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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.
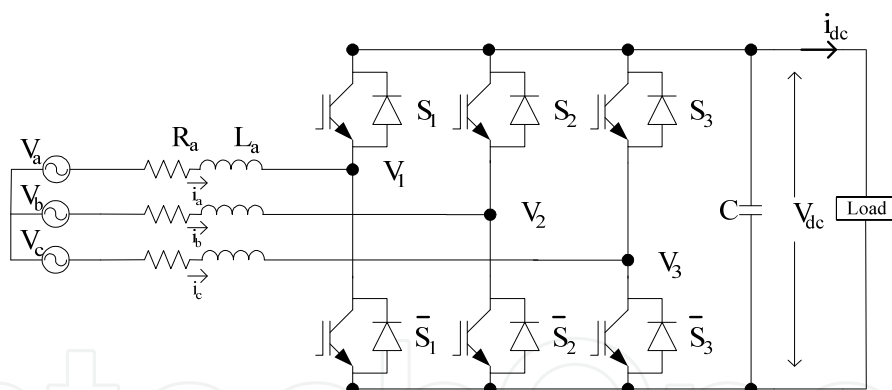

Fig. 1. L filtered VSC

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.

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

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

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

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

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.
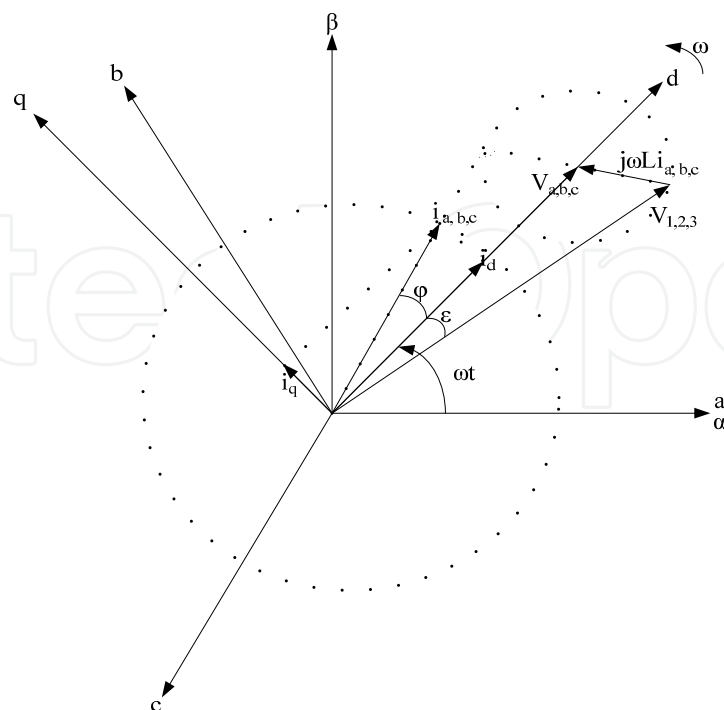

Fig. 2. Coordinates diagram of a-b-c, α-β and d-q

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).

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

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

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

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);

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

$$y = h(x) \qquad (16)$$

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.

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

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

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

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.

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

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).

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

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

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).

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} \ , y^* = \begin{bmatrix} I_d^* \\ 0 \end{bmatrix} \tag{37}$$

Differentiating outputs of (37), (38) is obtained. The order of derivation process, finding a relation between y outputs and u inputs, is called as relative degree. It is also seen that the relative degree of the system is '1'.

$$\dot{y} = \begin{bmatrix} \dot{i_d} \\ \dot{i_q} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}V_{dc} & 0 \\ 0 & -\frac{1}{L}V_{dc} \end{bmatrix} u + \begin{bmatrix} -\frac{R}{L}i_d + \omega i_q + \frac{V_m}{L} \\ -\omega i_d - \frac{R}{L}i_q \end{bmatrix} \tag{38}$$
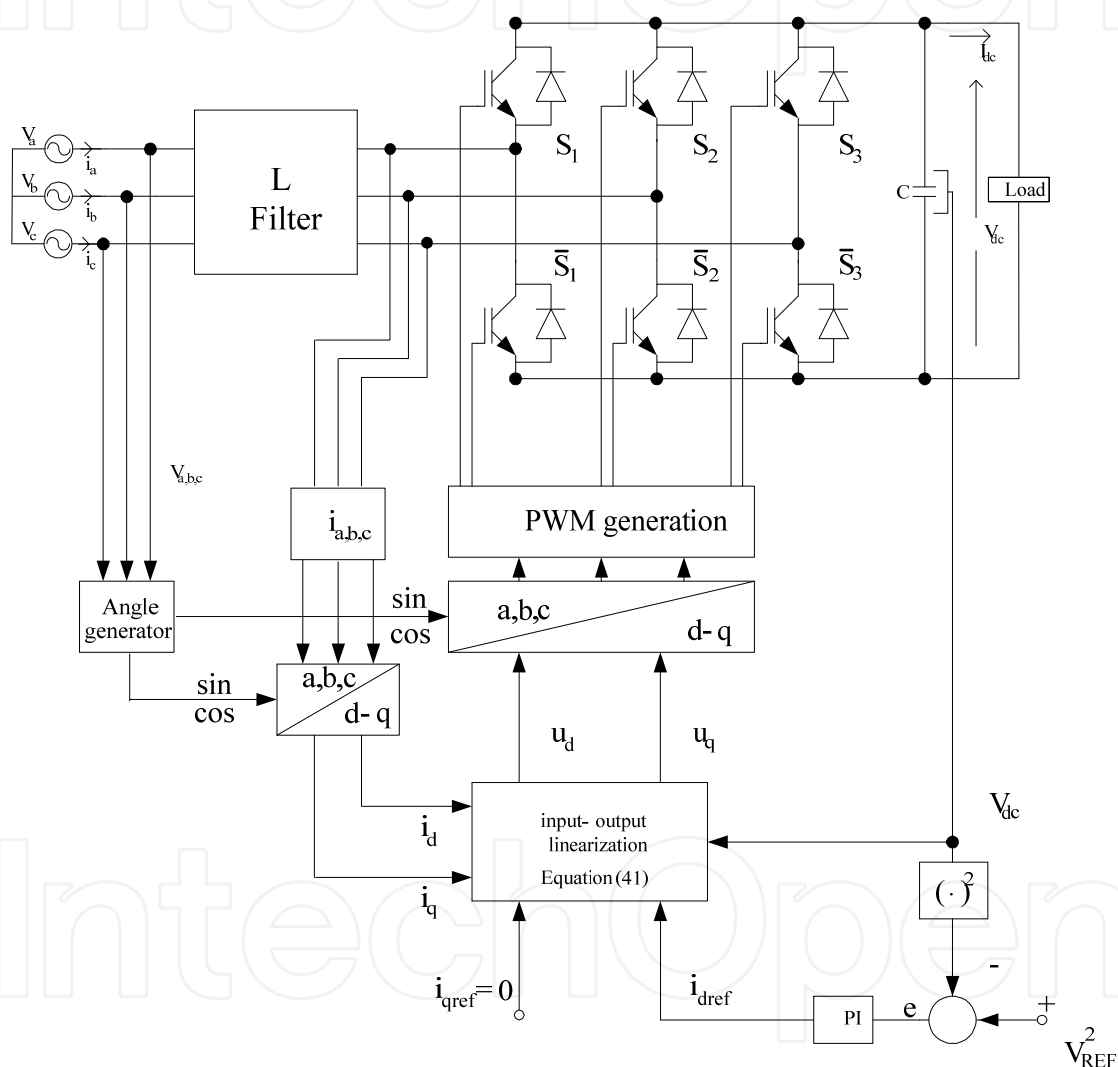
Fig. 3. Input-output feedback linearization control algorithm of VSC

