

Control of HVDC-Light Transmission for Offshore Wind Farms Based on Input-Output Feedback Linearization and PSO

WANG GUO-QIANG, WANG ZHI-XIN

Department of Electrical Engineering

Shanghai Jiaotong University

No.800 Dong Chuan Road, Shanghai 200240

CHINA

cock_wgq@126.com

Abstract: - HVDC-Light has the advantages of flexible operating ways and reliability, especially in the transmission problem of offshore wind power. But it needs many PI controllers in the two converters (wind farm side, grid side). So there are many parameters need to be set which is difficult. This paper adopted the control mode that the outside loop controlled the voltage and the inside loop controlled the current. The inside loop made use of input-output feedback linearization method to make the nonlinear coupled converter mathematical model be linearization and decoupled. And it can substitute pole placement for PI parameters setting. Namely that it changed the problem of adjusting PI parameters to the one of pole placement. The control objective is to track the given values of active and reactive current from outside loops. The outside loop PI parameters are optimized with cooperation random particle swarm optimization(CRPSO) algorithm. Simulation results of Matlab/Simulink were compared with the conventional PI controller which show that the control method of this paper is effective.

Key-Words: - VSC-HVDC; Nonlinear control; Feedback linearization; Wind farm; PSO

1 Introduction

With the development of power electronics and full controlled devices, application range of high power electronics converters is wider and wider. Recent years the technology of HVDC-Light based on full controlled devices for example IGBT becomes research hotspot. Especially with large-scale development of offshore wind farm, long power transmission is the key technology of new energy development. Tradition HVDC technology is mature. But it has limitation that it needs high capacity var equipment and can't supply power for isolated island. HVDC-Light solves the above problems effectively.

Papers about feedback linearization used for HVDC-Light are rear presently. In most papers rectifier is donated by a three-order state equation in which state variable are direct voltage u_{dc} , d-axis current i_d and q-axis current i_q [1]-[3]. This kind of method realized decoupling and made the system linearization and paper [4] control rectifier by this theory. They all got satisfactory results. This paper design the feedback linearization control system based on two-order instead of three-order state equation in dq coordinate and the state variables are

dq-axis current i_d, i_q . It can avoid calculating two-order derivative of direct voltage and the control signals worked out don't contain high-order differential phase of error signals. And test the validity of designed method by Matlab/Simulink.

2 System Description And Modelling

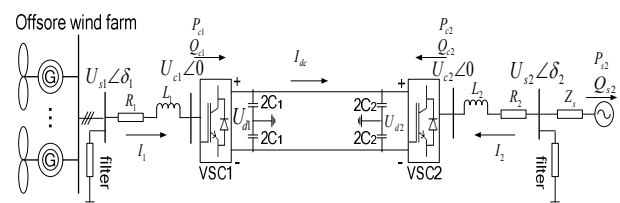


Fig.1 Simplified equivalent HVDC-Light circuit diagram for wind energy transmission

It concludes four wind generators which are 1.5MW, 6.6kV permanent magnet synchronous generator directly driven by wind turbine. The whole capacity is 6MW. This kind of turbine doesn't contain gear box and has high reliability, so it is adopted by most wind farms. We considered the

four wind turbine in the same area in simulation, so their speed are approximately equal and control them with the signal of their average speed. The main control system objective is tracking maximum power point and make wind turbines variable speed constant frequency operate. We also assume that the wind turbines rating speed is high enough and power losses in the whole system are neglected. Then the whole wind farm can be represented by one lumped generator model[5]. In order to simplify the model for purposes of converter control design, this paper represented the wind farm with AC source for simplification further. The simplified HVDC-Light system circuit diagram is showed in Fig.1. It mainly includes two converters based on voltage source (VSC1,VSC2), converter reactors (L_1, L_2) and equivalent losses(R_1, R_2) of converter and lines. In Fig.1 i_{dc} is direct current and u_{dc} is dc side capacitor voltage, $u_{dc} = U_{d1} = U_{d2}$. C is dc side capacitor, $C = 2C_1 = 2C_2$. The one side(VSC1 or VSC2) mathematical model of HVDC-Light can be described with equation (1).

$$\begin{cases} L \frac{di_{an}}{dt} + Ri_{an} = u_{san} - u_{can} \\ L \frac{di_{bn}}{dt} + Ri_{bn} = u_{sbn} - u_{cbn} \\ L \frac{di_{cn}}{dt} + Ri_{cn} = u_{scn} - u_{ccn} \end{cases} \quad (1)$$

Where i_{an}, u_{san} ($n=1,2$) are the ac system current and voltage of phase A, and subscripts 1,2 are for the two sides of VSC1 and VSC2 respectively. u_{can} is input voltage of converters of phase A. The subscript s and c represent the ac system side and the converter side respectively. Variables of the other two phases (B,C) are donated in the same way. Assume that the three-phase voltages of ac system are balance. Transform (1) into a synchronous rotating reference frame with the transformation (2).

