_i \\ y_i = h_i(x) \end{cases}, i = 1, 2, \dots, n \quad (20)$$

Where

$$f(x) = \begin{pmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{pmatrix} = \begin{pmatrix} \frac{-R}{L} x_1 + \omega x_2 \\ \frac{-R}{L} x_2 - \omega x_1 \\ \frac{3}{2C x_3} v x_1 \end{pmatrix}$$

$$g = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \end{pmatrix}$$

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} i_{sd} \\ i_{sq} \\ v_{dc} \end{pmatrix}; \quad u = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} v_{sd} - v_{od} \\ v_{sq} - v_{oq} \end{pmatrix}$$

Where:

- x is the state vector,
- u is the control input vector,
- g is the input matrix,
- $f(x)$ is a nonlinear vector field.

3. 1. Control of the outputs

The aim of the control strategy is to regulate the dc link voltage and to control the reactive power current component. Therefore, the output equation is given by

$$y = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_1(x) \\ h_2(x) \end{pmatrix} = \begin{pmatrix} i_{sq} \\ v_{dc} \end{pmatrix}$$

3. 2. Relative degree

We calculate the relative degree r_i associated with each output variable, y_i which will be chosen so that it corresponds to the number of times to divert this output to make explicit one of the control variables.

$$\begin{cases} \frac{d^{r_1} y_1}{dt} = L_f^{r_1} h_1(x) + L_g L_f^{r_1-1} h_1(x) u \\ \frac{d^{r_2} y_2}{dt} = L_f^{r_2} h_2(x) + L_g L_f^{r_2-1} h_2(x) u \end{cases} \quad (21)$$

3. 2.1. Relative degree of the reactive power

The Lie derivative to the reactive power is given by:

$$\dot{h}_1(x) = L_f h_1(x) + L_{g1} h_1(x) u_1 + L_{g2} h_1(x) u_2 \quad (22)$$

From Equation (19) we can deduce that:

$$\begin{cases} L_f h_1(x) = \frac{-R}{L} x_2 - \omega x_1 = f_2(x) \\ L_{g1} h_1(x) = 0 \\ L_{g2} h_1(x) = \frac{1}{L_s} = g_2 \end{cases} \quad (23)$$

So equation (23) gives:

$$\dot{y}_1 = \dot{h}_1(x) = \frac{di_{sq}}{dt} = f_2(x) + g_2 u_2 \quad (24)$$

The input appears in the first derivative of the output i_{sq} . We stop, so that the relative degree associated to the output y_1 is: $r_1 = 1$

3. 2.2. Relative degree of DC voltage

The Lie derivative for DC voltage is given by:

$$\dot{h}_2(x) = L_f h_2(x) + L_{g1} h_2(x) u_1 + L_{g2} h_2(x) u_2 \quad (25)$$

After simplification we get:

$$\begin{cases} L_f h_2(x) = \frac{3}{2Cx_3} vx_1 \\ L_{g1} h_2(x) = 0 \\ L_{g2} h_2(x) = 0 \end{cases} \quad (26)$$

The input does not appear in the derivative of the output y_2 so we have derived a second time y_2 .

The development of equation (25) gives:

$$\ddot{h}_2(x) = L_f^2 h_2(x) + L_{g1} L_f h_2(x) u_1 + L_{g2} L_f h_2(x) u_2 \quad (27)$$

After simplification we get:

$$\begin{cases} L_f^2 h_2(x) = -\frac{3}{2Cx_3^2} vx_1 f_3 + \frac{3}{2Cx_3} v f_1 \\ L_{g1} L_f h_2(x) = \frac{3}{2Cx_3} v g_1 \\ L_{g2} L_f h_2(x) = 0 \end{cases} \quad (28)$$

So Equation (27) becomes:

$$\ddot{y}_2 = \ddot{h}_2(x) = -\frac{3}{2Cx_3^2} vx_1 f_3 + \frac{3}{2Cx_3} v f_1 + \frac{3}{2Cx_3} v g_1 u_1 \quad (29)$$

The input appears finally in the second derivative of the output v_{dc} . So the relative degree associated with the output y_2 is $r_2 = 2$.

