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# Review of Power System Stability with High Wind Power Penetration

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*Abstract*—**This paper presents an overview of researches on power system stability with high wind power penetration including analyzing methods and improvement approaches. Power system stability issues can be classified diversely according to different considerations. Each classified issue has special analyzing methods and stability improvement approaches. With increasing wind power penetration, system balancing and the reduced inertia may cause a big threaten for stable operation of power systems. To mitigate or eliminate the wind impacts for high wind penetration systems, although the practical and reliable choices currently are the strong outside connections or sufficient reserve capacity constructions, many novel theories and approaches are invented to investigate the stability issues, looking forward to an extra-high penetration or totally renewable resource based power systems. These analyzing methods and stabilization techniques are presented and discussed in this paper.**

***Keywords—power system stability; high wind power penetration; stability modeling, instability identification; stability improvement***

## I. Introduction

As energy crisis approaching, more and more wind power resources are integrated into power systems every passing day. With the increased penetration level, power system stability will suffer the consequent impacts. In contemporary high wind power penetration systems such as Danish power system, maintaining the voltage stability and reliability of such a large wind power system relies on strong AC connections to neighboring power systems with sufficient reactive and voltage control and on control of central power plants [1]. Nowadays, based on the synchronous generator emulation control strategies and decoupling control methods, the stored kinetic energy and inertia inside the wind turbines are not fully used yet. To meet the ambitious targets proposed in [2], more researches should be investigated to take full advantage of the flexible controllability of the power electronic devices and figure out optimal configuration of energy storage systems (ESS).

According to the current classifications, the stability issues mainly contain angle stability and voltage stability based on the physical nature of the resulting instability considerations. From other aspects like the size of the disturbance or time span, the stability problems can be classified into transient stability, mid-term stability, long-term stability, etc. [3]. This paper mainly delineates the steady-state stability, small signal stability and transient stability issues with high wind power penetration. Power system is a non-linear dynamics system which can be modeled and depicted by Difference-Differential-Algebraic-Equations (DDAE). The integration of wind power raises the non-linearity further and causes the variety of the difference and differential components' proportion and structure in DDAE. Thus, the analysis methodology of power system with high and extra-high wind power penetration can still mainly center on the analysis of DDAE from steady-state to dynamic state. Reference [4] provides the improved small signal analysis methods for angle stability investigation. Reference [5] describes the stability analysis for networks with low inertia, droop controlled generators. At the aspect of voltage stability issues including steady-state and dynamic state, novel proposed methods based on bifurcation theory, time dominant simulation and power flow computation are gradually taking non-linearity components like on load tap changer (OLTC) in to account. For stabilization techniques, according to the applied phases and locus, they can be sorted as stability programming and planning methods [6]-[9], which are usually conducted before the building of wind farms; ESS and STATCOM configuration methods which are very essential for voltage stabilization especially for induction generator based wind farms [10]-[12]' stability control strategies and schemes [13]-[16]. These methods are partially applied to the current power systems with relatively high wind power penetration level like Denmark, Germany, Spain, etc. to make the wind farms able to meet the standards and grid codes [17][18].

To augment wind power penetration, it's a tendency that more and more wind farms will participate in frequency and voltage regulation. Along with the more and more popular concepts of smart grid, more requirements will be brought forward to make them act as virtual power plant for providing higher reliability and performance. Considering the obvious tendency that the squirrel-cage generators used in wind turbines in early stage have been displaced or retrofitted [17], stability researches on variable speed wind turbine equipped with DFIG and PMSG are mainly discussed in this paper. An overview of researches on power system stability with high wind power penetration including analyzing methods and improvement approaches is presented and discussed in the paper.

## II. High Wind Power Penetration Stability Issues

### A. High Wind Penetration Stability In Distribution Level

Wind power application in distribution level is relatively located in weak ac grids. In recent researches, DFIG based or PMSG based wind source units are required to contribute voltage and frequency regulation with the help of wind forecast tools when in islanding or weak grid mode. Thus, conventional droop control strategies including conventional P/f and Q/V droop are extensively used or examined in these systems for power assignment. In these systems, a secondary, usually dispatchable, source of energy was employed to restore the frequency and voltage to their nominal values. Nowadays, more and more novel droop strategies like torque droop, power droop and wind droop [19] are proposed for power sharing and stability enhancement at the same time without regulating control parameters. Consequently, the stability characteristics is determined by the droop loop. Paper [5] reveals the relationship between droop gains and system stability with a three-inverter-ring-connected microgrid and justifiable assumptions.