When (38) is ordered like (28), (39) is obtained.

$$u = \begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}V_{dc} & 0 \\ 0 & -\frac{1}{L}V_{dc} \end{bmatrix}^{-1} \cdot \left(-\begin{bmatrix} -\frac{R}{L}i_d + \omega i_q + \frac{V_m}{L} \\ -\omega i_d - \frac{R}{L}i_q \end{bmatrix} + v \right) \tag{39}$$

After taking inverse of matrix (39) and adding new control inputs from (40), (41) is obtained.

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} -k_1(y_1 - I_d^*) \\ -k_2(y_2 - I_q^*) \end{bmatrix} \tag{40}$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} -\frac{L}{V_{dc}} & 0 \\ 0 & -\frac{L}{V_{dc}} \end{bmatrix} \cdot \left(\begin{bmatrix} \frac{R}{L}i_d - \omega i_q - \frac{V_m}{L} \\ \omega i_d + \frac{R}{L}i_q \end{bmatrix} + \begin{bmatrix} -k_1(y_1 - I_d^*) \\ -k_2 y_2 \end{bmatrix} \right) \tag{41}$$

Control algorithm is seen in Fig.3. For both L and LCL filtered VSC, the same control algorithm can be used. Providing the unity power factor, angle values are obtained from line voltages. This angle values are used in transformation of a-b-c to d-q frames. Line currents which are transformed into d-q frame, are compared with d-q reference currents. d axis reference current i_{dref} is obtained by comparison of dc reference voltage V_{ref} and actual dc voltage V_{dc}. On the other hand, q axis reference current i_{qref} is set to '0' to provide unity power factor. And by using (41), switching functions of d-q components are found. Then, this d-q switching functions are transformed into a-b-c frames and they are sent to PWM block to produce pulses for power switches.

Providing the control of internal dynamics, in dc controller square of V_{ref} and V_{dc} are used (Lee, 2003).

6. DC machine and armature circuit model

Electrical machines are used for the conversion of electric power to mechanical power or vice versa. In industry, there are wide range of electrical machines that are dc machines, induction machines, synchronous machines, variable reluctance machines and stepping motors. The Dc machines can be classified as a brushless and brushed dc machines. Furthermore, the advantage of brushed dc machines is the simplicity with regard to speed control in the whole machines. However, the main disadvantage of this kind of machines is the need of maintenance because of its brushes and commutators.

Fig. 4 shows the basic structure of brushed dc machines. Basic components of dc machines are field poles, armature, commutator and brushes (Fitzgerald et al., 2003).
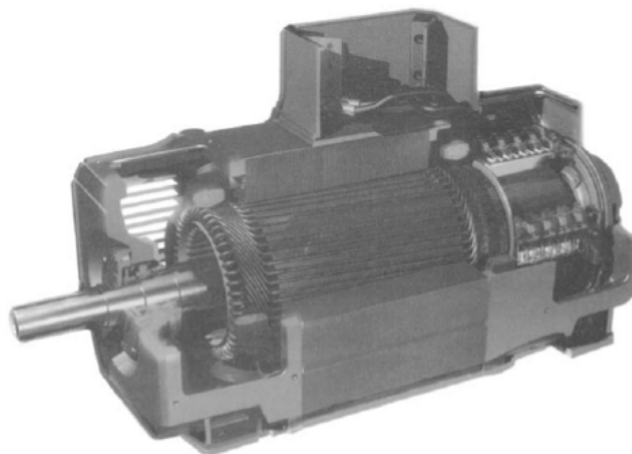

