APPLICATIONS OF NONLINEAR CONTROL

Edited by **Meral Altınay**

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Published by InTech
Janeza Trdine 9, 51000 Rijeka, Croatia

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Technical Editor Teodora Smiljanic
Cover Designer InTech Design Team

First published June, 2012
Printed in Croatia

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Applications of Nonlinear Control, Edited by Meral Altınay
p. cm.
ISBN 978-953-51-0656-2

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Preface

All practical systems contain nonlinear dynamics. Control system development for these systems has traditionally been based on linearized system dynamics in conjunction with linear control techniques. Sometimes it is possible to describe the operation of systems by a linear model around its operating points. Linearized system can provide approximate behavior of the system. But in analyzing the overall system behavior, the resulting system model is inadequate or inaccurate. Moreover, the stability of the system cannot be guaranteed. However, nonlinear control techniques take advantage of the given nonlinear dynamics to produce high-performance designs.

Nonlinear Control Systems represent a new trend of investigation during the last few decades. There has been great excitement over the development of new mathematical techniques for the control of nonlinear systems. Methods for the analysis and design of nonlinear control systems have improved rapidly. A number of new approaches, ideas and results have emerged during this time. These developments have been motivated by comprehensive applications such as mechatronic, robotics, automotive and air-craft control systems.

The book is organized into eleven chapters that include nonlinear design topics such as Feedback Linearization, Lyapunov Based Control, Adaptive Control, Optimal Control and Robust Control. All chapters discuss different applications that are basically independent of each other. The book will provide the reader with information on modern control techniques and results which cover a very wide application area. Each chapter attempts to demonstrate how one would apply these techniques to real-world systems through both simulations and experimental settings.

Lastly, I would like to thank all the authors for their excellent contributions in different applications of Nonlinear Control Techniques. Despite the rapid advances in the field, I believe that the examples provided here allow us to look through some main research tendencies in the upcoming years. I hope the book will be a worthy contribution to the field of Nonlinear Control, and hopefully it will provide the readers with different points of view on this interesting branch of Control Engineering.

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1

Application of Input-Output Linearization

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1. Introduction

In nature, most of the systems are nonlinear. But, most of them are thought as linear and the control structures are realized with linear approach. Because, linear control methods are so strong to define the stability of the systems. However, linear control gives poor results in large operation range and the effects of hard nonlinearities cannot be derived from linear methods. Furthermore, designing linear controller, there must not be uncertainties on the parameters of system model because this causes performance degradation or instability. For that reasons, the nonlinear control are chosen. Nonlinear control methods also provide simplicity of the controller (Slotine & Li, 1991).

There are lots of machine in industry. One of the basic one is dc machine. There are two kinds of dc machines which are brushless and brushed. Brushed type of dc machine needs more maintenance than the other type due to its brush and commutator. However, the control of brushless dc motor is more complicated. Whereas, the control of brushed dc machine is easier than all the other kind of machines. Furthermore, dc machines need to dc current. This dc current can be supplied by dc source or rectified ac source. Three – phase ac source can provide higher voltage than one phase ac source. When the rectified dc current is used, the dc machine can generate harmonic distortion and reactive power on grid side. Also for the speed control, the dc source must be variable. In this paper, dc machine is fed by three – phase voltage source pulse width modulation (PWM) rectifier. This kind of rectifiers compared to phase controlled rectifiers have lots of advantages such as lower line currents harmonics, sinusoidal line currents, controllable power factor and dc – link voltage. To make use of these advantages, the filters that are used for grid connection and the control algorithm must be chosen carefully.

In the literature there are lots of control methods for both voltage source rectifier and dc machine. References (Ooi et al., 1987; Dixon&Ooi, 1988; Dixon, 1990; Wu et al., 1988, 1991) realize current control of L filtered PWM rectifier at three – phase system. Reference (Blasko & Kaura, 1997) derives mathematical model of Voltage Source Converter (VSC) in d-q and α-β frames and also controlled it in d-q frames, as in (Bose, 2002; Kazmierkowski et al., 2002). Reference (Dai et al., 2001) realizes control of L filtered VSC with different decoupling structures. The design and control of LCL filtered VSC are carried out in d-q frames, as in (Lindgren, 1998; Liserre et al., 2005; Dannehl et al., 2007). Reference (Lee et al., 2000; Lee, 2003) realize input-output nonlinear control of L filtered VSC, and also in reference (Kömürcügil & Kükrer, 1998) Lyapunov based controller is designed for VSC. The feedback linearization technique for LCL filtered VSC is also presented, as in (Kim & Lee, 2007; Sehirli