### B. High Wind Penetration in Transmission Level

In the transmission level, wind turbines are firstly integrated to form a relatively large scale wind farm offshore or onshore, then they are connected to the power system through HVDC [21]-[25]. With the augmenting penetration, the grid side probably becomes a weak ac system with a low Short-Circuit Ratio (SCR) [3]. In result, problems like high dynamic overvoltage, voltage instability, harmonic resonance and objectionable voltage flicker will be arisen. Meanwhile, Direct Torque Control (DTC) and Direct Power Control (DPC) associated with Maximum Power Point Tracking (MPPT) methods are applied widely in these kinds of wind farms. It has been shown that DPC is more efficient than DTC control [26]. For HVDC connected offshore wind farms, HVDC links are interties, characterized by controllability, large adjustable capacity and fast responses [27]. Multi-machine system and wind farms are decoupled in synchronization, which makes it possible to design damping control strategies on HVDC inverter side. The concerns still mainly focus on the unmatched instantaneous power with load which can significantly affect the DC voltage of the connected STATCOM thereby weaken the voltage stability. When the penetration is at a high level, some active power balancing means must be adopted.

### C. Models Used for Stability Analysis

Aggregated model is adopted for the stability analysis because the DFIGs or PMSGs are usually connected to the grid at a single substation although they are distributed within the wind farm [27]. Moreover, the time dominant simulation of a cluster of wind turbines is time consuming, the time cost might be unacceptable. For further simplicity according to some papers, the PMSG and DFIG equivalent model is replaced by synchronous generator.

The common control system structures of PMSG and DFIG are depicted in figure 1 and figure 2, respectively [19], [20].

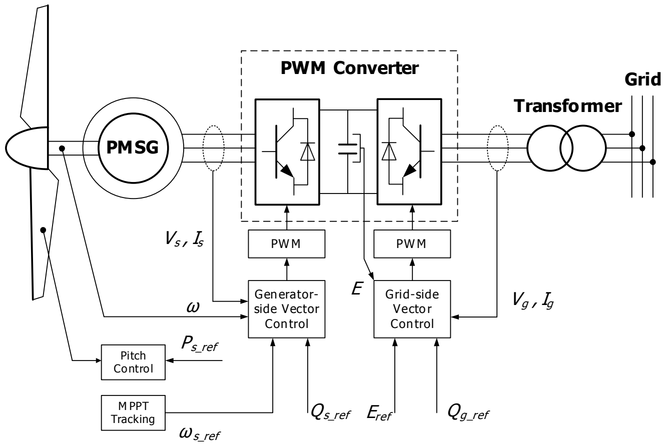


Figure 1. Control system of a DFIG based wind turbine

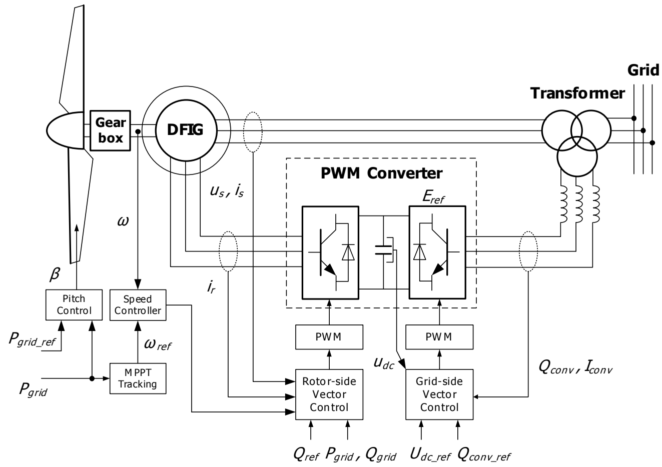


Figure 2. Control system of a PMSG based wind turbine

The captured mechanical power of a variable speed wind turbine (VSWT) is usually modeled as following:

$$P_m = 0.5 \cdot \rho \cdot A_r \cdot V_W^3 \cdot C_p(\lambda, \beta) \quad (1)$$

where $\rho$ is the air density (kg/m$^3$), $A_r$ is the blade impact area (m$^2$), $V_w$ is the wind speed (m/s), $\lambda$ is the tip speed ratio, $\beta$ is the blade pitch angle and $C_p$ is the dimensionless power coefficient of the VSWT. The more detailed explanations and expressions of these parameters can be found in [20]. Taking these equations into consideration, the relationship between stability issues and wind speed can be established.