Fig. 4. Dc machine

Field poles produce the main magnetic flux inside of the machines with the help of the field coils which are wound around the poles and carry the field current. Some of the dc

machines, the magnetic flux is provided by the permanent magnet instead of the field coils. In Fig. 5, the field coils and field poles of dc machines are shown (Bal, 2008).
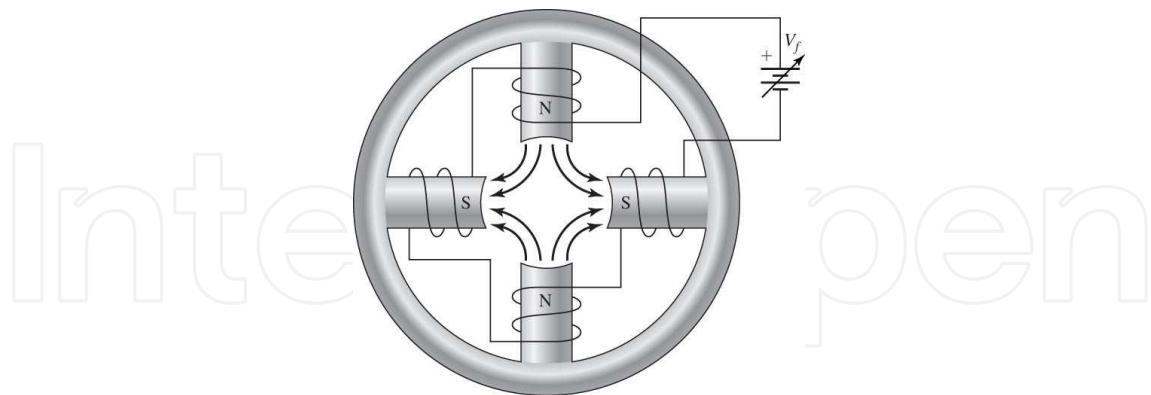

Fig. 5. Field coils and field poles of a dc machine

The rotating part of the dc machine is called as an armature. The armature consists of iron core, conductors and commutator. Besides, there is a shaft inside of armature that rotates between the field poles. The other part of the machine is commutator which is made up of copper segments and it is mounted on the shaft. Furthermore, the armature conductors are connected on the commutator. Another component of dc machine is brushes. The brushes provide the electric current required by armature conductors. In dc machine to ensure the rotation of the shaft, the armature conductors must be energized. This task is achieved by brushes that contact copper segments of commutator. Also, the brushes generally consist of carbon due to its good characteristic of electrical permeability. Fig. 6 shows the armature, commutator and the brushes (Fitzgerald et al., 2003; Bal, 2008).
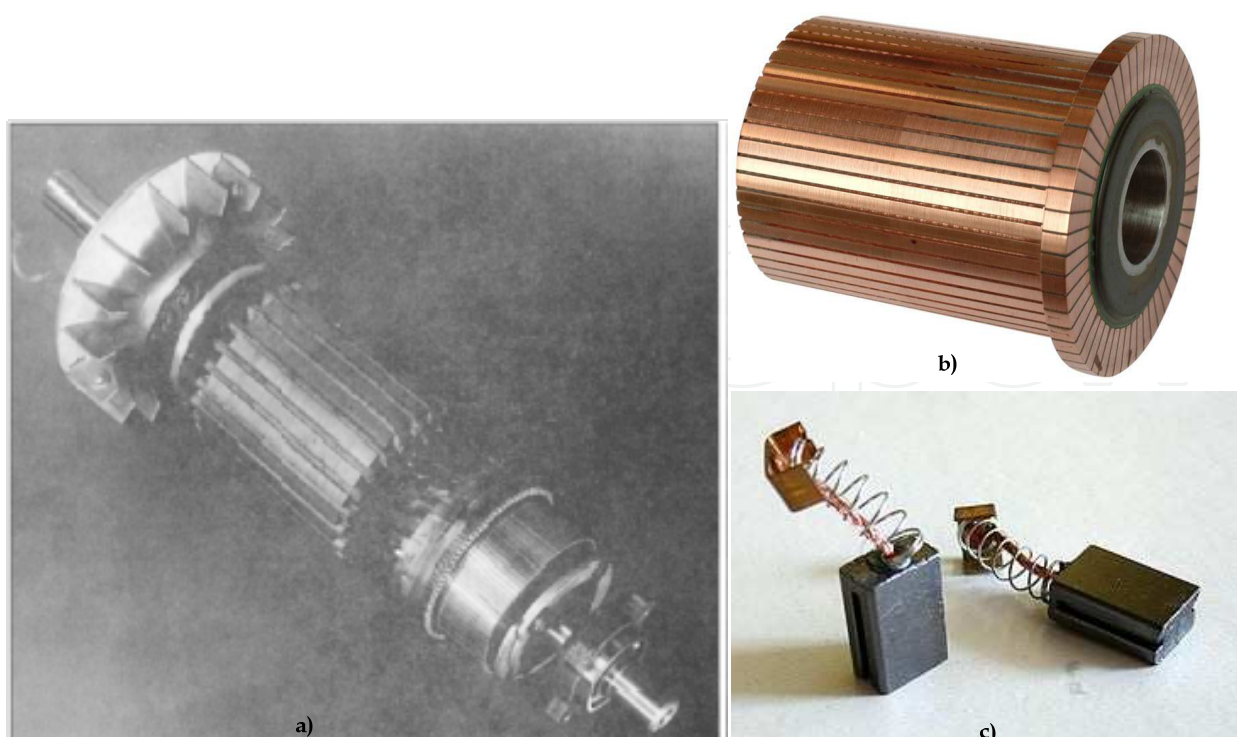