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\alpha & \cos(\alpha-120^\circ) & \cos(\alpha+120^\circ) \\ -\sin\alpha & -\sin(\alpha-120^\circ) & -\sin(\alpha+120^\circ) \end{bmatrix} \quad (2)$$

Then the mathematical model of the converters is equation(3) [6].

$$\frac{d}{dt} \begin{bmatrix} i_{dn} \\ i_{qn} \end{bmatrix} = \begin{bmatrix} -R/L & \omega_n \\ -\omega_n & -R/L \end{bmatrix} \begin{bmatrix} i_{dn} \\ i_{qn} \end{bmatrix} - \begin{bmatrix} (u_{cdn} - u_{sdn})/L \\ u_{cqn}/L \end{bmatrix} \quad (3)$$

Where ω_n (the same above $n=1,2$) is voltage vector angular speed; and $u_{sdn}, u_{sqn}, u_{cdn}, u_{cqn}$ and i_{dn}, i_{qn} are the dc components of the ac system voltages and currents in the synchronous frame. The subscript letter s represents the system side and the subscript c represents the converter side (corresponding with $U_{s1,2}, U_{c1,2}$ in Fig.1). If the space vector of the ac voltage is taken as the direction of d axis, then $u_{sqn} = 0$, $u_{sdn} = U_{sn}$ (U_{s1}, U_{s2} are amplitudes of voltage space vector). Active and reactive power of converter's ac side and the power of converter's dc side can be expressed as follows.

$$\begin{cases} P_{ac} = U_{sn} \cdot i_{dn} \\ Q_{ac} = -U_{sn} \cdot i_{qn} \end{cases} \quad (4)$$

$$P_{dc} = u_{dc} \cdot i_{dc} \quad (5)$$

3 Feedback Linearization

Consider the tracking control problem of a multiple-input multiple-output system as follow[4]:

$$\dot{x} = f(x) + G(x)u \quad (6)$$

$$y = h(x) \quad (7)$$

Where x is $n \times 1$ state vector, and u (its element is u_i) is $m \times 1$ control input vector, and y (it's element is y_i) is $m \times 1$ output vector, and f is smooth vector field, and h is smooth vector function, and G is $n \times m$ matrix whose column is smooth vector g_i .

To obtain the input-output linearization expression, differentiate the outputs until the inputs appear. Assume that r_i is the smallest integer such that at least one of the inputs appear in $y_i^{(r_i)}$, then

$$y_i^{(r_i)} = L_f^{r_i} h_i + \sum_{j=1}^m L_{g_j} L_f^{r_i-1} h_i u_j \quad (8)$$

Where L_f and L_{g_j} represent Lie derivatives along with the vector field $f(x)$ and $g_j(x)$. There is at least one j making $L_{g_j} L_f^{r_i-1} h_i(x) \neq 0$ in the neighborhood Ω_i of x_0 . Then[7][8]

$$\begin{bmatrix} y_1^{(r_1)} \\ \vdots \\ y_1^{(r_m)} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ \vdots \\ L_f^{r_m} h_m(x) \end{bmatrix} + E(x)u \quad (9)$$

Where E is $m \times m$ matrix corresponding to $\sum_{j=1}^m L_{g_j} L_f^{r_i-1} h_i$.

The desired linear system is $y_i^{(r_i)} = v_i$, where v_i is new input. If the $E(x)$ is nonsingular the control variables of the original nonlinear system are given by:

$$u = E^{-1}(x) \cdot \left\{ v - \begin{bmatrix} L_f^{r_1} h_1(x) \\ \vdots \\ L_f^{r_m} h_m(x) \end{bmatrix} \right\} \quad (10)$$

4 Nonlinear Control of Converter

Rewrite the dynamic mathematical model (3) in the form of (6) and (7). We can get:

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L}x_1 + \omega_n x_2 \\ -\frac{R}{L}x_2 - \omega_n x_1 \end{bmatrix} \quad (11)$$

$$G = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \quad (12)$$

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} i_{dn} \\ i_{qn} \end{bmatrix} \quad (13)$$

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} u_{sdn} - u_{cdn} \\ -i_{qn} \end{bmatrix} \quad (14)$$

Choose the output of the system are:

$$y_1 = x_1 = i_{dn} \quad (15)$$

$$y_2 = x_2 = i_{qn} \quad (16)$$

According to the input-output feedback linearization method above, differentiate (15) and (16) until a control input appears and arranging them in the form of (9)[9].

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = A(x) + E(x) \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (17)$$

Where:

$$A(x) = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \quad (18)$$

$$E(x) = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix} \quad (19)$$

Since $E(x)$ is nonsingular, then control law is given as

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = E^{-1}(x) \left[-A(x) + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \right] \quad (20)$$

Where:

$$E^{-1}(x) = \begin{bmatrix} \frac{1}{g_1} & 0 \\ 0 & \frac{1}{g_2} \end{bmatrix} \quad (21)$$

According to the bounded tracking control principle [10], we can get new input v_1, v_2 as equation (22) and add integral control for robustness to parameter perturbation.

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

Where $e = y - y_{ref}$. So the output error equation is:

$$\ddot{e}_1 + k_{11}\dot{e}_1 + k_{12}e_1 = 0 \quad (23)$$

$$\ddot{e}_2 + k_{21}\dot{e}_2 + k_{22}e_2 = 0 \quad (24)$$

According to linear control theory, the gains k_{ij} is determined by placing the desired pole location[11]. All the poles locate at the right side of complex

plane, and the closer to the $j\omega$ -axis the more impact to the system.

Substitute (22) into (20):

$$u_1 = Ri_{dn} - \omega_n Li_{qn} + Lv_1 \quad (25)$$

$$u_2 = Ri_{qn} + \omega_n Li_{dn} + Lv_2 \quad (26)$$

The d,q-axis order signals of converter respectively are:

$$u_{cdn}^* = u_{sdn} - u_1 \quad (27)$$

$$u_{cqn}^* = u_{sqn} - u_2 = -u_2 \quad (28)$$

As a consequence of the above, the control block diagram of inside current loop is shown in Fig.2.