The matrix defining the relationship between physical inputs (u) and the derivatives of the outputs ($y(x)$) is given by:

$$\begin{pmatrix} \dot{y}_1 \\ \dot{y}_2 \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} L_f h_1(x) \\ L_f^2 h_2(x) \end{pmatrix} + \begin{pmatrix} L_{g1} h_1(x) & L_{g2} h_1(x) \\ L_{g1} L_f h_2(x) & L_{g2} L_f h_2(x) \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad (30)$$

$$\begin{pmatrix} \dot{y}_1 \\ \dot{y}_2 \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = A(x) + D(x) \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad (31)$$

According to this formula, the decoupling matrix is given by:

$$D(x) = \begin{pmatrix} 0 & g_2 \\ \frac{3vg_1}{2Cx_3} & 0 \end{pmatrix} \quad (32)$$

Controls of u_1 and u_2 can be determined if the decoupling matrix is not singular,

$$\text{Det}(D(x)) = \frac{3vg_1g_2}{2Cx_3} \neq 0 \quad (33)$$

$\text{Det}(D(x))$ is non-nil then the matrix $D(x)$ is invertible.

We have :

$$A(x) = \begin{pmatrix} f_2 \\ \frac{3}{2Cx_3} v f_1 - \frac{3f_3}{2Cx_3^2} vx_1 \end{pmatrix} \quad (34)$$

We then define the non-linear control:

$$\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = D^{-1}(x) \left(-A(x) + \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \right) \quad (35)$$

3. 3. Control loop

For tracking control, the closed-loop error equations are given as follows:

$$\begin{cases} \dot{e}_1 + k_{11}e_1 = 0 \\ \dot{e}_2 + k_{21}e_2 + k_{22}e_2 = 0 \end{cases} \quad (36)$$

Where $e_1 = i_q^* - i_q$ and $e_2 = v_{dc}^* - v_{dc}$

Tracking errors was achieved by locating the desired poles on the left-half plane. Table I gives the values of the desired poles.

Table I. VALUE OF CONTROLLER GAINS

Control loop	Poles values
$x_2 = i_{sq}$	$\mu_1 = -0.5$
$x_3 = v_{dc}$	$\mu_1 = -0.0005 + 0.3162i$
	$\mu_2 = -0.0005 - 0.3162i$

The gains calculated were k_{ij} equation (37) and asymptotic tracking control to the reference was obtained [11].

$$\begin{bmatrix} k_{11} \\ k_{12} \end{bmatrix} = \begin{bmatrix} 10^4 \\ 100 \end{bmatrix}; \begin{bmatrix} k_{21} \\ k_{22} \end{bmatrix} = \begin{bmatrix} 10^9 \\ 10^6 \\ 10^8 \end{bmatrix} \quad (37)$$

Consequently, the state feedback controlled inputs $v_{1,2}$ could be finally computed as in (38) by:

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} \dot{y}_{1ref} + k_{11}e_1 + k_{12} \int e_1 dt \\ \dot{y}_{2ref} + k_{21}e_2 + k_{22}e_2 + k_{23} \int e_2 dt \end{pmatrix} \quad (38)$$

The proposed nonlinear control block diagram of the multilevel ASVC is shown in Figure 5.