Fig. 6. a) armature, b) commutator and c) brushes of a dc machine

To produce the main flux, the field must be excited. For this task, there are four methods which are separately, shunt, series and compound to excitation of dc machines and are shown in Fig. 7. However, separately excited dc machine is the most useful method because it provides independent control of field and armature currents. Therefore, this structure is used in this chapter (Krishnan, 2001; Fitzgerald et al., 2003).
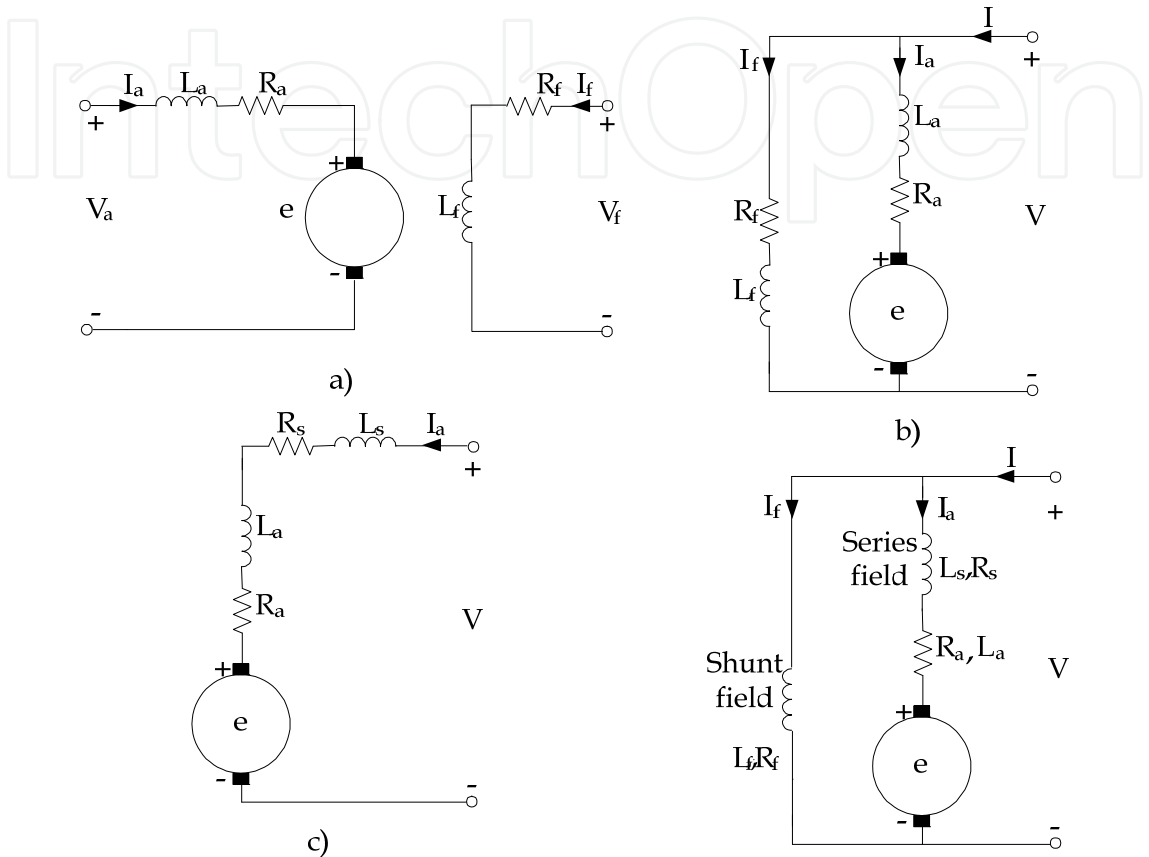

Fig. 7. Excitation methods of dc machine a) separately, b) shunt, c) series, d) compound excitation

There are two basic speed control structure of dc machine which are armature and field, as in (Krishnan, 2001). The armature circuit model of dc machine is shown in Fig. 8.
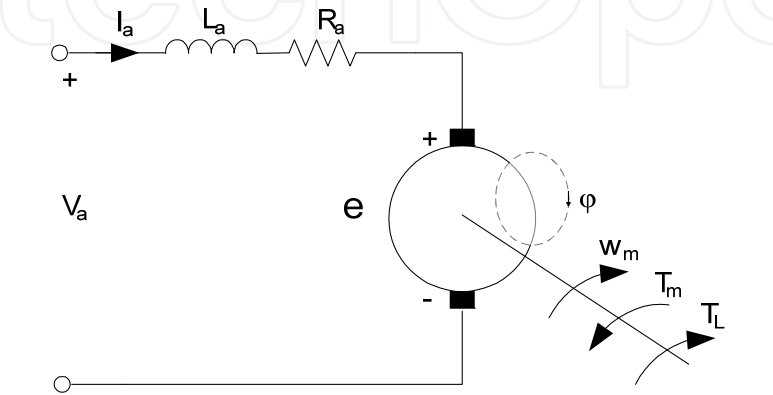
Fig. 8. Armature circuit model of dc machine

The mathematical model of armature circuit can be written by (42).

$$v = e + R_a I_a + L_a \frac{di_a}{dt} \qquad (42)$$

In steady state, $\frac{di_a}{dt}$ part is zero because of the armature current is constant. The armature model is then obtained by (43), (Krishnan, 2001).

$$v = e + R_a I_a \qquad (43)$$

$$e = K \Phi_f \omega_m \qquad (44)$$

(43) is written in (44), (45) is derived.

$$\omega_m \approx \frac{(V - R_a I_a)}{I_f} \qquad (45)$$

The speed of dc machine depends on armature voltage and field current, as shown in (45). In field control, the armature voltage is kept constant and the field current is set. The relation between speed and field current is indirect proportion. However, in armature control, the relation between armature voltage and speed is directly proportional. Furthermore, in armature control, the field current is kept constant and the armature voltage is set.

In this chapter, the armature control of dc machine is realized.