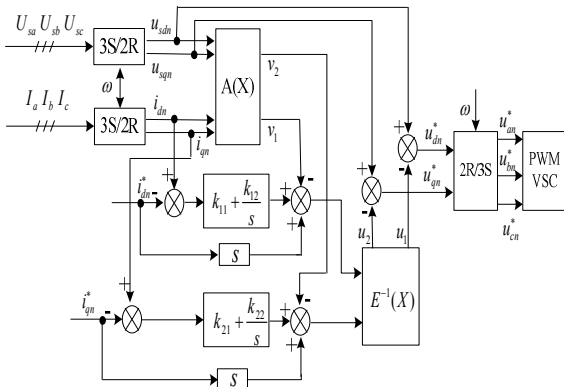


Fig.2 nonlinear control block diagram of converter

5 Control Modes Of HVDC-LIGHT and PSO Algorithm

In this section the common control mode of HVDC-Light is introduced based on PI regulators and the PSO algorithm is applied for optimization of PI parameters.

5.1 Control Mode

There are several HVDC-Light control modes as follows: (1) constant dc voltage or constant active power, (2) constant direct current, (3) constant reactive power or constant ac voltage. The control mode of constant ac voltage is adopted to supply power for passive networks, and the other control modes are appropriate for the situation that the two sides are all active networks. The reactive power is

controlled independently by two side converters respectively[12].

In this paper VSC1 is controlled by constant dc voltage u_{dc} and constant reactive power Q_{ac} mode. From equation(5), the active current order i_{dn}^* is proportional to transmission active power P_{ac} , which is used for maintaining the capacitor voltage of converter dc side. The PI controller is adopted for dc voltage regulator and the active current order is

$$i_{sd1}^* = k_{p1}(u_{dc}^* - u_{dc}) + k_{i1} \int (u_{dc}^* - u_{dc}) dt \quad (29)$$

VSC2 is controlled by the mode of constant active and reactive power[13]. The same as above PI controller is adopted for active power regulating, and active current order is

$$i_{sd2}^* = k_{p2}(P_{ac}^* - P_{ac}) + k_{i2} \int (P_{ac}^* - P_{ac}) dt \quad (30)$$

From equation(4), the reactive current order is proportional to the absorbing (or emitting) reactive power, so we can regulate absorbing (or emitting) reactive power of the converter by controlling the reactive current order. PI controller is adopted for reactive power regulator, and the reactive current order is

$$i_{sqn}^* = k_{p3}(Q_{ac}^* - Q_{ac}) + k_{i3} \int (Q_{ac}^* - Q_{ac}) dt \quad (31)$$

The inside current loop is linearization, so its equivalence closed-loop transfer Function can be expressed as (32)[14]

$$W_{ci} = \frac{1}{3T_s s + 1} \quad (32)$$

Where T_s is PWM carrier period. The converter can be equivalent as a proportional component and all the PI parameters of outside loops can be set and optimized with particle swarm optimization (PSO) algorithm.

5.2 Optimization of Parameters for outside loop PI controller

In this section the transfer function is established firstly, and then we apply PSO algorithm for optimization of PI parameters[15].

5.2.1 transfer function of the system

The voltage loop of VSC-HVDC system is showed in fig.3. The structure of active and reactive loop is similar with it, so we take the voltage loop for example to optimize the parameters of PI controllers and the optimization procedure of other controllers is elided[16].

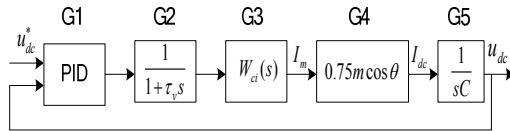


Fig.3 Transfer function of the HVDC-Light

Where u_{dc}^* , u_{dc} are the given and feedback value respectively in the fig.3. I_m is the rms value of grid current and s is laplace operator. And the definition of G1,G2,G3,G4,G5 is as follow:

1. G1 is PI controller and K_p , K_i are amplification of proportion and integration unit respectively.
2. G2 is sampling unit of voltage and its inertia time constant τ_v is two times of PWM switching period

3. G3 is equivalent transfer function of inside current loop, $W_{ci}(s) = \frac{1}{1+3T_s s}$. T_s is PWM switch period, which is set with 1/1350s considering of the large power of the system and K_{PWM} is the equivalent amplification of the converter. We combine the voltage sampling time constant with equivalent inside current loop constant and don't consider the disturb of dc current. The G3 unit can be written as: $G3 = \frac{1}{1+0.0037s}$.

4. G4 is the equivalent unit of converter in which θ is the phase angle of reference wave and m is PWM modulation ratio. We take maximal proportional gain as the whole unit for simplification namely $G4=0.75$.

5. G5 is the equivalent unit of dc capacitor and the capacitance is 1500 μF , namely that $G5 = \frac{1}{0.0015s}$

We can get the open-loop transfer function of the system is as equation(33)

$$G_k = \frac{0.75}{5.55 \times 10^{-6} s^2 + 0.0015s} \quad (33)$$

5.2.2 PSO

particle swarm optimization (PSO) is proposed at first early in 1995 by Eberhart and Kennedy

together[17]. The basic ideas are simulating the bird colonies foraging to search global optimization point under some kind of performance index. One particle presents a bird and the it can calculate the adaptive value of current position. And every particle record the optimal value searched by itself and the one searched by all the birds in the group. The two optimal values are named with p_{best} (local optimum) and g_{best} (globe optimum) which make the bird group close toward the orientation of them to a certain extent. The above simplified model proposed is the PSO algorithm[19].

