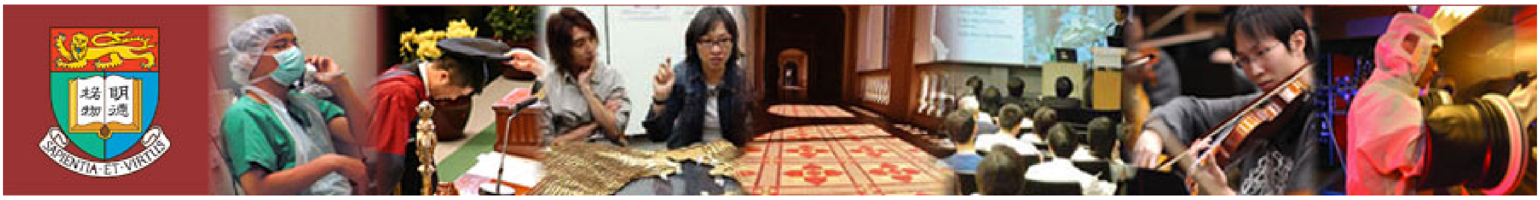

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STATCOM Control for Integration of Wind Farm to the Weak Grid

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***Abstract*—This paper focuses on the STATCOM modeling and nonlinear controller design for fast voltage regulation during the grid disturbance when the wind farm is integrated to a weak grid. A sliding mode inverse controller for the STATCOM connected at the PCC of the wind farm is proposed. It utilizes the inverse system theory to form a pseudo-linear system of the STATCOM. Then the variable structure sliding mode control, with the feature of insensitivity to parameters variation, could be implemented to enhance the system robustness. The comprehensive control scheme could maintain the dc-link voltage of STATCOM and rapidly regulate the ac voltage at PCC to its reference by injecting the reactive current, so as to enhance the voltage stability of wind farm during the transient response. Simulation in PSCAD/EMTDC verified that the STATCOM with the controller proposed can reduce the voltage drop experienced by the wind farm by providing dynamic reactive power support, thus improving the fault ride-through capability of the wind farm.**

***Index Terms*-- Inverse system; sliding mode controller; STATCOM; wind farm**

I. INTRODUCTION

With the penetration of the wind power growing, especially the expanded scale of the wind farm, it will cause a serious impact on the stability and reliability of the power system [1][2]. The unpredictable wind speed variations will definitely cause the severe voltage fluctuation at the point of common coupling (PCC) where the wind farm is connected with the existing power grid [3]. In addition, the fault occurrence at the PCC will inevitably result in the voltage dip, which may be propagated to fairly remote locations in the grid, especially in the case of weak grids. The voltage dip may trip many wind turbines in a large wind farm during grid faults if no measured is taken. Therefore, voltage stability is the crucial issues in maintaining uninterrupted operation of the wind farm integration with the weak grid.

Despite the fact that the gird codes prescribe that wind farms should support the grid by generating reactive power during a network fault, to support and restore the grid voltage [4]. However, this reactive power support achieved by double fed induction generator (DFIG) converters indicates a high expense of increased power losses and reduced efficiency [5].

Up until now, different methods have been investigated to enhance the fault rid through capability and to fulfill grid code requirement, in which, the Static Synchronous Compensator (STATCOM) is widely adopted due to its unique advantages [6].

The STATCOM can react to the variation of the ac voltage within a few power frequency cycles and can thus eliminate the necessity for rapid switching of capacitor banks or transformer tap-change operations for reactive power adjustment. The main advantage of STATCOM superior to the static var compensator (SVC) lying in the compensating current will not depend on the PCC voltage level and thus the current is not lowed as the ac voltage drops [7]. The rapid response of the STATCOM provides finer reactive power control by injecting the dynamic reactive power independent of the grid voltage during transient conditions such as the wind farm output power variation and grid fault. It could improve and stabilize the wind turbine behavior, and reduce the amount of wind power lost during system disturbance [8].