The speed control loop is added to nonlinear control loop. Firstly, the actual speed is compared with reference speed then the speed error is regulated by PI controller and after that its subtraction from armature current, the reference current is obtained. The reference current obtained by speed loop, is added to nonlinear control loop instead of reference i_d current, which is obtained by the comparison of the square of reference voltage and actual voltage.
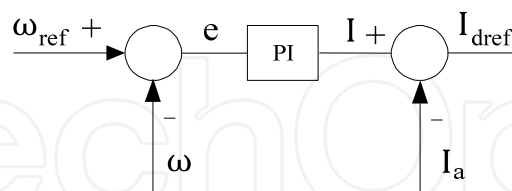
In Fig. 9, speed control loop is shown.

Fig. 9. Armature speed control loop of dc machine

7. Simulations

Simulations are realized with Matlab/Simulink. Line voltage is taken 220 V, 60 Hz. The switching frequency is also chosen 9 kHz. L filter and controllers parameters are shown in Table.1 and Table.2.

Simulation diagram is shown in Fig.10. By simulation, steady-state error and settling time of dc motor speed, harmonic distortions and shapes of line currents and unity power factor are examined.

Passive Components		
L Filter		Dc-Link
L (H)	R (Ω)	C_{dc} (μF)
0.0045	5.5	2200

Table 1. Values of L filter components

Controllers			
Speed Controller		Input-output current controller	
K_p	K_i	k (10^3)	K (10^5)
10	0.01	30	50

Table 2. Values of controllers

Fig. 10. Simulation diagram of dc machine controller in Simulink

Fig.11 shows the structure of input-output controller diagram.

Fig. 11. Input-output controller diagram

Equation (41) is written in the block of input-output controller which is shown in Fig.12.
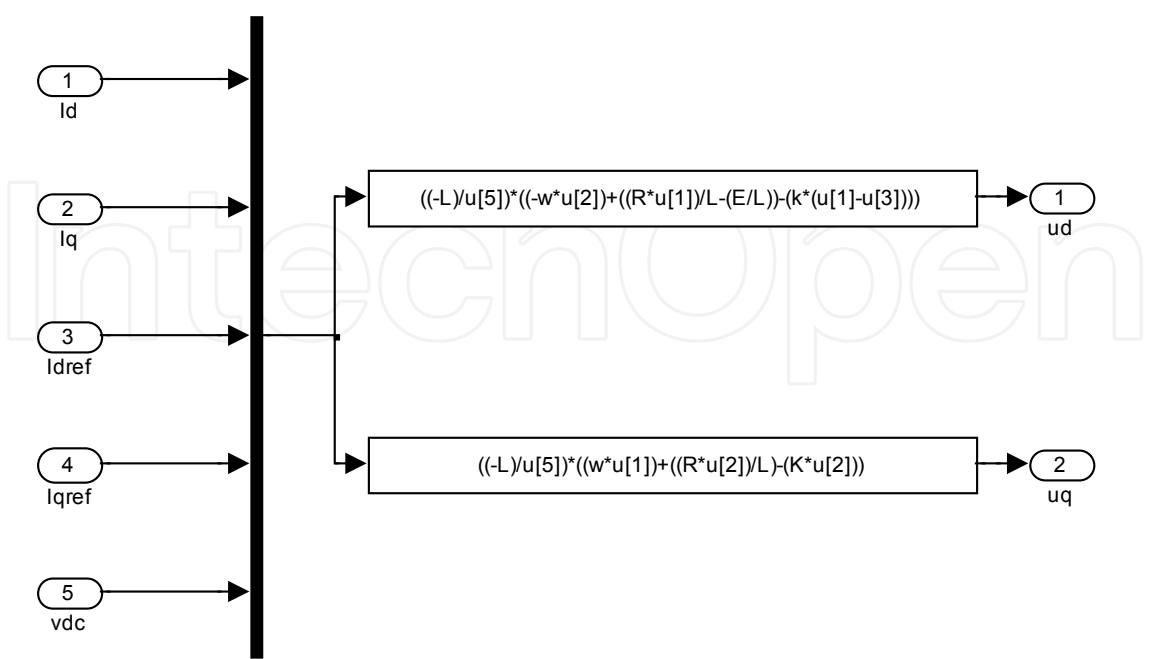
Fig. 12. Input – output controller

Fig. 13 shows the speed controller of dc machine.
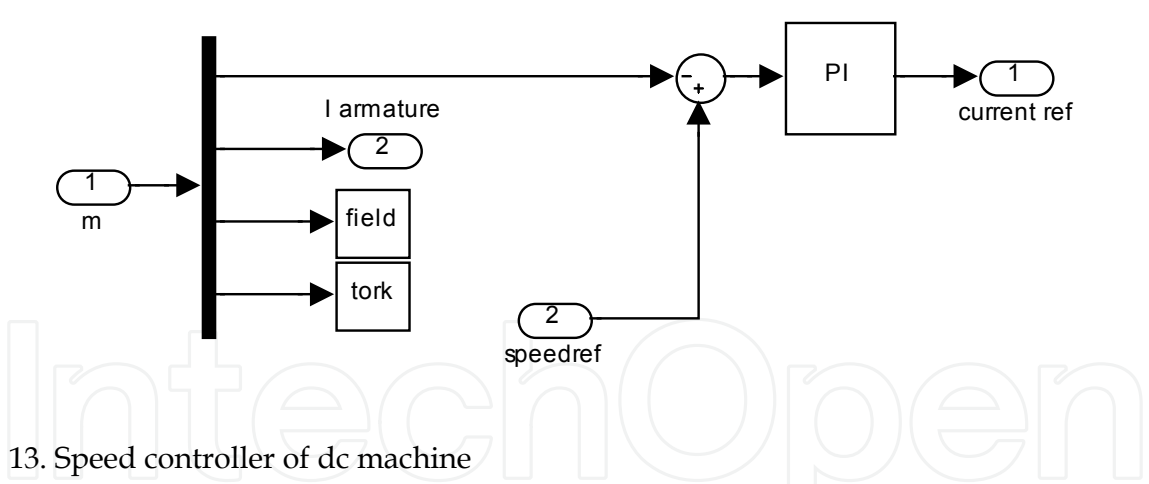
Fig. 13. Speed controller of dc machine

Fig.14 shows the dc machine speed. Reference speed value is changed from 150 rad/s to 200rad/s at 0.5 s. Settling time to the first reference is shorter than 0.15 s, but settling time of second reference is 0.1 s.