The basic PSO algorithm has many defects for example falling into local optimum because of insensitive to Environment variables and Precocious and so on. Many papers have proposed improved algorithm for example Discrete Particle Swarm, Niche PSO and Hybrid Particle Swarm and so on. We adopted cooperative PSO of paper[3]. This kind of PSO has multi-group particles to search different parts of the solution space. It retains optimum position g_{best} of this group besides keeping the optimum position $g_{best}(r)$ of different random sub group which comes form CRPSO(cooperation random PSO) algorithm. It said that the two kinds of optimum position are used for updating position and speed of particle that avoid the defect of overemphasizing Social-sharing mechanisms and weakening itself optimal. And the random cooperation mechanisms balances the ability of global and local searching. The update formula of this algorithm is equation (34)

$$\begin{cases} v_i(k+1) = \omega v_i(k) + 0.5 \cdot c_1 \cdot r_1 \cdot [p_{best} - x_i(k)] + \\ \quad 0.5 \cdot c_2 \cdot r_2 \cdot [g_{best} - x_i(k)] + \\ \quad 0.5 \cdot c_2 \cdot r_2 \cdot [g_{best}(r) - x_i(k)], \\ x(k+1) = x(k) + v(k+1) \end{cases} \quad (34)$$

Where $i = 1, \dots, n$, is quantity of sub group and r is random integral number between 1 to n . c_1 and c_2 are the accelerating factors. Coefficient 0.5 is used for balancing p_{best} , g_{best} and $g_{best}(r)$ which are particle optimum position, sub group optimum position and other sub group optimum position respectively.

In this paper we take the parameters of PI regulators (K_p , K_i) As a particle swarm optimization parameters. It is said that every particle search optimal value and the position of particles be

constitutive of PI parameters K_p and K_i . The calculation is as follows:

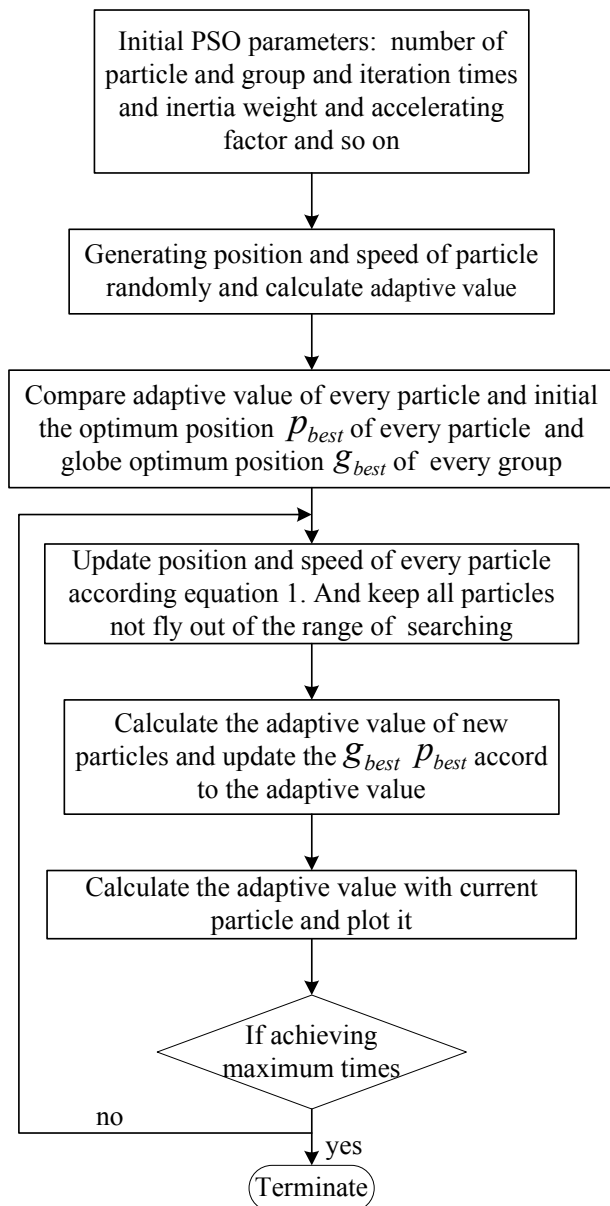


Fig.4 Program flow chart of PSO

First step: initialize the PI parameters and particle position. Initialize the range and speed of searching. Set particle quantity of every group and group quantity and some essential parameters

Second step: the first iteration is operated. The ITAE index $J = \int_0^{+\infty} t|e(t)|dt$ is used which considers the steady error and setting time. Program calculate J value of every particle in all sub group as their adaptive value and then we can get the initial value of p_{best} and g_{best} through selecting the particles with the minimal J value.

Third step: start iteration and update position and speed of particles with equation (1). Update the p_{best} and g_{best} according to J value.

Fourth step: judge terminal condition of the arithmetic. If it is satisfied programme terminate and output the optimization value of K_p and K_i . If not satisfied programme go back to the third step.

According to the above the program flow chart of cooperation PSO optimizing PI parameters is as fig4. And the program code of MTALAB is in appendix.

5.3 PSO setting PI parameters

Cooperation PSO algorithm parameters are set as follow:

Particle numbers: 30

Sub group number: 3

Sample number of input: 200

Range of searching: [0,+100]

number of iteration: 50

accelerating factors: [2,2]

inertia weight: $0.9 - \frac{0.85}{N} \cdot (1:N)$ where N is

number of iteration.