& Altınay, 2010). Reference (Holtz, 1994) compares the performance of pulse width modulation (PWM) techniques which are used for VSC. In (Krishnan, 2001) the control algorithms, theories and the structure of machines are described. The fuzzy and neural network controls are applied to dc machine, as in (Bates et al., 1993; Sousa & Bose, 1994).

In this chapter, simulation of dc machine speed control which is fed by three – phase voltage source rectifier under input – output linearization nonlinear control, is realized. The speed control loop is combined with input-output linearization nonlinear control. By means of the simulation, power factor, line currents harmonic distortions and dc machine speed are presented.

2. Main configuration of VSC

In many industrial applications, it is desired that the rectifiers have the following features; high-unity power factor, low input current harmonic distortion, variable dc output voltage and occasionally, reversibility. Rectifiers with diodes and thyristors cannot meet most of these requirements. However, PWM rectifiers can provide these specifications in comparison with phase-controlled rectifiers that include diodes and thyristors.

The power circuit of VSC topology shown in Fig.1 is composed of six controlled switches and input L filters. Ac-side inputs are ideal three-phase symmetrical voltage source, which are filtered by inductor L and parasitic resistance R, then connected to three-phase rectifier consist of six insulated gate bipolar transistors (IGBTs) and diodes in reversed parallel. The output is composed of capacitance and resistance.

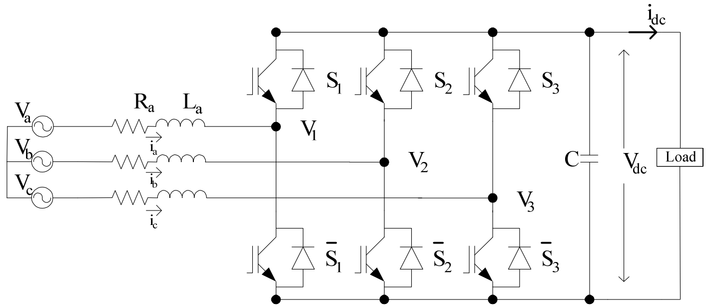

Fig. 1. L filtered VSC

3. Mathematical model of the VSC

3.1 Model of the VSC in the three-phase reference frame

Considering state variables on the circuit of Fig.1 and applying Kirchhoff laws, model of VSC in the three-phase reference frame can be obtained, as in (Wu et al., 1988, 1991; Blasko & Kaura, 1997).

The model of VSC is carried out under the following assumptions.

- The power switches are ideal devices.
- All circuit elements are LTI (Linear Time Invariant)
- The input AC voltage is a balanced three-phase supply.

For the three-phase voltage source rectifier, the phase duty cycles are defined as the duty cycle of the top switch in that phase, i.e., d_a= $d(S_1)$, d_b= $d(S_3)$, d_c= $d(S_5)$ with d representing duty cycle.

$$\frac{di_a}{dt} = -\frac{R}{L}i_a - V_{dc}\left(d_a - \frac{1}{3}\sum_{k=a}^{c} d_k\right) + V_a \quad (1)$$

$$\frac{di_b}{dt} = -\frac{R}{L}i_b - V_{dc}\left(d_b - \frac{1}{3}\sum_{k=a}^{c} d_k\right) + V_b \quad (2)$$

$$\frac{di_c}{dt} = -\frac{R}{L}i_c - V_{dc}\left(d_c - \frac{1}{3}\sum_{k=a}^{c} d_k\right) + V_c \quad (3)$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C}(i_a d_a + i_b d_b + i_c d_c) - \frac{1}{C}i_{dc} \quad (4)$$

This model in equations (1) – (4) is nonlinear and time variant. Using Park Transformation, the ac-side quantities can be transformed into rotating d-q frame. Therefore, it is possible to obtain a time-invariant system model with a lower order.