The research concerned with the STATCOM in wind power application has evolved in the last few years. Initially, STATCOM is closely related with the fixed-speed wind turbines (FSWT)[9][10]. FSWT consumes large amount of reactive power, which may lead to the voltage collapse and further fault propagation in the network as well as slowing down the voltage restoration after a fault [11]. STATCOM is intended to enable the fault ride-through capability of FSWT, so as to avoid the over-speeding of the wind turbines and the voltage instability incurred. With the development of the variable-speed wind turbine (VSWT) equipped with the DFIG, STATCOM is applied to ensure the uninterrupted operation of wind farm during grid fault [12]. A damping controller of the STATCOM is designed by using modal control theory to contribute effective damping characteristics and to stabilize the grid-connected offshore wind farm [13]. In [14][15], the STATCOM incorporated with the hybrid battery energy storage is developed to enable the active power control ability of the STATCOM in order to smoothen

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the wind power fluctuation. As linear control techniques have been predominately used for controlling the STATCOM, in [7][16][17] the conventional proportional integral (PI) control, the pole placement control and the linear Quadratic Regulator are developed and compared. But those methods can't realize better dynamic decoupling and may not be able to provide satisfactory control performance. Another method is to linearize the system around an operating point using the state space equation [18]. However, the control design depends largely on the operating point, which is not appropriate in the event of large disturbance.

This paper presents a control method for adjusting the reactive power support of the STATCOM. Firstly, the system configuration and mathematical model are proposed. Then, the inverse system theory is introduced and utilized to derive an approximate pseudo-linear system of the STATCOM. Based on the pseudo-linear system, the variable structure sliding mode controller is designed to enhance the system robustness. The system model associated with the wind farm, the STATCOM and the grid are established in PSCAD/EMTDC. The controller performance is evaluated and proved to be effective for suppressing the voltage fluctuation, especially reducing the voltage dip in the case of the grid fault and contributing to the voltage recovery.

II. SYSTEM CONFIGURATION

Fig.1 shows the system diagram to be investigated in this paper. The wind farm consisting of DFIG based wind turbines is connected to the PCC through the two step-up transformers: 0.69kV/ 13.8kV and 13.8kV/35kV. The rated power for the wind farm is 200MVA. The weak grid is represented by the voltage source with equivalent internal impedance with the short circuit ratio (SCR) 2.5. The weak grid cannot define an independent ac voltage reference for the DFIG to excite and control its power. Therefore, a voltage source converter based STATCOM is equipped at the PCC through the transformer, which could be deemed as a voltage source to provide the excitation voltage required by DFIG start-up and dynamic reactive power compensation for the grid during disturbances and fault conditions.

The ac voltage at the PCC is represented by U_G. The voltage on the ac side of STATCOM is denoted as U_s and its dc link voltage is E_s. Under different operational modes, the ac side current I_s of STATCOM is bidirectional. C_s denotes the dc-link capacitance. L_s and R_s represent the inductance and resistance of the step-up transformer installed on the ac side of the STATCOM.

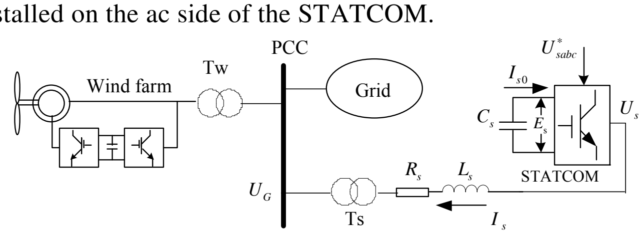

Fig.1 Wind farm integration using STATCOM

The mathematical model of the three-phase system is transformed to an equivalent synchronous dq axis rotating frame by applying the Park transformation. In addition, using the power balance equation between the ac side and dc side of the STATCOM, the STATCOM model can be expressed in the synchronous dq frame:

$$\begin{cases} \dfrac{dI_{sd}}{dt} = \omega I_{sq} - \dfrac{1}{L_s}\left(U_{sd} - U_{Gd}\right) - \dfrac{1}{L_s} R_s I_{sd} \\ \dfrac{dI_{sq}}{dt} = -\omega I_{sd} - \dfrac{1}{L_s}\left(U_{sq} - U_{Gq}\right) - \dfrac{1}{L_s} R_s I_{sq} \\ \dfrac{dE_{dc}}{dt} = \dfrac{3\left(U_{sd} I_{sd} + U_{sq} I_{sq}\right)}{2E_{dc}C} \end{cases} \tag{1}$$

where, U_{Gd} and U_{Gq} are the d-axis and q-axis components of the as bus voltage at PCC; U_{sd} and U_{sq} are the d-axis and q-axis components of STATCOM terminal voltage.