We set step response of input signal which is 0.7pu at start time and step 1pu at 150 sample point. The parameters by PSO is used in the next section and the convergence curve of adaptive function J is showed in fig.5. the optimization result for dc voltage regulator is $K_p=46.36$ (proportion unit) and $K_i=8.8$ (integral unit).

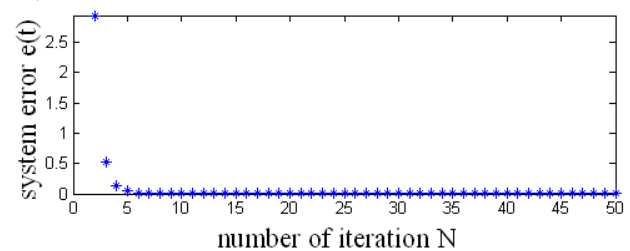


Fig.5 convergence curve of adaptive value

6 Simulation And Analysis

MATLAB is used to validate the effectiveness of the designed control method above. The proposed HVDC-Light control system shown in Fig.1 is simulated, and the primary parameters are as follows. Converter reactors are $L_1 = L_2 = 5.61\text{mH}$, and their equivalent losses are $R_1 = R_2 = 0.0176\Omega$ respectively. The rated voltages of ac systems are $U_{s1} = U_{s2} = 6.6\text{kV}$ and the equivalent resistance

and inductance are 0.2Ω and 1.5mH of the source respectively. The capacitors of dc side are $C_1 = C_2 = 1250\mu\text{F}$. The equivalent resistance and inductance of the dc lines are equal to 0.075Ω and 1mH . The set value of dc voltage is 20kV . The converters run with SPWM control mode and carrier frequency is 1350Hz . The PI regulator parameters of DC voltage are $k_{p1}=8.47$, $k_{i1}=18.8$, and of active power are $k_{p2}=6.47$, $k_{i2}=15.8$ and of reactive power are $k_{p3}=0.85$, $k_{i3}=20$. For equation (23), (24) place the desired pole locations are $-400 \pm 300j$.

Fig.6,7 shows the ac voltage and current (U_a, I_a) responses of phase A on both sides when the setting value of reactive power is zero. Their steady state phases are the same or opposite extremely, so power factor is 1. Fig.8, 9 are active and reactive responses (P, Q) where P^*, Q^* are the corresponding given values. We can see that the steady state tracking precision of the system is satisfactory and response fast. But the converters start-up directly, so the charge current of capacitor is large and the overshoot of reactive power is big too. Charge resistance should be added in front of the capacitor and open the trigger pulses after voltage of the capacitor achieving the voltage of $\sqrt{2}U_{sn}$, for avoiding the overshoot of the reactive power and dc voltage.

Fig.10 is dc voltage response which includes three curves. The U_{dc}^* is the given value of dc voltage and the U_{dc1} is the response of this paper controller and the U_{dc2} is the result of conventional PI controller. We can see that the nonlinear controller has better dynamic performance than PI controller, for example smaller overshoot and more quickly response. So the converters can track the fluctuant output power of wind farm faster and it is important for stable operation of the whole system.

Fig.11 is system responses during the transient process of grid. We set severe perturbation in the AC system. a three-phase to ground fault started at 0.5s in the grid side and recovered at 0.62s (sustained 0.12s). Fig.11(a) is dc voltage curve (U_{dc}) which shows that dc voltage can resume fast when the grid is normal. And dc voltage is zero during the fault period, so there was no power transmitted from one terminal to the other. Fig. 11(b) and (c) are the active and reactive power response curves (P, Q). And they come back to the

given value (P^*, Q^*) which cost less than 0.2s after the fault clearing. These results shows that the system will keep connection with grid in the fault period and the dc voltage overshoot is small during recovery process. So there will not be over voltage fault or off-network accident and the system has the ability of disturbance rejection.