3.2 Coordinate transformation

On the control of VSC, to make a transformation, there are three coordinates whose relations are shown by Fig 2, that are a-b-c, α-β and d-q. a-b-c is three phase coordinate, α-β is stationary coordinate and d-q is rotating coordinate which rotates ω speed.

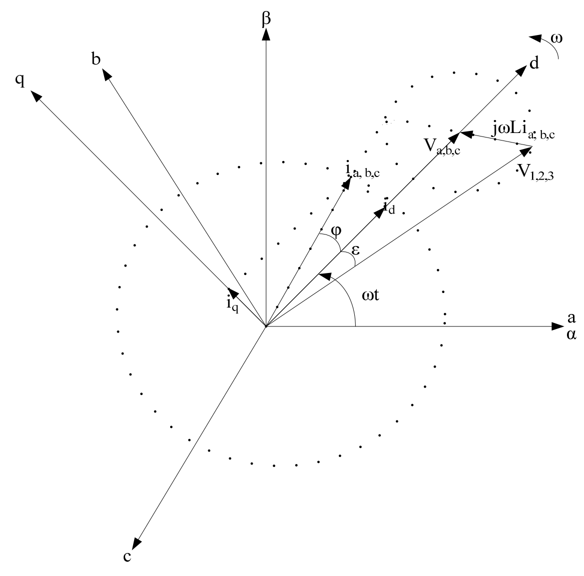

Fig. 2. Coordinates diagram of a-b-c, α-β and d-q

The d-q transformation is a transformation of coordinates from the three-phase stationary coordinate system to the d-q rotating coordinate system. A representation of a vector in any n-dimensional space is accomplished through the product of a transpose n-dimensional vector (base) of coordinate units and a vector representation of the vector, whose elements are corresponding projections on each coordinate axis, normalized by their unit values. In three phase (three dimensional) space, it looks like as in (5).

$$X_{abc} = \begin{bmatrix} a_u & b_u & c_u \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{5}$$

Assuming a balanced three-phase system, a three-phase vector representation transforms to d-q vector representation (zero-axis component is 0) through the transformation matrix T, defined as in (6).

$$T = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2}{3}\pi) & -\sin(\omega t + \frac{2}{3}\pi) \end{bmatrix} \tag{6}$$

In (6), ω is the fundamental frequency of three-phase variables. The transformation from X_{abc} (three-phase coordinates) to X_{dq}(d-q rotating coordinates), called Park Transformation, is obtained through the multiplication of the vector X_{abc} by the matrix T, as in (7).

$$X_{dq} = T.X_{abc} \tag{7}$$

The inverse transformation matrix (from d-q to a-b-c) is defined in (8).

$$T' = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & -\sin(\omega t + \frac{2}{3}\pi) \\ \cos(\omega t - \frac{2}{3}\pi) & -\sin(\omega t - \frac{2}{3}\pi) \\ \cos(\omega t + \frac{2}{3}\pi) & -\sin(\omega t + \frac{2}{3}\pi) \end{bmatrix} \tag{8}$$

The inverse transformation is calculated as in (9).

$$X_{abc} = T'.X_{dq} \tag{9}$$

3.3 Model of the VSC in the rotating frame

Let x and u be the phase state variable vector and phase input vector in one phase of a balanced three-phase system with the state equation in one phase as in (10).

$$\dot{X} = Ax + Bu \tag{10}$$

Where A and B are identical for the three phases. Applying d-q transformation to the three-phase system, d-q subsystem with d and q variables is obtained (x_d-x_q and u_d-u_q). The system equation in (10) becomes as in (11) (Mao et al., 1998; Mihailovic, 1998).

$$\begin{bmatrix} \dot{X}_d \\ \dot{X}_q \end{bmatrix} = \begin{bmatrix} A & \omega I \\ -\omega I & A \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix} + \begin{bmatrix} B & 0 \\ 0 & B \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} \tag{11}$$

Where I is the identity matrix and 0 is a zero matrix, both having the same dimension as x. (11) can transform any three-phase system into the d-q model directly.

When equations (1) – (4) are transformed into d-q coordinates, (12) – (14) are obtained, as in (Blasko & Kaura, 1997; Ye, 2000; Kazmierkowski et al., 2002).