Since the model of STATCOM shown in Equ.(1) is highly nonlinear, the linear approaches make it difficult to design an effective controller that could guarantee fast and stable regulation under all operating conditions. The inverse system theory is introduced and applied in the controller design below.

III. CONTROL STRATEGY

A. Inverse System

For a given nonlinear system called the original system, a α th order (α is the relative order of the original system; α=m-n, where m and n denote the order numbers of input and output, respectively) integral inverse system could be derived to compensate the original system, so as to form an approximate pseudo-linear system [19]. Then the linear control theory could be utilized to realize the control for the pseudo-linear system [20].

Take the system Σ for example, the input and output are defined as u(t) and y(t) and, for $t \geq t_0$, the initial condition is $x\left(t_0\right) = x_0$. The y(t) could be described using the operator θ:

$$y\left(t\right) = \theta\left[x_0, u(t)\right] \tag{2}$$

Setting a system H_a with the initial state $\dot{x}\left(t_0\right) = \dot{x}_0$. The operator $\hat{\theta}_a$ is used to express the relationship $\hat{\theta}_a : \varphi \rightarrow u$. If $\varphi = y^{(\alpha)}(t)$, the expression below could be obtained.

$$\theta \hat{\theta}_a \varphi = \theta \hat{\theta}_a \left(D^\alpha y_d\right) = \theta u = y_d \tag{3}$$

in which, $D = d/dt$.

The system H_a is called the α order integral inverse system for the original system Σ. The composition operator $\theta\hat{\theta}_a$ represents a system with the linear transfer relationship and could be implemented with α integrators in series.

The controller design aims to the pseudo-linear system indicated by the dotted line in Fig.2 . r denotes the reference input and θ_r represents the linear controller to establish a closed-loop control system. The system is treated as α th order linear system, in which various linear control method could be implemented to design an additional controller.

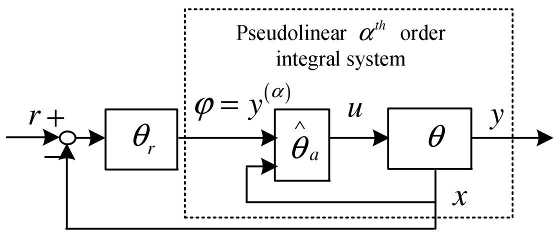

Fig. 2 Control scheme design with the inverse system

Due to the fact that the charging behavior of the capacitor determining its response is much slower than the transient current in terms of time scale. Therefore, the dc-link voltage variable in Equ.(1) may not be considered. The state variables are defined as $\mathbf{x} = [x_1, x_2]^T = [i_{sd}, i_{sq}]^T$; the input variables are $\mathbf{u} = [u_1, u_2]^T = [u_{sd}, u_{sq}]^T$; the output variables are denoted as $\mathbf{y} = [y_1, y_2]^T = [i_{sd}, i_{sq}]^T$.

The mathematical model could be rewritten as follows:

$$\begin{cases} \dot{x} = f(x,u) = \begin{bmatrix} -\dfrac{R_s}{L_s} & \omega \\ -\omega & -\dfrac{R_s}{L_s} \end{bmatrix} x + \begin{bmatrix} \dfrac{1}{L_s} & 0 \\ 0 & \dfrac{1}{L_s} \end{bmatrix} u - \begin{bmatrix} \dfrac{U_{Gd}}{L_s} \\ \dfrac{U_{Gq}}{L_s} \end{bmatrix} \\ y = h(x,u) = [y_1, y_2]^T = [x_1, x_2]^T \end{cases} \quad (4)$$

The model of the STATCOM is the two inputs and two outputs coupling non-linear system. The derivative of the output variables will be obtained to enable the input control variables appearing in the expression. The order number of the system equals to the relative order α, that is, α=n=1. The system is proved to be invertibility under the initial conditions and the inverse system exists.