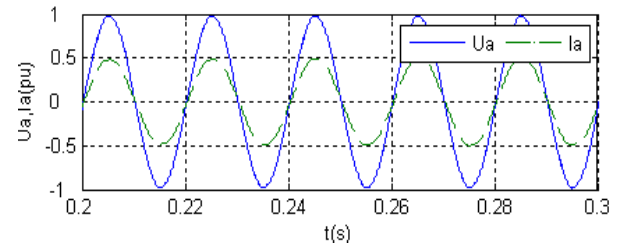


Fig.6 Ac system voltage, current response of phase A for VSC1 side

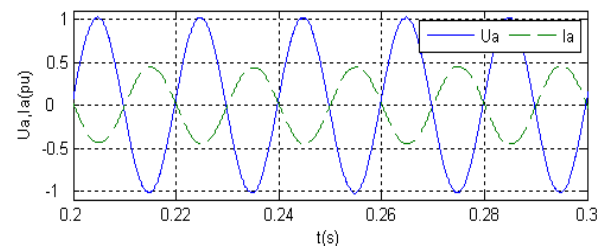


Fig.7 Ac system voltage, current response of phase A for VSC2 side

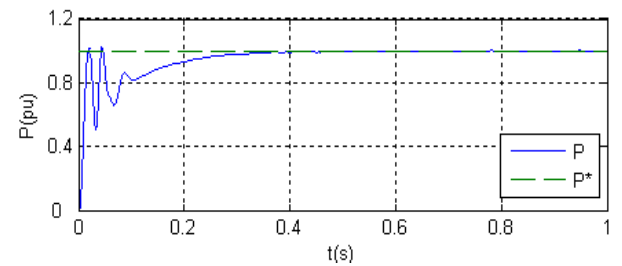


Fig.8 Active power response

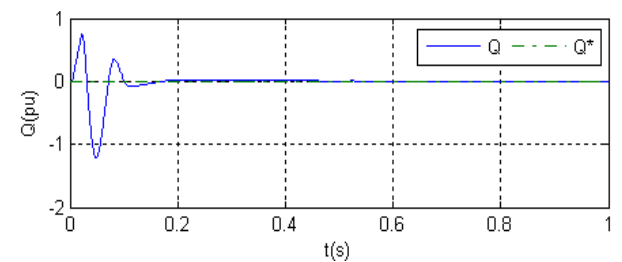


Fig.9 Reactive power response

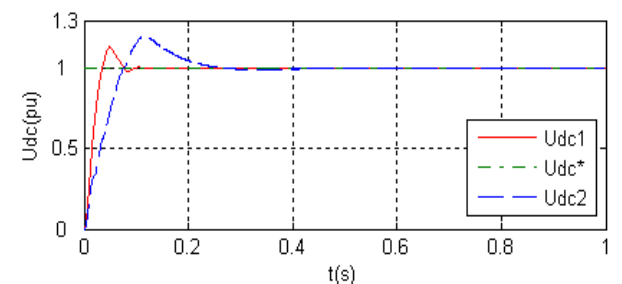


Fig.10 Comparison of dc voltage response

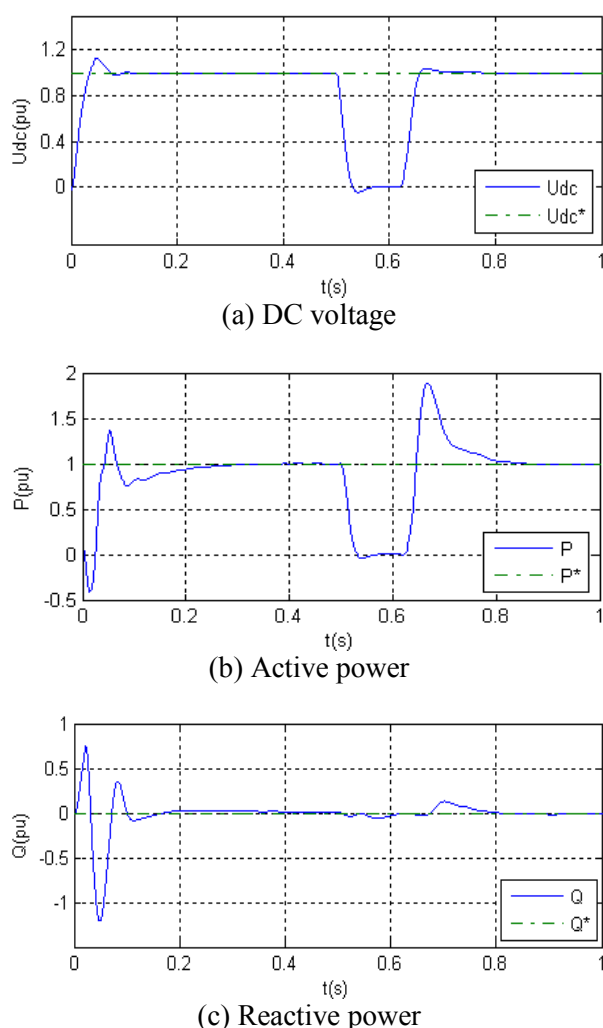


Fig.11 HVDC-Light system responses during grid transient process(three-phase to ground fault)

7 Conclusion

This paper study the wind farm grid-connected converter control strategy based on VSC-Light. The input-output feedback linearization method and particle swarm algorithm(PSO) were combined with traditional double-loop converter control method.

1. for the inside current loop, according to the mathematic model of voltage source converter in synchronous rotating dq coordinate system. inner current loop MIMO feedback linearization control model was derived after a reasonable simplification. The introduction of state feedback linearization method for nonlinear system based on differential geometric theory realized decoupling control of active and reactive current. The nonlinear controller based on the above strategy has the advantages of Simple structure and well following performance. The controller can make the dq-axis current of

inside loop track the regulator output of outside loop and make active power and reactive power be controlled independently. Also it avoids the process that PI parameters are needed to be adjusted again and again. And provides another way, which is easy to calculate and set the PI parameters of inside current loop (poles placement).

2. For the outside voltage loop, conventional PI regulator was used for controlling the system DC voltage, reactive power and active power to follow the given values. The control system transfer function of outside loop was established and PSO algorithm was used to obtain the optimal PI parameters through repeated iteration. It made the process of controller parameters optimization have advantages of systematic and deterministic. We compared the control performance of PI controller obtained by engineering turning method and by PSO algorithm. The simulation results showed that the controller obtained by PSO algorithm has the better performance.

3. For the transient process of power system, simulation study was carried out. A three-phase ground fault of short time was set and analysis output wave of the system. The results showed that the designed system has satisfactory anti-interference ability. Also the converter can export reactive power during the transient process to enhance power system stability.

Nonlinear control theory and PSO algorithm are applied for converter of HVDC-Light system in this paper. A new controller based on input-output linearization theory is proposed for inside current loop control and the PSO algorithm is used for outside loop parameters optimizing. It is an effective control method for converters which are used for wind farm connecting to the grid and long distance transmission of offshore wind energy. The simulation results shows that the control method proposed in this paper is effective.