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + \omega i_q - \frac{1}{L}V_{dc}d_d - \frac{U_d}{L} \tag{12}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q - \omega i_d - \frac{1}{L}V_{dc}d_q - \frac{U_q}{L} \tag{13}$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C}(i_d d_d + i_q d_q) - \frac{1}{C}i_{dc} \tag{14}$$

Where i_d and i_q are the d-q transformation of i_a, i_b and i_c. v_d and v_q are the d-q transformation of v_a , v_b and v_c. d_d and d_q are the d-q transformation of d_a, d_b and d_c .

4. Input-output feedback linearization technique

Feedback linearization can be used as a nonlinear design methodology. The basic idea is first to transform a nonlinear system into a (fully or partially) linear system, and then to use the well-known and powerful linear design techniques to complete the control design. It is completely different from conventional linearization. In feedback linearization, instead of linear approximations of the dynamics, the process is carried out by exact state transformation and feedback. Besides, it is thought that the original system is transformed into an equivalent simpler form. Furthermore, there are two feedback linearization methods that are input-state and input-output feedback linearization (Slotine & Li, 1991; Isidori, 1995; Khalil, 2000; Lee et al., 2000; Lee, 2003).

The input-output feedback linearization technique is summarized by three rules;

- Deriving output until input appears
- Choosing a new control variable which provides to reduce the tracking error and to eliminate the nonlinearity
- Studying stability of the internal dynamics which are the part of system dynamics cannot be observed in input-output linearization (Slotine & Li, 1991)

If it is considered an input-output system, as in (15)-(16);

$$\dot{X} = f(x) + g(x)u \tag{15}$$

$$y = h(x) \tag{16}$$

To obtain input-output linearization of this system, the outputs y must be differentiated until inputs u appears. By differentiating (16), equation (17) is obtained.

$$\dot{y} = \frac{\partial h}{\partial x}[f(x) + g(x)u] = L_f h(x) + L_g h(x)u \tag{17}$$

In (17), $L_f h$ and $L_g h$ are the Lie derivatives of f(x) and h(x), respectively and identified in (18).

$$L_f h(x) = \frac{\partial h}{\partial x}f(x), \quad L_g h(x) = \frac{\partial h}{\partial x}g(x) \tag{18}$$

If the k is taken as a constant value; k. order derivatives of h(x) and 0. order derivative of h(x) are shown in (19) - (20), respectively.

$$L_f^k h(x) = L_f L_f^{k-1} h(x) = \frac{\partial (L_f^{k-1} h)}{\partial x} f(x) \tag{19}$$

$$L_f^0 h(x) = h(x) \tag{20}$$

After first derivation, If $L_g h$ is equal to "0", the output equation becomes $\dot{y} = L_f h(x)$. However, it is independent from u input. Therefore, it is required to take a derivative of output again. Second derivation of output can be written in (23), with the help of (21)-(22).

$$L_g L_f h(x) = \frac{\partial (L_f h)}{\partial x} g(x) \tag{21}$$

$$L_f^2 h(x) = L_f L_f h(x) = \frac{\partial (L_f h)}{\partial x} f(x) \tag{22}$$

$$\ddot{y} = \frac{\partial L_f h}{\partial x} [f(x) + g(x)u] = L_f^2 h(x) + L_g L_f h(x) u \tag{23}$$

If $L_g L_f h(x)$ is again equal to "0", $\ddot{y}$ is equal to $L_f^2 h(x)$and it is also independent from u input and it is continued to take the derivation of output. After r times derivation, if the condition of (24) is provided, input appears in output and (25) is obtained.

$$L_{g_i} L_f^{r_i - 1} h_i(x) \neq 0 \tag{24}$$

$$y_i^{r_i} = L_f^{r_i} h_i + \sum_{i=1}^{n} \left(L_{g_i} L_f^{r_i - 1} h_i \right) u_i \tag{25}$$

Applying (25) for all n outputs, (26) is derived.

$$\begin{bmatrix} y_1^{r_1} \\ \vdots \\ y_1^{r_n} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ \vdots \\ L_f^{r_n} h_n(x) \end{bmatrix} + E(x) \begin{bmatrix} u_1 \\ \vdots \\ u_n \end{bmatrix} = a(x) + E(x)u \tag{26}$$

