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Auto-disturbance-rejection Controller for SVC to Enhance Eind Farm Voltage Stability

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Abstract –This paper present a nonlinear controller for static var compensator (SVC) control system based on auto-disturbance-rejection control theory. This control theory is model free and with strong robustness. The work investigates the effect of this SVC on dynamic voltage stability of wind farm composed of fixed-speed induction generator (FSIG). The SVC with ADRC provides an optimal signal in order to avoid the low voltage and voltage fluctuation problem which come from wind farm integration. Simulation results show that ADRC is an effective solution to overcome anticipative problem.

Keywords - Wind power generation, SVC, auto-disturbance-rejection controller, voltage stability

I. INTRODUCTION

Wind energy is exhaustless, clean and reproducible energy. Many countries attach importance to it because wind power generation is normally with simple structure, convenience to maintenance and easy to operate. Due to the development and widely application of control theory and power electronic technology, wind energy conversion system (WECS) is developing fast, and wind power is become the first place of new energy to exploit in many countries.

Fixed-speed induction generator (FSIG) is the mainstream sort using in many wind farms, but induction generator absorbs reactive power from power system during its operation. This characteristic makes low-voltage issue in the power system. Moreover, power flow will be changed when a large-scale wind farm integrated with the utility grid because the output of wind farm is vary minute to minute due to the variation of wind speed. It makes low-voltage and voltage fluctuation get worse [1]. Reactive power compensation is applied to provide voltage support at the point of common coupling (PCC) and generator terminal. Capacitor-banks are applied to maintain the power factor (PF). Flexible AC Transmission Systems (FACTS) such as static var compensator (SVC) and static synchronous compensator (STATCOM) are also used [2,3]. They have better control of voltage profile at steady state, but hard to satisfies the dynamic characteristic.

This paper presents a control strategy for SVC based on auto-disturbance-rejection control (ADRC) [4]. The concept does not rely on exact mathematical model and the whole disturbance including model inconsistency together with outside disturbance can de evaluated. It is applied to industrial applications of time-variant, high-coupled systems [5,6].

This paper is organized as follows: Section II describes the ADRC scheme. Section III is describes the wind farm model using in this paper. Section IV is devoted to the ADRC for SVC. In section V, simulation results show the performance of the proposed controller on the models in the PSCAD/EMTDC.

II. AUTO-DISTURBANCE-REJECTION CONTROL

A typical ADRC is consisted of the following parts: tracking differentiator (TD), nonlinear state error feedback (NLSEF) and extended states observer (ESO), as shown in Fig.1.

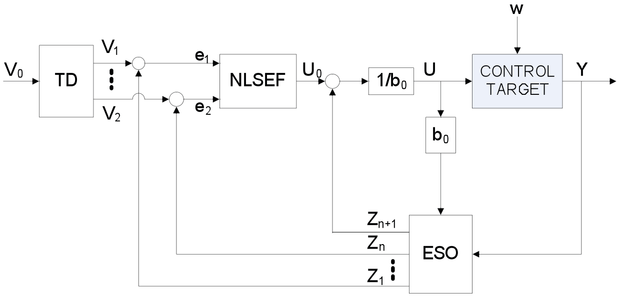

Fig.1: The block diagram of ADRC

The TD is responsible for the arrangement of an appropriate transient process and provides proper differential signals of each order from the input reference signal. A nonlinear system can be described by the follow equations:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2) \end{cases} \tag{1}$$

If the system is stable at origin, then for any bounded integrals function *v(t)*, $t \in [0, \infty)$ there exists

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = r^2 f(x_1 - v(t), x_2 / r) \end{cases} \tag{2}$$

That satisfies, $\lim_{r \to \infty} \int_0^T \left| x_1(r,t) - v(t) \right| dt = 0$. x_1 tracks reference *v(t)*, and $x_2(r,t)$ approximates to the “generalized differentiation” of *v(t)*. As long as r is sufficiently large, x_1 can track *v(t)* arbitrarily fast with certain precision. The most important feature of TD is its capability to obtain the derivatives of noisy signals with a good signal-to-noise ratio and the derivatives are acquired via integration. Therefore, TD can avoid unnecessary noise and can also be used as a reference generator.