Acknowledgment

National Science Foundation of China(60934005), China Postdoctoral Fund (20080440088), Shanghai High Technology Industrialization projects (2009-041), Shanghai Science and Technology Development Funds (09195802900), Fund of Magnolia Science and Technology Talent(2009B075)

References:

- [1] Guo-Jie Li, Siye Ruan, Lin Peng et al. A novel nonlinear control for stability improvement in

- HVDC light system, *IEEE Conf. on Power Engineering Society*, Beijing, Vol.1, 2005. pp. 837-845.
- [2] Liu Zhongqi, Shao Wenjun, Song Qiang, et al. A Novel Nonlinear Decoupled Controller For VSC-HVDC System, *IEEE Conf. on Power and Energy Engineering*, Wuhan, 2009. pp. 1-5.
- [3] Dong-Choon Lee, Ki-Do Lee, G-Myoung Lee et al. Voltage control of PWM converters using feedback linearization, *IEEE Conf. on Industry Application*, Kyungbuk, vol.2, 1998, pp.1491 - 1496.
- [4] Hairong Chen, Zheng Xu, Fan Zhang, Nonlinear control for VSC based HVDC system, *IEEE Conf. on Power Engineering Society*, Montreal, 2006, pp. 1-5.
- [5] Lie Xu, Liangzhong Yao, Christian Sasse, Power Electronics Options for Large Wind Farm Integration VSC-Based HVDC Transmission, *IEEE Conf. on Power Systems*. Atlanta, 2006, pp.760-767.
- [6] Padiyar, K.R, Prabhu, N. Modelling, control design and analysis of VSC based HVDC transmission systems, *IEEE Conf. on Power System Technology*. Bangalore, Vol.1, 2004, pp. 774-779.
- [7] Cheng Daizhan. *Applied Nonlinear Control*. China Machine Press, China, 2009.
- [8] Sanjay Bharadwaj, Anil V. Rao, Kenneth D. Mease, Entry Trajectory Tracking Law via Feedback Linearization, *Journal of Guidance, Control, and Dynamics*, Vol.36, No.3, 1998, pp. 726-32.
- [9] Dong-Choon Lee, G-Myoung Lee, Ki-Do Lee, DC-bus voltage control of three-phase ac/dc PWM converters for renewable energy applications, *IEEE Tran. Ind. Appl.*, Vol.36, No.3, 2000, pp. 826-33.
- [10] Mease, K. D, Kremer, J. P, Shuttle Entry Guidance Revisited Using Nonlinear Geometric Methods, *Journal of Guidance, Control, and Dynamics*, Vol. 17, No. 6, 1994, pp. 1350-1356.
- [11] O'Reilly, J, Wood, A.R, Osauskas, C.M, Frequency domain based control design for an HVdc converter connected to a weak ac network, *IEEE Tran. Power Delivery*, Vol. 18, No. 3, 2003, pp. 1028-1033.
- [12] Ruihua, Song, Chao, Zheng, Ruomei, Li, VSCs based HVDC and its control strategy, *IEEE Conf. on Transmission and Distribution*, Dalian, 2005, pp. 1-6.
- [13] Wei Xiaoguang, Tang Guangfu, Research of AC/DC Parallel Wind Farm Integration Based On VSC-HVDC, *IEEE Conf. on Power System Technology*, Chongqing, 2006, pp. 1-5.
- [14] Lou H, Mao C, Lu J et al, Pulse width modulation AC/DC converters with line current harmonics minimization and high power factor using hybrid particle swarm optimization, *IET Tran. Power Electron.*, Vol. 2, No. 6, 2009 , pp. 686-696.
- [15] PIAO Hai-guo, WANG Zhi-xin, ZHANG Hua-qiang, Nonlinear control system of PID neural network based on cooperated particle swarm optimization (PSO), *Control Theory & Applications*, Vol. 26, No. 12, 2009, pp. 1317-1324
- [16] Zhang Cong-wei, Zhang Xing. *PWM Rectifier and Control*, Bei Jing: China machine press , China, 2005.
- [17] James Kennedy, Russell Eberhart, Particle Swarm Optimization, Perth, *IEEE Conf. on Neural Networks*, vol.4, 1995, pp. 1942-1948
- [18] Wang Zhi-xin, LI Xiang, LIU Wen-jin, Research on Converter of Offshore Wind Energy Flexible Direct Current Transmission, *Power System and Clean Energy*, Vol. 24, No. 8, 2008, pp. 33-37.
- [19] Po-hung Chen, Cheng-Cheng K, Fu-Hsien Chen, Refined Binary Particle Swarm Optimization and Application in Power System, *WSEAS Transactions on Systems*, Vol. 8, No. 2, 2009, pp. 169-178.
- [20] W. Jatmiko, A. Nugraha, R, Effendi, Localizing Multiple Odor Sources in a Dynamic Environment Based on Modified Niche Particle Swarm Optimization with Flow of Wind, *WSEAS Transactions on Systems*, Vol. 8, No. 11, 2009, pp. 1187-1196.