Assuming $\varphi = \left[\dot{y}_1, \dot{y}_2\right]$ is taken as the input variables and $v = [v_1, v_2]^T = [u_{sd}, u_{sq}]^T$ the output variables, and defining $\mathbf{z} = [z_1, z_2]^T = [y_1, y_2]^T$, the first-order integral inverse system $\alpha(1,1)$ model is described as

$$\begin{cases} \dot{z} = \varphi \\ v = -\begin{bmatrix} R_s & \omega L_s \\ -\omega L_s & R_s \end{bmatrix} x + \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix} \varphi + \begin{bmatrix} U_{Gd} \\ U_{Gq} \end{bmatrix} \end{cases} \quad (5)$$

Actually, after the transformation, directly combining the first order inverter with the original system forms an approximate pseudo-linear system. The relationship between the input and output of the pseudo-linear system can be expressed below:

$$\dot{y} = \varphi \quad (6)$$

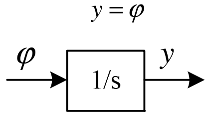

Fig. 3 First order integral composite system

B. Sliding Mode Control

The control of STATCOM is simplified properly as the control of the first order linear system. Combing with the variable structure sliding mode control to form a composite controller, the control performance of the whole nonlinear system could be improved greatly in the case of the system parameters change.

The switching function based on the variable structure control theory is intended to realize the variable structure control [21]. The stable operational point is set to be $X_\infty = \left[z_1^*, z_2^*\right]^T$ and the sliding surface is defined as:

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} == \begin{bmatrix} z_1^* - z_1 \\ z_2^* - z_2 \end{bmatrix} \quad (7)$$

in which, $z_1^* = I_{sd}^*$ and $z_2^* = I_{sq}^*$.

The derivative of Equ.(7) could be written as

$$\begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \end{bmatrix} = \begin{bmatrix} -\dot{z}_1 \\ -\dot{z}_1 \end{bmatrix} \quad (8)$$

According to the variable structure theory, the state variables are expected to reach the switching surface under the exponential law below.

$$\begin{aligned} \begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \end{bmatrix} &= \begin{bmatrix} -\xi_1 \operatorname{sgn}(S_1) - k_1 S_1 \\ -\xi_2 \operatorname{sgn}(S_2) - k_2 S_2 \end{bmatrix} \\ &= \begin{bmatrix} -\xi_1 \operatorname{sgn}(i_{sd}^* - i_{sd}) - k_1\left(i_{sd}^* - i_{sd}\right) \\ -\xi_2 \operatorname{sgn}(i_{sq}^* - i_{sq}) - k_2\left(i_{sq}^* - i_{sq}\right) \end{bmatrix} \end{aligned} \quad (9)$$

in which, $\xi > 0$, $k > 0$

Substituting Equ.(8) into Equ.(9) yields

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} \xi_1 \operatorname{sgn}(i_{sd}^* - i_{sd}) + k_1\left(i_{sd}^* - i_{sd}\right) \\ \xi_2 \operatorname{sgn}(i_{sq}^* - i_{sq}) + k_2\left(i_{sq}^* - i_{sq}\right) \end{bmatrix} \quad (10)$$

Hence, the controller could be designed as follows,

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} -R_s & -\omega L_s \\ \omega L_s & -R_s \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix} \begin{bmatrix} \xi_1 \operatorname{sgn}(S_1) + k_1 S_1 \\ \xi_2 \operatorname{sgn}(S_2) + k_2 S_2 \end{bmatrix} + \begin{bmatrix} U_{Gd} \\ U_{Gq} \end{bmatrix} \quad (11)$$

If **v** is substituted by **u,** the controller for the original system could be described as

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -\begin{bmatrix} R_s & \omega L_s \\ -\omega L_s & R_s \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix} \begin{bmatrix} \xi_1 \operatorname{sgn}(i_{sd}^* - i_{sd}) + k_1\left(i_{sd}^* - i_{sd}\right) \\ \xi_2 \operatorname{sgn}(i_{sq}^* - i_{sq}) + k_2\left(i_{sq}^* - i_{sq}\right) \end{bmatrix} + \begin{bmatrix} U_{Gd} \\ U_{Gq} \end{bmatrix} \quad (12)$$

The Lyapunov stability and convergence is proved below. The Lyapunov function is set to be $V = S^T \cdot S / 2$ to verify the asymptotic stability of S.

