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Design and Research on Passive Controller for Three-phase Voltage-source PWM Rectifier

***Abstract**. This paper designs crude oil electric dehydration pulse power rectifier control system based on passivity-based control theory. This paper deduces the mathematical model of PWM rectifier on the basis of Euler-Lagrange (EL) Equation, proves passivity stability of PWM rectifier, deduces passivity-based control laws of the system and PWM modulation laws, and finally completes design of PWM rectifier controller.*

***Streszczenie.** W artykule opisano sterowanie dla prostownika pracującego w systemie do dehydratacji ropy naftowej metodami elektrycznym, o impulsowym poborze mocy. Algorytm oparty został na teorii pasywności. Zaprezentowano, oparty na równaniach Euler'a-Lagrange'a model matematyczny prostownika. Przedstawiono opracowane algorytmy sterowania i modulacji oraz dowód stabilności pasywnej urządzenia. (**Projekt i badania sterownika pasywnego dla trójfazowego prostownika napięcia MSI**).*

Keywords: Passivity-based control; Euler-Lagrange model; PWM rectifier; Electric dehydrator
Słowa kluczowe: sterowanie pasywne, model Eulere'a-Lagrange'a, prostownik MSI, dehydratacja metodami elektrycznymi.

Introduction

The concept of "passivity" is abstracted from energy consumption network with extensive engineering background. Passivity-based control theory becomes an important role for analysis and design of nonlinear system and is widely used in research field about adaptive control and robust control. Passivity-based control method is generated by Ortega et.al. who are inspired by robot-based control. Passivity in electromechanical system is an extension of the concept of passivity in circuit network, namely, if energy of one system is always less than or equal to the sum of initial energy of the system and externally provided energy, then it indicates that the system only absorb energy from the outside and the system itself does not release energy to the outside; thus, this system can be called the passive system. Passivity has many good control performances. Passivity is one control method of global definition and global stability. This method has no singularity (and is appropriated for low speed and even starting situation). Passivity-based control method uses damping injection method to make subsystem of electrical machine be passive strictly, and accordingly, to make the system be susceptible to parameter change of rotor resistance.

Establishment of Euler-Lagrange model equation of rectifier

The cause of adopting Euler-Lagrange system to establish the mathematical model of PWM rectifier to design nonlinear passivity-based controller is that it describes the characteristics of large quantities of project systems.

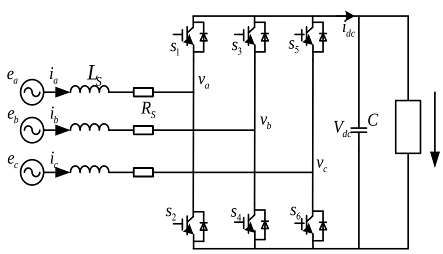

Fig.1. Structure of three-phase voltage-type PWM rectifier

Figure 1 shows topological structure of the crude oil electric dehydration pulse power rectifier. e_a, e_b, e_c are AC input phase voltage with the amplitude value of E_m ; C is DC-side filtering capacitance; *L*B*SB* is AC-side inductance; the sum of parasitic resistance of inductance and internal resistance of voltage source and switching element is equivalent to resistance *R*B*S*. The current and voltage of rectifier input end are *I* and *v*B*kB* respectively, *k*=*a*, *b*, *c*. The resistance *R*B*S*. is equivalent load. When Euler-Lagrange Equation is applied to PWM rectifier system, q and q respectively stand for electric quantity and current of the system; $L(q,\dot{q})$ is Lagrange function of the system; $F(\dot{q})$ is Rayleith dissipative function; *Q* represents the power supply or others which are applied to the system. $T(q,\dot{q})$ and $P(q)$ represent kinetic energy and potential energy on the circuit.