Appendix

```
clear;
clear;
format long;
%initialization
Max_Gen=50;
stepcount=0;
ps=30;
cc=[2 2];
iw=0.9-(1:50).*(0.85/50);
D=2;
kkk=100;
VRmin(1:D)=0;
VRmax(1:D)=100;
mv=0.05*(VRmax-VRmin);
```

```

VRmin= repmat(VRmin,ps,1);
VRmax= repmat(VRmax,ps,1);
Vmin= repmat(-mv,ps,1);
Vmax=-Vmin;
pos1=(VRmin+(VRmax-VRmin).*rand(ps,D));
pos2=(VRmin+(VRmax-VRmin).*rand(ps,D));
pos3=(VRmin+(VRmax-VRmin).*rand(ps,D));
vel1=Vmin+2.*Vmax.*rand(ps,D);
vel2=Vmin+2.*Vmax.*rand(ps,D);
vel3=Vmin+2.*Vmax.*rand(ps,D);
VRmincell={VRmin,VRmin,VRmin};
VRmaxcell={VRmax,VRmax,VRmax};
Vmincell={Vmin,Vmin,Vmin};
Vmaxcell={Vmax,Vmax,Vmax};
poscell={pos1,pos2,pos3};
velcell={vel1,vel2,vel3};
gbest={zeros(1,D) zeros(1,D) zeros(1,D)};
pbest={zeros(ps,D) zeros(ps,D) zeros(ps,D)};
Je={zeros(ps,1) zeros(ps,1) zeros(ps,1)};
% the first iteration
for ii=1:3
    pos=poscell{ii};
    for m=1:ps
        Je{ii}(m,1)=fitness(poscell{ii}(m,:),D);
    end
    pbest{ii}(m,:)=poscell{ii}(m,:);
    end
    pbestval(ii)=Je{ii}(1,1);
    gbest{ii}(1,:)=pbest{ii}(1,:);
    for i=2:ps
        if Je{ii}(i,1)<pbestval(ii)
            gbest{ii}(1,:)=pbest{ii}(i,:);
            gbestval(ii)=Je{ii}(i,1);
        end
    end
end
pbestval=Je;
%the main iteration
for t=1:Max_Gen
    for jm=1:3
        for km=1:ps
            rr=randi(23,rand);
            if rr==jm
                rr=rr+1;
                if rr>=4
                    rr=rr-3;
                end
            end
            r=rr;
            aa(km,:)=0.5.*cc(1).*rand(1,D).*(pbest{j m}(km,:)-
poscell{j m}(km,:))...
+0.5.*cc(2).*rand(1,D).*(gbest{j m}(1,:)-
poscell{j m}(km,:))...
+0.5.*cc(2).*rand(1,D).*(gbest{r}(1,:)-
poscell{j m}(km,:));

```

```

velcell{j m}(km,:)=iw(t).*velcell{j m}(km,:)+aa(km,
:);
velcell{j m}(km,:)=(velcell{j m}(km,:)>mv).*mv+(v
elcell{j m}(km,:)<=mv).*velcell{j m}(km,:);
velcell{j m}(km,:)=(velcell{j m}(km,:)<(-mv)).*(-
mv)+(velcell{j m}(km,:)>=(-
mv)).*velcell{j m}(km,:);
poscell{j m}(km,:)=poscell{j m}(km,:)+velcell{j m}(
km,:);
poscell{j m}(km,:)=((poscell{j m}(km,:)>=VRmincel
l{j m}(1,:))&(poscell{j m}(km,:)<=VRmaxcell{j m}(
1,:))).*poscell{j m}(km,:)...
+(poscell{j m}(km,:)<VRmincell{j m}(1,:)).*(VRmi
ncell{j m}(1,:)+0.25.*(VRmaxcell{j m}(1,:)-
VRmincell{j m}(1,:)).*rand(1,D))...
+(poscell{j m}(km,:)>VRmaxcell{j m}(1,:)).*(VRma
xcell{j m}(1,:)-0.25.*(VRmaxcell{j m}(1,:)-
VRmincell{j m}(1,:)).*rand(1,D));
Je{j m}(km,1)=fitness(poscell{j m}(km,:),D);
If Je{j m}(km,1)<pbestval{j m}(km,1)
    pbest{j m}(km,:)=poscell{j m}(km,:);
    pbestval{j m}(km,1)=Je{j m}(km,1);
end
if pbestval{j m}(km,1)<gbestval(jm)
    gbest{j m}(1,:)=poscell{j m}(km,:);
    gbestval(jm)=Je{j m}(km,1);
end
end
optimum_val=gbestval(1);
optimum_pos=gbest{1}(1,:);
for s=2:3
    if gbestval(s)<optimum_val
        optimum_val=gbestval(s);
        optimum_pos=gbest{s}(1,:);
    end
end
stepcount=stepcount+1;
plot(stepcount,optimum_val,'*','LineWidth',1)
hold on;
end
hold off;
disp('*****')
disp('global optimization position')
Solution=optimum_pos'
disp('the optimization value')
Result=optimum_val
disp('*****')
%adaptive value calculation
function result=fitness(x,D)
e_sum=0;
sample=200;

```

```

eesum=0;
for j=1:sample
    ri(j)=0.7;
if j>100
    ri(j)=1;
end
y(j)=0;
vo(j)=0;
end
for k=2:sample
y(k + 1) = 1.437*y(k)-0.4373*y(k-1)
+0.04772*vo(k)+0.03627*vo(k-1);
e(k)=ri(k)-y(k+1);
e_sum=e_sum+e(k);
eesum=eesum+e_sum^2;

```

```

vo(k)=x(1,1)*e(k)+x(1,2)*e_sum;
end
result=eesum/sample;

%random number
function rr=rand123(a)
if a>0 & a<=0.3333
    rr=1;
elseif a>0.3333 & a<=0.6666
    rr=2;
else
    rr=3;
end

```