Fig. 15 shows the steady-state error of dc machine speed. It is seen that the steady – state error changes between ±2 rad/s.

The one phase voltage and current is shown in Fig. 16. It is also seen that unity power factor is obtained but not as desired.

Fig. 17 shows the line currents. The shapes of line currents are sinusoidal.
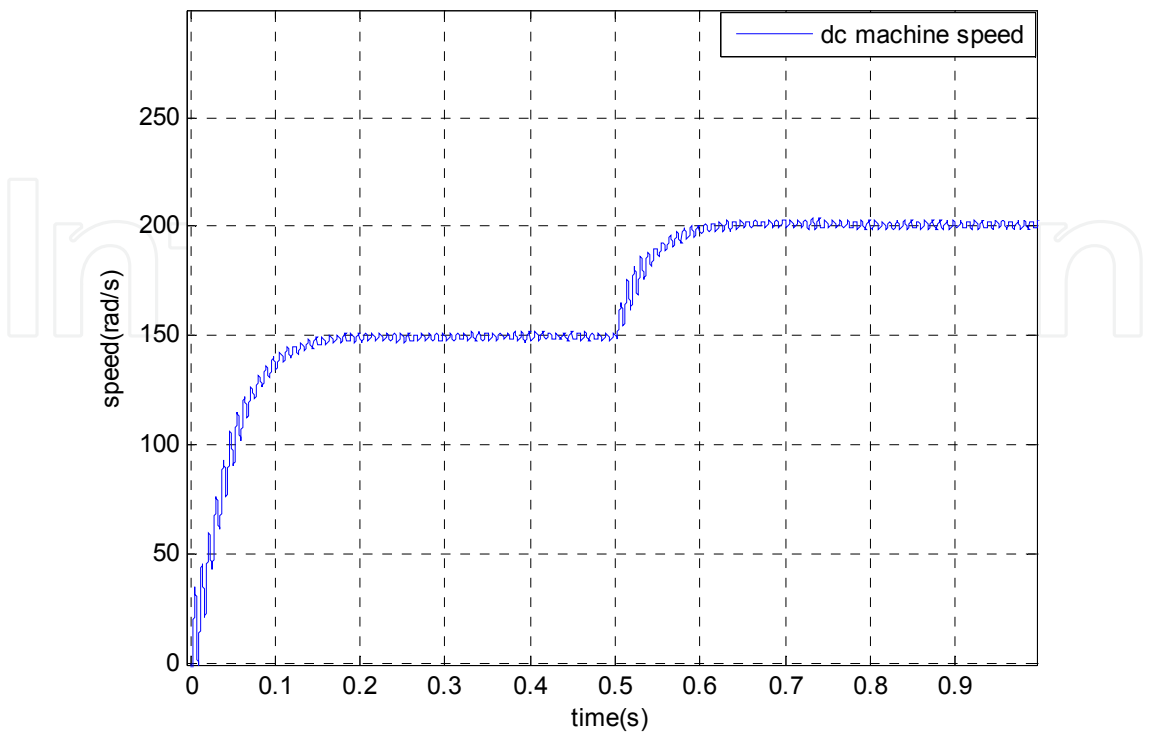
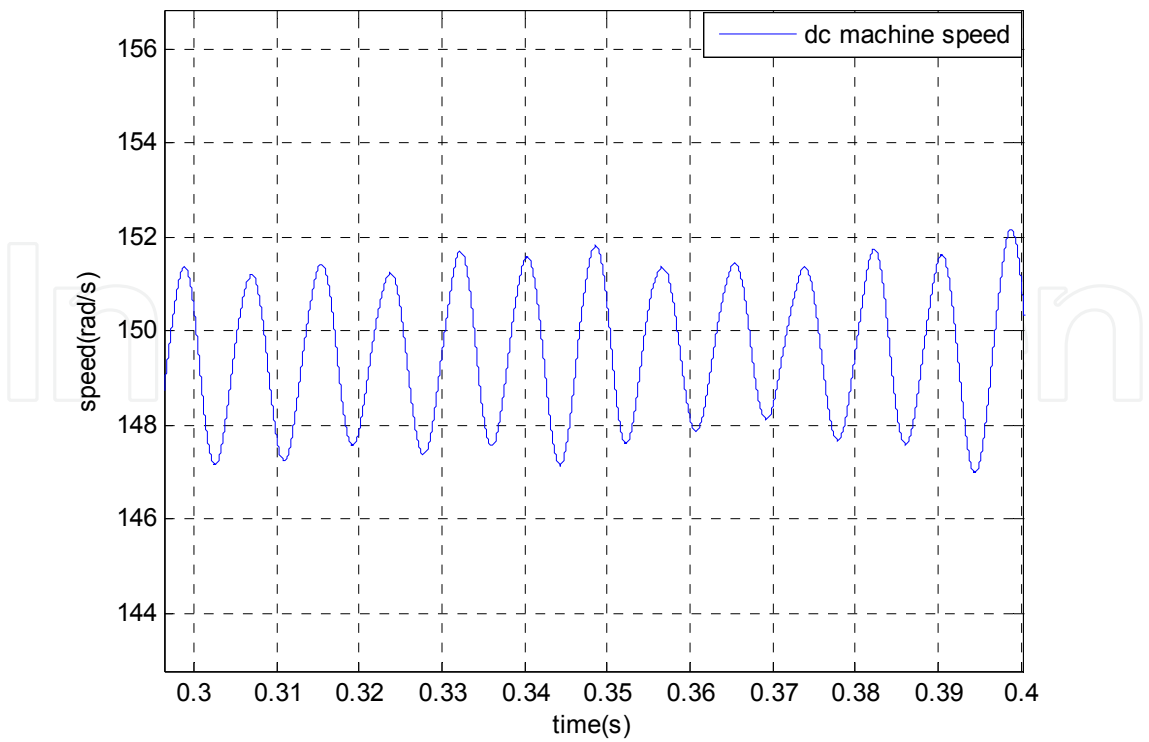Fig. 14. Dc machine speed