Through analysis of three-phase PWM rectifier circuit, input current i_a, i_b, i_c of three-phase PWM rectifier can expressed as $\dot{q}_a$, $\dot{q}_b$, $\dot{q}_c$, while $\dot{q}_{dc}, q_{dc}$ represent DC-side current and electric quantity respectively. Thus, the following is obtained:

(1) $$T(q,\dot{q}) = \frac{1}{2}L(\dot{q}_a{}^2 + \dot{q}_b{}^2 + \dot{q}_c{}^2)$$

(2) $$P(q) = \frac{1}{2C}q_{dc}{}^2$$

(3) $$F(\dot{q}) = \frac{1}{2}R(\dot{q}_a{}^2 + \dot{q}_b{}^2 + \dot{q}_c{}^2) + \frac{1}{2}R_{dc}[\dot{q}_{dc} - \frac{1}{2}(u_a\dot{q}_a + u_b\dot{q}_b + u_c\dot{q}_c)]$$

(4) $$Q = [e_a, e_b, e_c]^T$$

Where, ua, ub and uc are switching functions of the system. In order to describe the switch state vividly and separate it from voltage sign u , define the switching function of the system as S_a , S_b and S_c .

(5) $$S_j = u_j = \begin{cases} 1, & u_j : closed \\ -1, & \bar{u}_j : closed \end{cases}, j = a,b,c$$

Substitute (1), (2), (3), (4) and (5) into above equation, Euler-Lagrange model of three-phase PWM rectifier can be obtained:

(6) $$\begin{cases} L_S\dfrac{di_a}{dt} + R_S i_a + \dfrac{1}{2}S_a Vdc = e_a \\ L_S\dfrac{di_b}{dt} + R_S i_b + \dfrac{1}{2}S_b Vdc = e_b \\ L_S\dfrac{di_c}{dt} + R_S i_c + \dfrac{1}{2}S_c Vdc = e_c \\ C\dfrac{dVdc}{dt} + \dfrac{1}{2}(S_a i_a + S_b i_b + S_c i_c) + \dfrac{Vdc}{R_L} = 0 \end{cases}$$

In order to simplify the mathematical model for analysis, mathematical space coordinate system transformation concept is adopted. Three-phase system under abc coordinate system mentioned in the previous section can be transformed in $\alpha\beta$ two-phase coordinate system. The equivalent condition under three-phase coordinate system, two-phase coordinates system and rotating coordinate system is that they can produce the same rotating magnetomotiveforce. Make Phase A axis and real axis of plural coordinate system coincide, and make abc three-phase coordinate become $\alpha\beta$ two-phase coordinate. The coordinate is transformed as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C_{3s/2s} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Transform the matrix according to this coordinate, and rewrite the mathematical model of the rectifier under $\alpha\beta$ coordinate system.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C_{3s/2s} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{7}$$

The model equation obtained is the transformational model under two-phase rest coordinate system. In order to facilitate controller design, the mathematical model of three-phase PWM rectifier is transformed to two-phase synchronous rotating dq coordinate system from two-phase rest coordinate system, with transformation matrix $T_{dq}/T_{\alpha\beta}$. Thus, equation (8) can be deduced:

$$\begin{cases} \frac{di_d}{dt} = -\frac{R_S}{L_S} i_d + \omega i_q - \frac{S_d}{L_S} V_{dc} + \frac{1}{L_S} e_d \\ \frac{di_q}{dt} = -\omega i_d - \frac{R_S}{L_S} i_q - \frac{S_q}{L_S} V_{dc} + \frac{1}{L_S} e_q \\ \frac{dV_{dc}}{dt} = \frac{3S_d}{2C_{dc}} i_d + \frac{3S_q}{2C_{dc}} i_q - \frac{1}{C_{dc}} i_L \end{cases} \tag{8}$$

The mathematical model of the parallel convertor under dq rotating coordinate system can be obtained through (9),

$$T_{abc-dq} = \frac{2}{3} \begin{bmatrix} \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin\omega t & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{9}$$

Thus, after the mathematical model of PWM rectifier is through continuous coordinate transformation, the Euler-Lagrange model can be transformed as:

$$\begin{cases} L_S \frac{di_d}{dt} + R_S i_d + \omega L i_q + \frac{1}{2} VdcS_d = E_m \\ L_S \frac{di_q}{dt} + R_S i_q - \omega L i_d + \frac{1}{2} VdcS_q = 0 \\ \frac{2C}{3}\frac{dVdc}{dt} - \frac{1}{2}(i_d S_d + i_q S_q) + \frac{2V_{dc}}{3R_L} = 0 \end{cases} \tag{10}$$

where, E_m is amplitude voltage of system phase voltage; S_d and S_q are control signals. When S_d and S_q are transformed to abc axis through dq coordinate system, they still represent the switching functions of the system.