The NLSEF determines control input by tracking the error signal and its different formats for optimal combinations with nonlinear algorithms for output. A typical nonlinear relationship for a nth NLSEF can be expressed as

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$$u_0 = k_1 fal(\varepsilon_1,\alpha,\delta)+\cdots+ k_n\, fal(\varepsilon_n,\alpha,\delta) \qquad (3)$$

Where ε_i is the error signal and its derivatives are obtained from an nth order TD.

The core of an ADRC is ESO, which is capable of observing system uncertainties and external disturbances and providing feedback for compensation. Suppose that there is an uncertain nonlinear plant with an unknown external disturbance *w(t)*, and the mathematical model can be represented by

$$y^{(n)} = f(y,\dot{y},\cdots y^{(n-1)},w(t))+b(t)u(t) \qquad (4)$$

Where *f(-)*, *w(t)* and *b(t)* are the unknown time-variant functions. Assuming that b_0 is the value of *b(t)* in the time of t_0, (4) can be rewritten as

$$y^{(n)} = f(y,\dot{y},\cdots y^{(n-1)},w(t))+[b(t)-b_0]u(t)+b_0u(t) \qquad (5)$$

Assuming $a(t) = f(\cdots)+[b(t)-b_0]u(t)$ be the total unknown disturbance.

Choose the n+1 dimension state variables. The n+1 dimensions extended state equation of the plant (5) can be described by

$$\begin{cases} \dot{x}_1 = x_2, \dot{x}_2 = x_3,\cdots,\dot{x}_{n-1} = x_n \\ \dot{x}_n = a(t)+b_0u(t) = x_{n+1}+b_0u(t) \\ y = x_1 \end{cases} \qquad (6)$$

An ESO can be designed as follow

$$\begin{cases} \dot{z}_1 = z_2 - g_1(z_1-y),\cdots,\dot{z}_{n-1} = z_n - g_{n-1}(z_1-y) \\ \dot{z}_n = z_{n-1}+b_0u(t)-g_n(z_1-y) \\ \dot{z}_{n+1} = -g_{n+1}(z_1-y) \end{cases} \qquad (7)$$

Where, $\dot{z}_i$ denotes the observing value of xi, and $g_i(z_1-y)$ is a nonlinear function, i=1,2,•••,n+1. Reference [4] has proved that if $g_i(z_1-y)$ is selected strong enough, the designed ESO can effectively observe all of n+1 dimension state variables.

The principle of one-order ADRC is shown below.

$$\begin{cases} \dot{v}_1 = -r\,fal(v_1 - v(t), \alpha_0,\delta_0) \\ \varepsilon = z_1 - y \\ \dot{z}_1 = z_2 - \beta_1 fal(\varepsilon, \alpha_1,\delta_1) + bu \\ \dot{z}_2 = -\beta_2 fal(\varepsilon, \alpha_1,\delta_1) \\ \varepsilon_1 = v_1 - z_1 \\ u_0 = \beta_3 fal(\varepsilon_1, \alpha_2,\delta_2) \\ u = (u_0 - z_2)/b \end{cases} \qquad (8)$$

Where $fal(\varepsilon, \alpha,\delta) = \begin{cases} |\varepsilon|^{\alpha}\,\mathrm{sgn}(\varepsilon), |\varepsilon| > \delta \\ \varepsilon/\delta^{1-\alpha}, |\varepsilon| \le \delta \end{cases}$ is nonlinear gain.

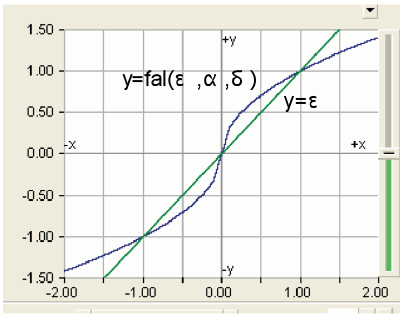

Fig.2 Comparison of linear and nonlinear gain(α=0.5 δ=0.1)

As fig.2 illustrated, when the error is smaller than one, nonlinear gain is bigger than linear gain; when the error is bigger than one, nonlinear gain is smaller than linear gain. The nonlinear function can zoom in or zoom out the error so that it arranges the reasonable observer value for the control system. It can effectively avoid the conflict between response time and overshoot.