The directly driven PMSG control system including generator side converter controller and grid side inverter controller can be described in figure 3.

According to these diagrams, the total transfer function can be derived, then the state differential equation can be obtained and regarded as a part of the system state equations.

The DFIG control system for rotor side converter and grid side converter can be modeled as figure 4. Using the same principle of PSMG-based wind turbine, the wind farm model can be integrated to the system state equations.

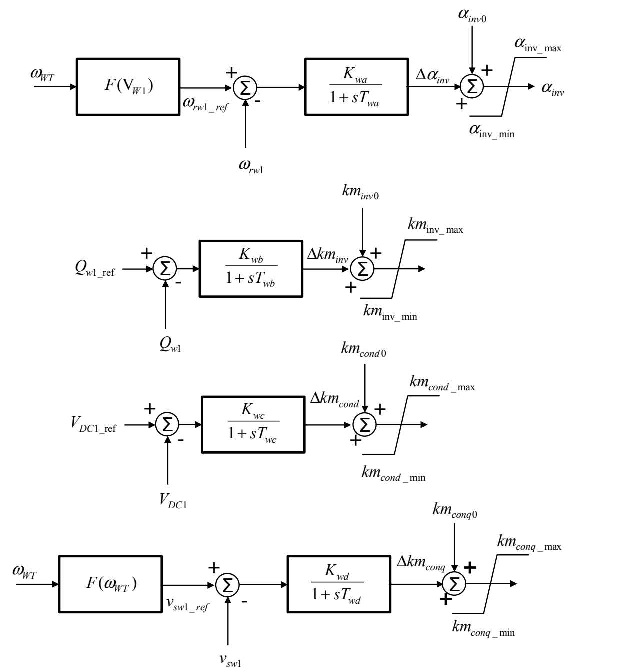

Figure 3. Grid side and generator side control diagrams of PMSG-based wind turbine

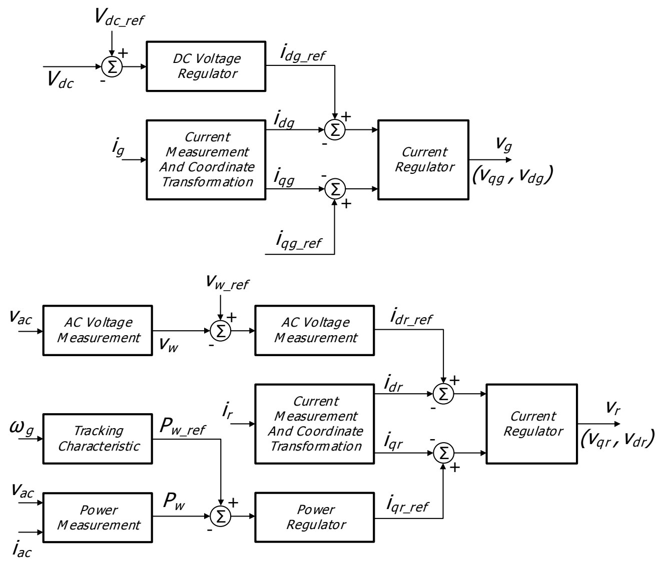


Figure 4. Grid side and rotor side control diagram of DFIG-based wind turbine

For transient stability analyzing, the two-inertia reduced-order equivalent mass-spring-damper model of the VSWT in figure 5 directly coupled to the rotor shaft of the PMSG [28]-[30] and DFIG are commonly employed. In addition, the mass-spring-damper concept can also be used to describe not only the shafts but also the whole wind turbines [31].

When modeling HVDC link associated with offshore wind farms, some papers consider to use constant current source or controllable source to represent them [32]. However, when the penetration arises, any imbalance operation between the transferred active power, dissipated losses and loads will cause the STATCOM dc-link voltage to vary, turning the STATCOM capacitor voltage into an indicator of active power imbalance [23]. Thus, more detailed model should be used for transient and stability study. The HVDC links and control strategies can be modeled in detail as [33] for stability research. For example, the typical wind farm system can be modeled as figure 6.