This differential equation is written as EL model equation expressed as matrix, i.e.:

$$M\dot{x} + [J_1 + J_2(u)]x + R_S x = \varepsilon \tag{11}$$

where,

$$M = \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & \frac{2}{3}C \end{bmatrix}, \quad u = \begin{bmatrix} S_d \\ S_q \end{bmatrix}, \quad x = \begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix}, \quad J_1 = \begin{bmatrix} 0 & \omega L & 0 \\ \omega L & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\varepsilon = \begin{bmatrix} E_m \\ 0 \\ 0 \end{bmatrix}, \quad J_2(u) = \begin{bmatrix} 0 & 0 & \frac{1}{2}S_d \\ 0 & 0 & \frac{1}{2}S_q \\ -\frac{1}{2}S_d & -\frac{1}{2}S_q & 0 \end{bmatrix}, \quad R_S = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & \frac{2}{3R_L} \end{bmatrix}.$$

The energy function of the system can be written as: $V = x^T M x / 2$.

Design of three-phase PWM rectifier controller

The goal of design of three-phase PWM rectifier controller is to make unit power factor at AC input side and DC voltage at output side maintain constant, i.e. when the system works in a stable state, the working point of the stable state is $i_d^* = I_m, i_q^* = 0,\ V_{dc}^* = V_{dc}$.

According to power equilibrium equation at AC and DC sides in a stable state: $\frac{3}{2}(U_m I_m - R I_m^2) = \frac{U^2}{R_L}$. Then get: $i_d^* = I_m = \frac{1}{2}\left[\frac{U_m}{R} - \sqrt{(\frac{U_m}{R})^2 - \frac{8U^2}{3RR_L}}\right]$. Due to $R_L = \frac{V_{dc}}{i_L}$, then we get:

$$i_d^* = I_m = \frac{1}{2}\left[\frac{U_m}{R} - \sqrt{(\frac{U_m}{R})^2 - \frac{8U^2 i_L}{3RV_{dc}}}\right]. \tag{12}$$

The target of the controller is $x_1 \to i_d^*$, $x_2 \to i_q^*$, $x_3 \to V_{dc}^*$, so it can be regarded as the tracking problem of given points of the same category. Thus, the controller is established according to the error model of Euler-Lagrange model of three-phase PWM rectifier. The variable of the error state is: $e = [i_d - i_d^*, i_q - i_q^*, V_{dc} - V_{dc}^*]^T$.

Make $R_d = (R_x + R_s)$, Where, damp injecting matrix: $R_x = \begin{bmatrix} r_{s1} & 0 & 0 \\ 0 & r_{s2} & 0 \\ 0 & 0 & r_{s3} \end{bmatrix}$. Due to: $M\dot{x} + [J_1 + J_2(u)]x + R_S x = \varepsilon$, $M\dot{x}^* + [J_1 + J_2(u)]x^* + R_S x^* = \varepsilon^*$

Euler-Lagrange model of three-phase PWM rectifier is rewritten as:

$$M\dot{e} + [J_1 + J_2(u)]e + R_d e = \varepsilon - (M\dot{x}^* + [J_1 + J_2(u)]x^* + Rx^* - R_s e) \tag{13}$$