$$V = S^T \cdot S / 2 \quad (13)$$

$$\dot{V} = S^T \cdot \dot{S} = [S_1, S_2]\begin{bmatrix} -\xi_1 \operatorname{sgn}(S_1) - k_1 S_1 \\ -\xi_2 \operatorname{sgn}(S_2) - k_2 S_2 \end{bmatrix}$$
$$= -S_1\left[-\xi_1 \operatorname{sgn}(S_1) - k_1 S_1\right] - S_2\left[-\xi_2 \operatorname{sgn}(S_2) - k_2 S_2\right] \quad (14)$$

For arbitrary $S_1 \neq 0$, $S_2 \neq 0$, $\dot{V} < 0$. The system will reach the sliding surface in the limited time. The state is possible to remain on the sliding manifold at all times and maintain the perfect tracking.

Fixing the d-axis voltage component U_{Gd} along the grid ac voltage: $U_{Gd} = U_G$, $U_{Gq} = 0$. The active power and reactive power at the PCC are described as:

$$\begin{cases} P_G = \frac{3}{2} U_{Gd} I_{sd} \\ Q_G = -\frac{3}{2} U_{Gd} I_{sq} \end{cases} \quad (15)$$

If the grid voltage is well controlled, the active power and reactive power control could be achieved by adjusting the current I_{sd} and I_{sq}, respectively, that is, to accommodate the STATCOM with the bi-directional reactive power compensation capability, the active current I_{sd} should be adjusted to maintain the dc-link voltage and balance the active power.

The dc-link voltage of the STATCOM and the ac voltage at PCC are regulated by the additional outer-loop control to derive the active current and the reactive current reference command I_{sd}^* and I_{sq}^*.

$$\begin{cases} I_{sd}^* = \left(k_{dcp} + \frac{k_{dci}}{s}\right)\left(E_{dc}^* - E_{dc}\right) \\ I_{sq}^* = \left(k_{acp} + \frac{k_{aci}}{s}\right)\left(U_G^* - U_G\right) \end{cases} \quad (16)$$

In Fig.4, the ac voltage control aims to generate the q-axis reference current I_{sq}^*, which is intended to regulate the ac voltage at PCC and ensure the voltage U_G towards U_G^*. It indicates the reactive power absorbed or generated to the ac grid. The inner loop control design is based the sliding mode control and inverse system theory to produce the desired ac voltage and drive the VSC-based STATCOM.

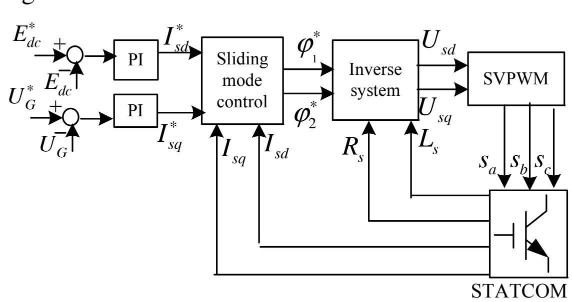

Fig. 4 Comprehensive control scheme for STATCOM

IV. Case Study

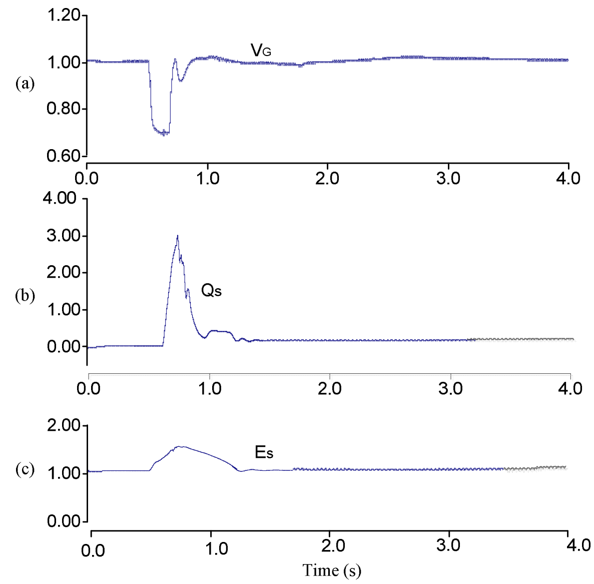

Fig.5 Three-phase short-circuit fault with STATCOM

(a) AC voltage level at PCC (p.u.) (b) STATCOM output reactive power (p.u.) (c) STATCOM dc-link voltage (p.u.).