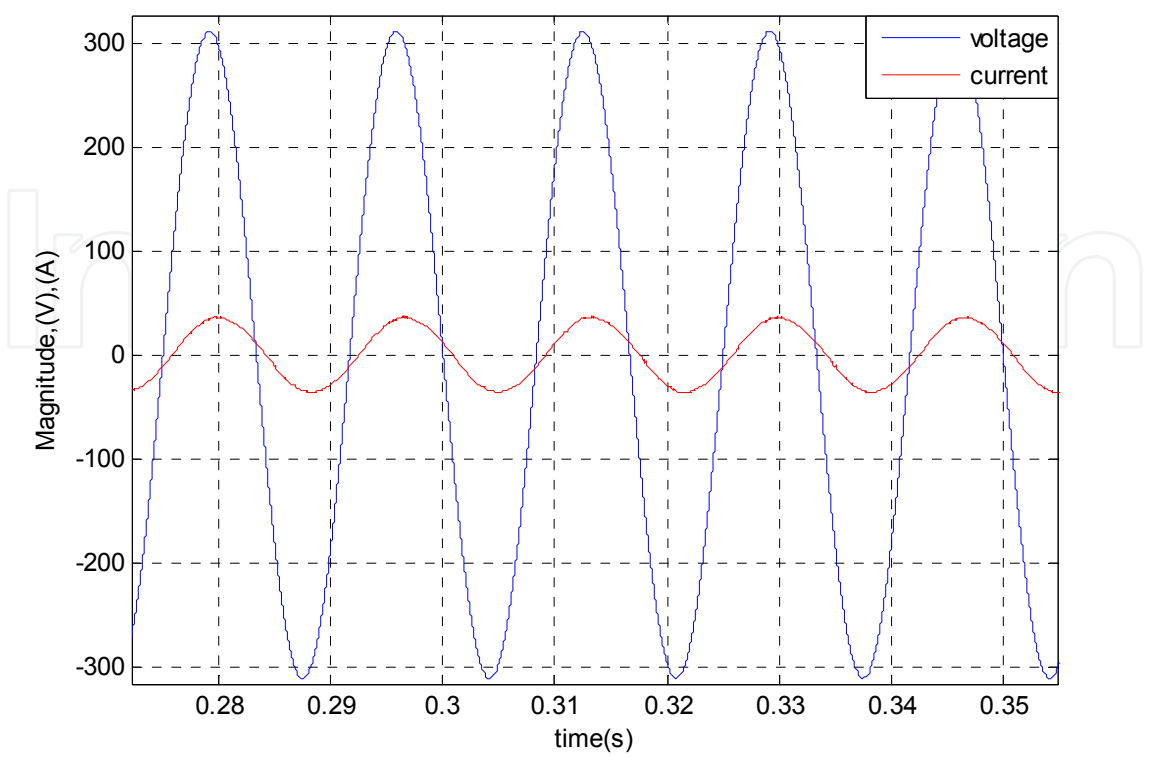Fig. 15. Steady-state error of dc machine speed