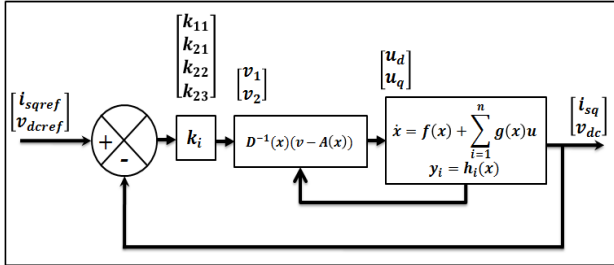
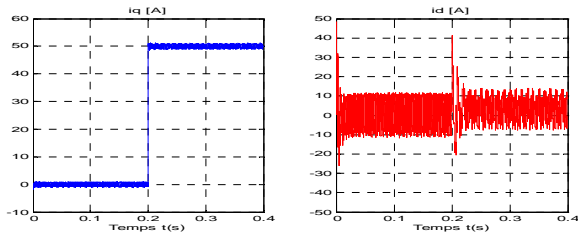
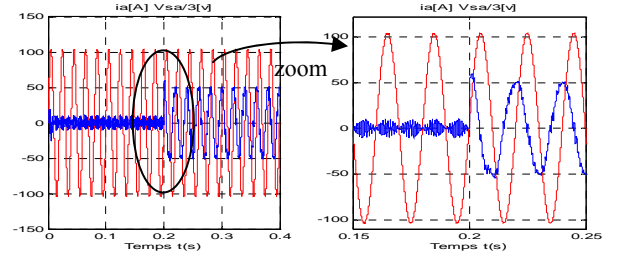


Fig.5. Block diagram of the state feedback controlled system

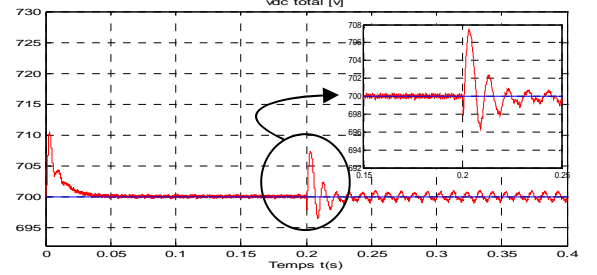
4. Simulation Results and Discussions



a) Simulated inverter current in dq frame

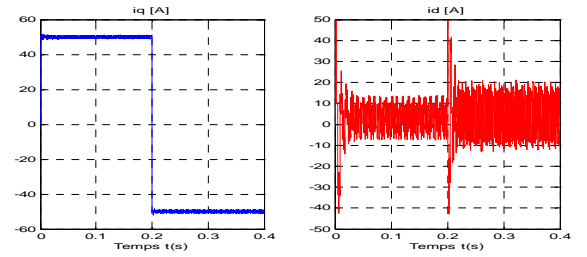


b) Simulated current and voltage waveforms

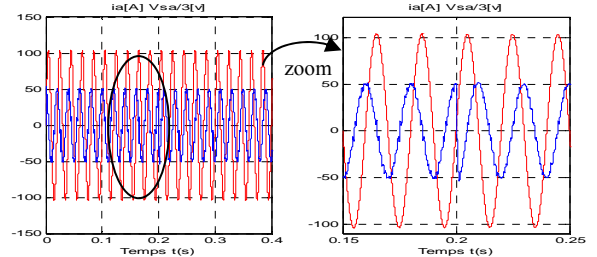


c) Simulated inverter DC Bus voltage

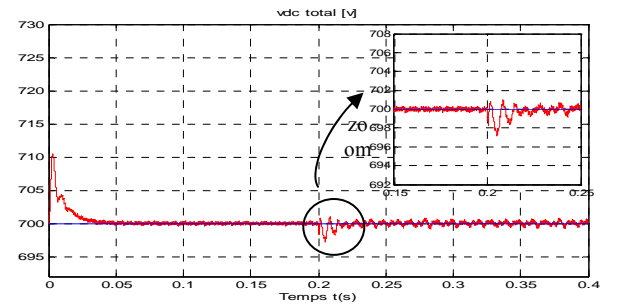
Fig.6. Simulation results for reactive power with reference change from 0A to 50A capacitive.



a) Simulated inverter current in dq frame.



b) Simulated current and voltage waveforms



c) Simulated inverter DC Bus voltage

Fig.7. Simulation results for reactive power with reference change from 50A capacitive to 50A inductive

Figures (6.a) and (7.a) show the waveforms of the reactive and active currents before and after the insertion of the compensator. As shown in Fig. 7.a, at first, the ASVC is connected to the load resistance. Hence, the compensator provides no reactive power. In other cases the ASVC is connected to a capacitive and inductive load, respectively then the compensator provides and absorbs reactive power ($Q = \pm 23 \text{ kVar}$).