Where k_1、a_1、δ_1、k_{21}、k_{22}、a_2、δ_2、k、a、δ are the parameters to be regulated. Normally they are obtained from simulation and experimental results. As well as, the regulation step is follow: first, according to the characteristic of the control target, system stability should be ensured. Then, the parameters of TD and ESO are regulated to evaluate the reference inputs, the variables of each state and disturbance, quickly and correctly. After then, NLSEF parameters are also adjusted to conform to the close-loop performance require.

III. WIND FARM MODEL

Compare to the conventional electric power generation, WECS is composed of multi-machines, the steady-state model of wind farm must take all the machines which under different operation state in to account. Moreover, the output of wind farm is time-variable in a big range and unpredictable. A way to model a wind farm is to regard it as a PQ bus in the power system [7].

If the wind speed is known, the active power can be estimated by the power curve for the WT from the manufacturer and the following function.

$$P_e \approx 0.5C_p(\lambda,\beta)\rho A V_W^3 \qquad (9)$$

Where C_p is power coefficient, which is function of λ and β, λ is the tip speed ratio (between the blade tip speed w_tR and wind speed V_w), β is the pitch angle. ρ is the air density, A is the turbine sweep area.

An example of power curve for a typical Danish 600 kW wind turbine is shown in Fig.3 [8].

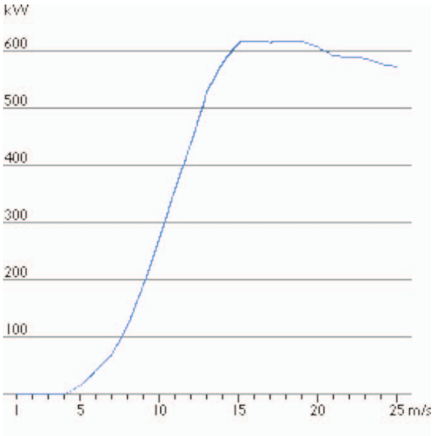

Fig3. Wind turbine power curve

The reactive power depends on the active power and the bus voltage. Neglecting the resistance of the stator and rotor for simplicity and the reactive power consumed by the generator is calculated.

$$Q_e = -\frac{V^2}{X_m} - \frac{X}{V^2}P_e^2 \qquad (10)$$

Where V is the generator terminal voltage, X_m is the magnetizing reactance, X is the sum of rotor and stator reactance.

The active power injected and the reactive power consumed by the wind farm is the sum of all the machines.

IV. SVC ADRC DESIGN

One-machine infinite-bus (OMIB) with SVC equipped is studied and shown in Fig.4.

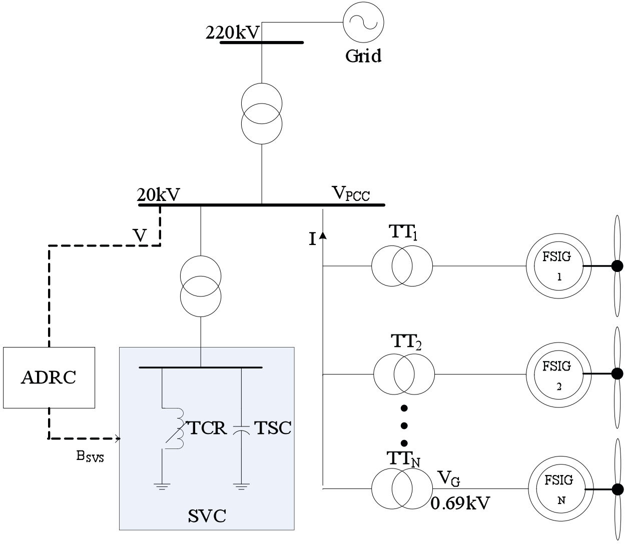

Fig.4 System model and control strategy

Supposed:

- The wind farm is regarded as a PQ bus model which presented in section III;
- SVC is equivalent as thyristors-controlled reactor, $Q_{svc} = (B_L + B_C)V_m^2$; and expressed as an one-order inertial tache: $\dot{B}_L = \frac{1}{T_B}(-B_L + B_{L0} + U_B)$;
- The resistances of the transformer and cable between generator and PCC are neglected. The power system voltage V_s is constant.