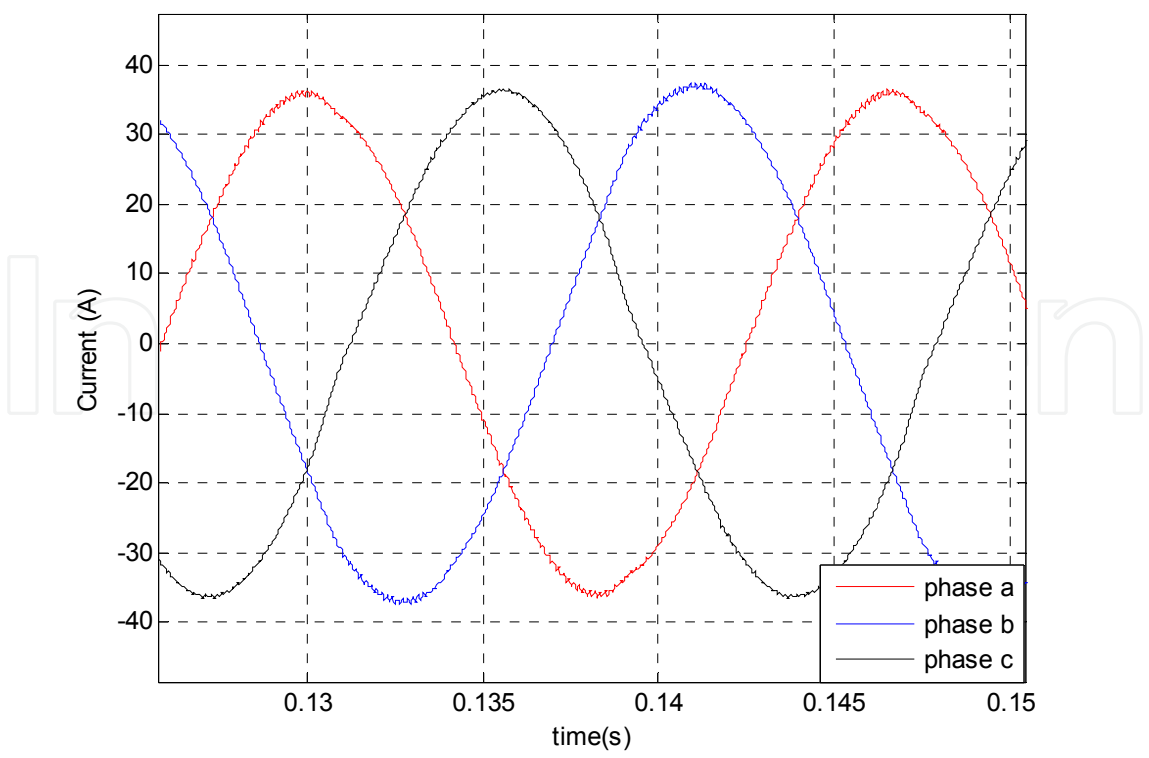Fig. 16. One phase voltage and current

Fig. 17. Three-phase phase current

Fig. 18 shows the harmonic distortions of line currents. Line currents include high order harmonic contents. However, total harmonic distortion value (THD) is under the value that is defined by standards. THD of line currents are %1.34, %1.71 and %2.84.
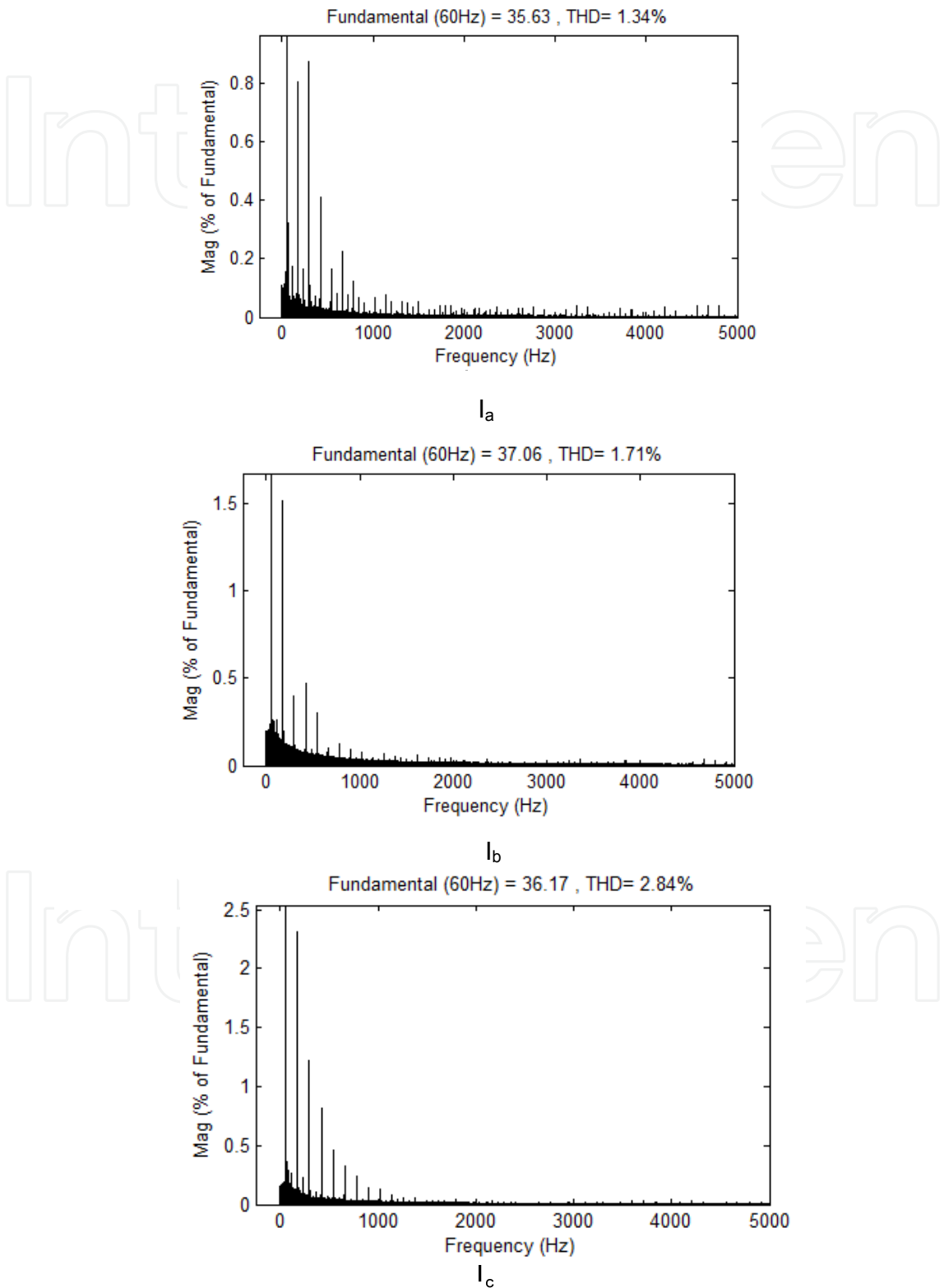
Fundamental (60Hz) = 35.63 , THD= 1.34%

I_a

Fundamental (60Hz) = 37.06 , THD= 1.71%

I_b

Fundamental (60Hz) = 36.17 , THD= 2.84%

I_c

Fig. 18. Harmonic distortions of line currents

8. Conclusion

In this chapter, simulation of dc machine armature speed control is realized. Dc machine is fed by voltage source rectifier which is controlled input – output linearization nonlinear control method. Furthermore, for the speed control, dc link voltage is regulated by the dc machine speed control loop. The control algorithm of voltage source rectifier and dc motor speed are combined. The required reference I_d current for voltage source rectifier is obtained by speed control loop. Simulations are carried through Matlab/Simulink. By means of the simulation results, the speed of dc machine, line currents harmonic distortions and power factor of grid are shown. It is shown that the voltage source rectifier with dc machine as a load provides lower harmonic distortion and higher power factor. Furthermore, dc machine speed can be regulated.

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