The left side must be zero, and then the following form can be written:

$$\varepsilon = M\dot{x}^* + [J_1 + J_2(u)]x^* + Rx^* - R_s e \tag{14}$$

Then the control equation of three-phase PWM rectifier is obtained:

$$(15)\quad \begin{cases} L\dfrac{di_d^{\,*}}{dt} = E_m - Ri_d^{\,*} - \omega Li_q^{\,*} - \dfrac{1}{2}V_{dc}^{\,*}S_d + r_{s1}(i_d - i_d^{\,*}) \\ L\dfrac{di_q^{\,*}}{dt} = \omega Li_d^{\,*} - Ri_q^{\,*} - \dfrac{1}{2}V_{dc}^{\,*}S_q + r_{s2}(i_q - i_q^{\,*}) \\ \dfrac{2C}{3}\dfrac{dV_{dc}^{\,*}}{dt} = \dfrac{1}{2}(i_d^{*}S_d + i_q^{*}S_q) - \dfrac{2V_{dc}^{*}}{3R_L} + r_{s3}(V_{dc} - V_{dc}^{*}) \end{cases}$$

Since i_d^* and i_q^* are given constant reference values, when calculating the derivative of the two, $di_d^{\,*}/dt = 0$, $di_q^{\,*}/dt = 0$. Through Formula (16), get:

$$(16)\quad \begin{cases} S_d = \dfrac{2}{V_{dc}^{\,*}}[E_m - Ri_d^{\,*} - \omega Li_q^{\,*} + r_{s1}(i_d - i_d^{\,*})] \\ S_q = \dfrac{2}{V_{dc}^{\,*}}[\omega Li_d^{\,*} + r_{s2}(i_q - i_q^{\,*}) - Ri_q^{\,*}] \end{cases}$$

Thus, control schematic diagram of the system is shown in figure 3.

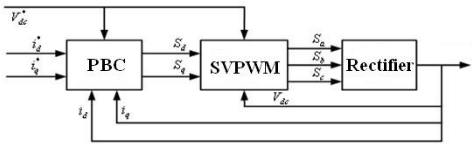

Fig.2. Schematic diagram of passivity-based control system

PWM modulation strategy of three-phase PWM rectifier

In recent years, as the algorithm is improved ceaselessly and control ships develop rapidly, SVPWM technology has been introduced in the research field of high-frequency PWM variable flow. Compared with SPWM, SVPWM is an optimized PWM technology. It has the following advantages: simple control, small current waveform distortion, convenient for realization of digitization, reduction in AC-side current harmonic component obviously, improving use ratio of DC voltage (15% higher than SPWM). Thus, it has the trend to replace SPWM. Three-phase PWM rectifier in this paper also adopts SVPWM modulation strategy, so SVPWM simulation diagram (as shown in figure 6) is set up in MTALAB/SIMULINK to complete the simulation experiment.

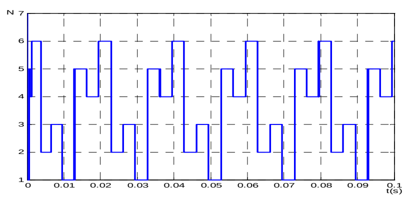

Fig.3. Section diagram

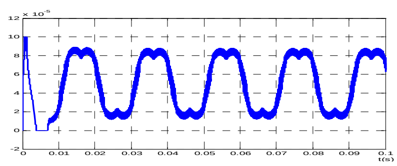

Fig.4. Saddle-shaped modulated wave

Figure 3 shows section distribution diagram generated by SVPWM modulation strategy. Figure 4 shows in connotative saddle-shaped PWM modulated wave SVPWM modulation method. The simulation result shows that on the on hand, high voltage use ratio of SVPWM displays wider linear modulation range and on the other hand displays higher power supply use ratio under the same linear modulation ratio.

Conclusions

The passivity-based controller of the rectifier is designed according to passivity-based control theory introduced. First, the mathematical model of three-phase PWM rectifier is established in the basis of Euler-Lagrange Equation. Based on such mathematical model, a new controller of three-phase PWM rectifier is designed through deducing the error model and using passivity-based control theory. Such passivity-based controller is defined overall and is stable overall. It has strong robustness for external disturbance and system parameter changes with simple algorithm, easy to realize. Thus, it has incomparable advantages, compared with traditional controllers.

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