To achieve the target of SVC which is to maintain the voltage dynamic stability, set the control object as below:

$$\begin{cases} \Delta\dot{V}_m = \dfrac{\dot{P}_e R + [\dot{Q}_e + \dfrac{1}{T_B}(-B_L + B_{L0} + U_B)V_m^2 + (B_L + B_C)2V_m\dot{V}_m]X}{V_s} \\ = a(t) + b_0 U_B \\ \qquad y = \Delta V_m = \dfrac{P_e R + (Q_e + Q_{svc})X}{V_s} \end{cases} \qquad (11)$$

Where

$$a(t) = \frac{1}{V_s}\{\dot{P}_e R + [\dot{Q}_e + \frac{1}{T_B}(-B_L + B_{L0} + U_B)(\Delta V_m^2 - 2\Delta V_m V_{m0})$$

$$+(B_L + B_C)2V_m\dot{V}_m]X\}$$

is the total unknown disturbance. And $b_0 = \frac{V_{m0}^2}{T_B}\cdot\frac{X}{V_s}$

As the function (11) describes, the system is one order.

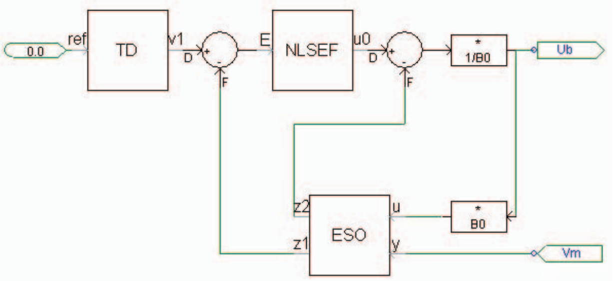

Fig.5 Control loop

The control target is bus voltage. The input for TD is voltage command value and it will arrange a proper temporary process. Set the one-order TD output as

$$\dot{v}_1 = -k_1 \cdot fal[(v_1 - \Delta v_{ref}), \alpha_1, \delta_1] \qquad (12)$$

Then the output v_1 is compared with observed voltage feedback from ESO, the different is the input of NLSEF to generate a proper u_0. And the control value of SVC becomes

$$\begin{cases} \varepsilon = z_1 - v_1 \\ u_0 = k\cdot fal(\varepsilon, \alpha, \delta) \\ u_B = (u_0 - z_2)/b_0 \end{cases} \qquad (13)$$

The actual measure voltage value form transducer will be feedback to ESO for state observation. Design the two-order ESO as follow and voltage state z_1, extended state z_2 will be given

$$\begin{cases} \varepsilon_2 = z_1 - \Delta v_m \\ \dot{z}_1 = z_2 - k_{21} fal(\varepsilon_2, \alpha_2, \delta_2) - b_0 U_B \\ \dot{z}_2 = -k_{22} fal(\varepsilon_2, \alpha_2, \delta_2) \end{cases} \qquad (14)$$

V. SIMULATION RESULT

The consider case study is shown in Fig.4. It is a 40MW wind farm composed of 40 squirrel cage induction generators with a rating of 1MW. Each wind turbine is connected to the wind farm internal 20kV cable network by a 1MVA, 0.69/20kV transformer. The wind farm is connected to the high voltage network by means of a 40MW, 20/220kV transformer [9].