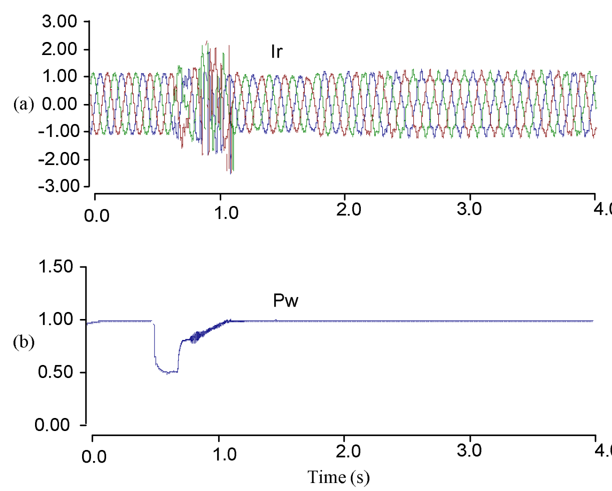

Fig.6 Wind farm response
(a) Rotor side current (p.u.) (b) Wind farm active power output (p.u.)

A validation study of the work mentioned above was performed through PSCAD/EMTDC. The per unit values shown below are based on 100MW power and 35kV voltage. For the sliding mode control, the parameters are designed as ξ_1=0.1, ξ_2=0.1, k1=100 and k2=100. The PI control is tuned using k_{dcp}=3, k_{dci}=20, k_{acp} = 2, k_{aci}=10.

The grid fault at PCC will absolutely cause the terminal voltage dip of the wind turbine due to the low series impedance between the fault and wind farm. In this extreme case, the restoration of the grid voltage faces large difficulty. The deep voltage sag may lead to the power unbalance in the wind turbine and thus incur the current transient problem. The rotor side converter of DFIG may usually be blocked to prevent the overcurrent appearance during a grid fault, resulting in the wind turbine tripping. To verify the effectiveness of STATCOM on enhancing the fault rid-through of the wind farm and keeping the wind farm uninterrupted operation, the worst case is simulated, that is, a three-phase short-circuit fault is applied at the PCC at t=0.5s and is cleared after 0.1s. Fig.5 shows the variation of the ac voltage at PCC, the wind farm output active power and the reactive power generated by the STATCOM.

During the fault, the voltage sag shown in Fig.5 (a) is detected, the controller will react to the voltage variation. In Fig5 (b), the STATCOM tries to inject fast reactive power and compensate the voltage sag at PCC. With the voltage support from STATCOM, the voltage dip at PCC is enhanced greatly, that is, the voltage nadir is raised up to 0.7p.u, which complies with the voltage level specified by the grid code. Meanwhile, the ac voltage could be reestablished quickly once the fault is cleared and return to the reference value.

In Fig.6 (a), the rotor current peak is reduced sharply without trigging the protection and is maintained to the limited value. As a result, the rotor side converter will not be blocked and the wind farm keeps output active power at a lower level instead of being disconnected from the grid in Fig.6 (b). However, the unbalance active power will be absorbed by the STATCOM, causing the dc-link voltage increasing slightly. This result in Fig.5 (a) shows that over-voltage in the dc-link may be mitigated and the possibility of tripping the STATCOM is prevented.

Note that the linear relationship between the inverse system control inputs φ_1 and φ_2 and the outputs y_1 and y_2 could be always maintained in the event of sever grid fault. The controller response is relatively independent of the voltage dip at PCC and is effective over a large operation range to enable the wind farm staying connected to the grid.

V. CONCLUSION

In this paper, the control scheme for STATCOM is based on the reformulation of the pseudo-linear system and then the variable structure control implementation. It forms a linear and robust control framework and covers a wide operating range to ensure the voltage stability in the event of the severest grid fault. The voltage instability during grid faults can be prevented, so as to avoid the disconnection of wind farm by regulating dynamic reactive compensation provided by the STATCOM. The effectiveness of the controller designed for the STATCOM in facilitating the integration of the wind farm with a weak power system is confirmed, and the methodology proposed is flexible and applicable to the wind farm integrated to a weak grid.

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