E(x) in (27) is a decoupling matrix, if it is invertible and new control variable is chosen, feedback transformation is obtained, as in (28).

$$E(x) = \begin{bmatrix} L_{g_1} L_f^{r_1 - 1} h_1 & \cdots & L_{g_n} L_f^{r_n - 1} h_1 \\ \vdots & \ddots & \vdots \\ L_{g_1} L_f^{r_n - 1} & \cdots & L_{g_n} L_f^{r_n - 1} h_n \end{bmatrix} \tag{27}$$

$$\begin{bmatrix} u_1 \\ \vdots \\ u_n \end{bmatrix} = -E^{-1} \begin{bmatrix} L_f^{r_1} h_1(x) \\ \vdots \\ L_f^{r_n} h_n(x) \end{bmatrix} + E^{-1} \begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix} \tag{28}$$

Equation (29) shows the relation between the new inputs v and the outputs y. The input-output relation is decoupled and linear (Lee et al., 2000).

$$\begin{bmatrix} y_1^{r_1} \\ \cdots \\ \cdots \\ y_1^{r_n} \end{bmatrix} = \begin{bmatrix} v_1 \\ \cdots \\ \cdots \\ v_n \end{bmatrix} \tag{29}$$

If the closed loop error dynamics is considered, as in (30) – (31), (32) defines new inputs for tracking control.

$$\begin{bmatrix} e_1^r + k_{1(r-2)}e_1^{r-1} + \cdots + k_{11}e_1^1 + k_{10}e_1 \\ \cdots \\ \cdots \\ e_n^r + k_{n(r-1)}e_n^{r-1} + \cdots + k_{21}e_1^1 + k_{20}e_n \end{bmatrix} = \begin{bmatrix} 0 \\ \cdots \\ \cdots \\ 0 \end{bmatrix} \tag{30}$$

$$\begin{bmatrix} e \\ \cdots \\ \cdots \\ e^r \end{bmatrix} = \begin{bmatrix} y - y^* \\ \cdots \\ \cdots \\ y^r - y^{*^r} \end{bmatrix} \tag{31}$$

$$\begin{bmatrix} v_1 \\ \cdots \\ \cdots \\ v_n \end{bmatrix} = \begin{bmatrix} -k_{1(r-1)}y^{r-1} - \cdots - k_{11(r-1)}y^1 - k_{10}(y_1 - y_1^*) \\ \cdots \\ \cdots \\ -k_{n(r-1)}y^{r-1} - \cdots - k_{21(r-1)}y^1 - k_{20}(y_n - y_n^*) \end{bmatrix} \tag{32}$$

k values in equations show the constant values for stability of systems and tracking of y references, as in (Lee, 2003).

5. The application of an input-output feedback linearization to the VSC

The state feedback transformation allows the linear and independent control of the d and q components of the line currents in VSC by means of the new inputs u_d and u_q .

For unity power factor, in (12 – 14) $u_d = V_m$ and $u_q = 0$ are taken, so mathematical model of this system is derived with (33-35), as in (Kömürcügil & Kükrer, 1998; Lee, 2003).

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + \omega i_q - \frac{1}{L}V_{dc}d_d - \frac{V_m}{L} \tag{33}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q - \omega i_d - \frac{1}{L}V_{dc}d_q \tag{34}$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C}(i_d d_d + i_q d_q) - \frac{1}{C}i_{dc} \tag{35}$$

If (33-35) are written with the form of (15), (36) is derived.

$$f(x) = \begin{bmatrix} -\frac{R}{L}\, i_d + \omega i_q + \frac{V_m}{L} \\ -\omega i_d - \frac{R}{L} i_q \\ \frac{1}{C} i_{dc} \end{bmatrix}, \; g(x) = \begin{bmatrix} -\frac{1}{L}V_{dc} & 0 \\ 0 & -\frac{1}{L}V_{dc} \\ \frac{1}{C}i_d & \frac{1}{C}i_q \end{bmatrix} \tag{36}$$

The main purpose of this control method is to regulate V_{dc} voltage by setting i_d current and to provide unity power factor by controlling i_q current. Therefore, variables of y outputs and reference values are chosen as in (37).

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