Table 1: wind turbine parameters

Stator resistance	Rs	0.066pu
Stator reactance	Xs	0.046pu
Rotor resistance	Rr	0.298pu
Rotor reactance	Xr	0.122pu
Magnetizing reactance	Xm	3.86pu
Nominal power	Pg	1MW
Nominal voltage	Vg	690V
Gearbox ratio	N	55
Wind turbine radius	R	28m
Pole pairs	P	3
Mechanical speed	ω_r	1000rpm

The result obtained form PSCAD/EMTDC is shown below.

A.Case1:

The wind turbines operating at the same wind speed which shown in Fig.6. The wind speed model is made up of mean wind, gust wind, ramp wind and noise. The output power of wind farm is variably accord to it. Without SVC, the voltage of 20kV bus is fluctuant. Simulation results show that the controller makes the signal for SVC tracking the compensation correctly. The reactive power from power system and 20kV bus voltage both maintain at the reference value.

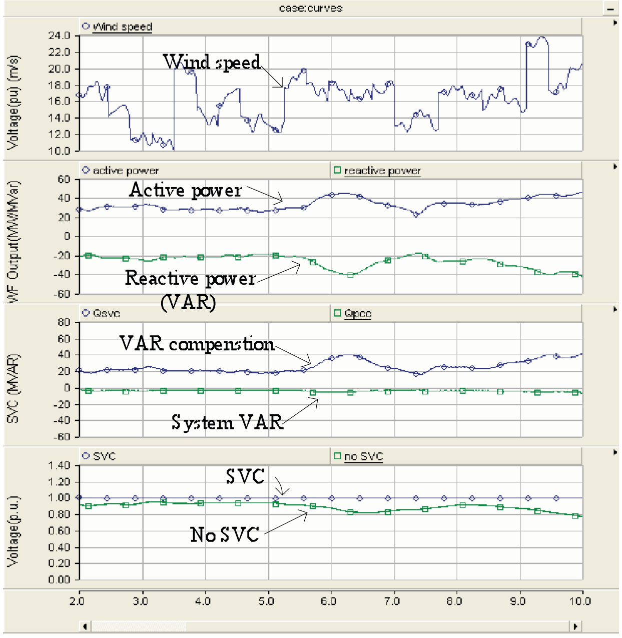

Fig.6 The curves of case1

B.Case2:

The wind farm will trip off when the wind speed die-out. And the output to be ramped down and finally becomes zero [10]. The sudden power flow change will influence the voltage stability. After trip off, WTs still connect to the power grid, "generation mode" will change to "motor mode" and absorb reactive power for the excitation. Fig.7 shows that the ADRC for SVC can solve this problem.

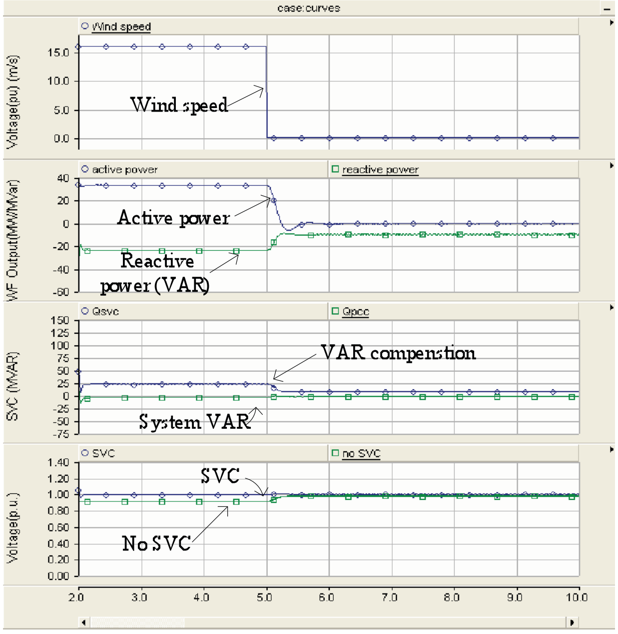

Fig.7 The curves of case2

VI. CONCLUSION

This paper has successfully presented a nonlinear controller based on ADRC with strong robust and adaptability for SVC control system. Simulation results show that SVC with the proposed controller can effectively maintain the wind farm voltage stability of the neighboring bus under different events.

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BIOGRAPHIES

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