The dynamic response of the reactive current i_q (its reference, $i_q^* = 50 \text{ A}$) is shown to be very fast.

The active current i_d is now a constant value which maintains the DC voltage unchanged. Decoupling of i_q and i_d is guaranteed.

Figures (6.b), (6.c), (7.b), and (7.c) show the responses of the DC voltage. The DC voltage follows its reference (700 V) perfectly. However, it fluctuates around its reference by 1 V ; this is due to the phenomenon of balancing the two DC voltages.

Figures (7.d) shows the simulated current and voltage waveforms to a step reference of reactive power.

5. Conclusion

A study and mathematical modeling of the dynamic performance analysis of an Advanced Static Var Compensator (ASVC) using three-level voltage source inverter has been presented in this paper. A nonlinear control strategy was proposed for the control of this compensator. The controller is based on two separate loops.

The inner loop decouples the current components in the ' dq ' referential and uses the exact feedback linearization with integral control to make the currents track their references in a fast and satisfactory manner.

The outer and slower loop regulates the dc voltage level using nonlinear feedback with integral control. The simulation results included show that the proposed nonlinear control law can improve considerably the system performance operation in different aspects.

References

1. N. Farokhnia, R. Khoraminia, G.B. Gharehpetian, "Optimization of PI Controller Gains in Nonlinear Controller of STATCOM Using PSO and GA", ICREPQ'10, Granada (Spain), 23rd to 25th March, 2010.
2. M. Benghanem, A. Draou, "A New modeling and control analysis of an Advanced Static Var Compensator using a three-level (NPC) inverter topology", Journal of Electrical Engineering, VOL. 57, NO. 5, 2006, pp. 285–290.
3. H.F. Wang, "Interactions and multivariable design of STATCOM AC and DC voltage control", science direct, Electrical Power and Energy Systems 25 (2003) 387–394.
4. X-p Yang, H-b Hao, Y-r Zhong, "The State-Space Modeling and Nonlinear Control Strategies of Multilevel DSTATCOM", IEEE Power and Energy Engineering Conference (APPEEC), Asia-Pacific, 28-31 March 2010.
5. P. Lattamus, H. Tuusa "Comparison of Five-Level Voltage-Source Inverter Based STATCOMs", IEEE Power Conversion Conference Nagoya, 2007. Page(s): 659 - 666.
6. Hung-Chi Tsai, Chia-Chi Chu "Nonlinear STATCOM Controller using Passivity-Based Sliding Mode Control", Circuits and Systems, 2006. IEEE Asia Pacific IEEE APCCAS, 4-7 Dec. 2006 Page(s): 1996 – 1999.
7. S.BACHA, J.P.ROGNON P.PETITCLAIR, "Averaged Modelling and Nonlinear Control of an ASVC (Advanced Static VAR Compensator)", IEEE, American Control Conference, 1990.
8. Diego Soto "Nonlinear Control Strategies for Cascaded Multilevel STATCOMs" IEEE Transactions on Power Delivery, vol. 19, NO. 4, October 2004.
9. A. Isidori, "Nonlinear Control Systems" Springer-VERLAG BERLIN, Heidelberg, Germany second edition 1989.
10. J.-J. E Slotine, "Applied Non-Linear Control", Prentice Hall, Inc., 1991.
11. L. Yacoubi, F. Fnaiech, K. Al-Haddad, L.-A. Dessaint, "Input State Feedback Linearization Control of a Three-phase Three-level Neutral Point Clamped Rectifier", IEEE Trans. Power Electronics 2001.
12. M.C. Benhabib, S. Saadate, "New control approach for four-wire active power filter based on the use of synchronous reference frame", Electric Power Systems Research 73, No, 2005, pp. 353–362.

Appendix

System Parameters

System simulation parameters used for the proposed system are as follows:

Three-phase power grid phase voltage = **220V**.

PWM switch frequency = **1 kHz**.

$R_s = 0.4 \Omega$,

$L_s = 3.10^{-3} \text{ H}$,

$C = 8800.10^{-6} \text{ F}$,

$\omega = 100\pi \text{ rad/s}$.