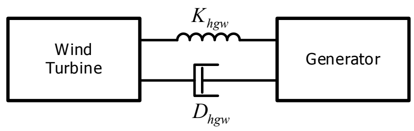


Figure 5. Two mass-spring-damper model of PMSG and DFIG

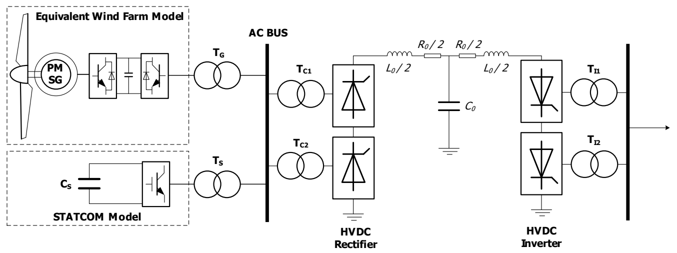


Figure 6. Wind farm with monopolar HVDC link model

## III. Stability Analysis Of High Wind Penetration System

### A. Static Stability Analysis

The steady-state stability analysis can be conducted by the power flow calculation. Usually, the wind farms are treated as a PV node. The limitation and margins for frequency and voltage stability can be calculated via the P/V curve and Q/V curve gained by power flow computation. There are also many indices to assess the system static stability such as probabilistic load flow (PLF) [34].

For example, with analytical description of the time series power flow in n buses system and defined most stressed situation, the operation limitations can be derived to identify the worst states [35].

For voltage steady-state stability, the basic indices which indicate the voltage sensitivity of operating point are also derived from the calculation. Furthermore, the voltage balancing is the local area and distributed issue with higher non-linearity to some extent. Thus, many other indicators for voltage stability are developed. For example, voltage collapse proximity indicator (VCPI) calculates the distance between the operating point and the point of collapse.

In [13], the interaction between reactive power variation and rotor angle variation has be discussed. The insufficient reactive power support will affect angle stability, and the angle instability will also mitigate the voltage stability. Although this issue is handled well by automatic voltage regulation in power system, its capability will be weaken with the increasing of wind power installation.

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial |V_1|} & \cdots & \frac{\partial P_1}{\partial \theta_n} & \frac{\partial P_1}{\partial |V_n|} \\ \frac{\partial Q_1}{\partial \theta} & \frac{\partial Q_1}{\partial |V_1|} & \cdots & \frac{\partial Q_1}{\partial \theta_n} & \frac{\partial Q_1}{\partial |V_n|} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \theta_1} & \frac{\partial P_n}{\partial |V_1|} & \cdots & \cdots & \cdots \\ \frac{\partial Q_n}{\partial \theta_1} & \frac{\partial Q_n}{\partial |V_1|} & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} \Delta \theta_1 \\ \Delta V_1 \\ \vdots \\ \Delta \theta_n \\ \Delta V_n \end{bmatrix} \quad (2)$$

$$|V| = \begin{bmatrix} |V_1| \\ \vdots \\ |V_n| \end{bmatrix} \quad (3)$$

$$\theta = \begin{bmatrix} \theta_2 \\ \vdots \\ \theta_n \end{bmatrix} \quad (4)$$

*B. Transient Stability Analysis*

Different from the basic methods which directly solve the DDAE, direct methods of transient stability research are realized by constructing the energy function. Although the method can avoid solving the system differential equations explicitly, it has difficulties in energy function construction and the constraints for the system model are relatively strong. The other transient stability investigation mainly relies on time dominant simulation using software like MATLAB/Simulink, PASCAD /EMTDC with numerical evaluation algorithms. Since the system stiffness is very significant for transient stability, it is useful to have a simple means of measuring and comparing relative strengths of ac systems to conduct stability estimation. The SCR has evolved as such a measure in basic level [3].

$$SCR = \frac{E_{ac}^2}{Z_{th}} \quad (5)$$

Where $E_{ac}$ is the rated bus voltage of PCC and $Z_{th}$ is the Thevenin equivalent impedance of the ac system.

TSI [27] can also be the transient stability index for assessing the severity of a contingency and the trajectory of a system following a disturbance.

*C. Small Signal Stability*

For angle stability analyzing of the high wind penetration system when it is suffering small disturbances, small signal model is still commonly used. The core concept of small signal analysis is using (7)-(9) to perturb and linearize the system state differential equations (6) at equilibrium point when they are derived from the control diagrams or transfer functions.

$$\begin{cases} \dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}) \\ \boldsymbol{y} = g(\boldsymbol{x}, \boldsymbol{u}) \end{cases}$$

(6)

$$\boldsymbol{x} = \boldsymbol{x}_0 + \Delta \boldsymbol{x} \qquad \boldsymbol{u} = \boldsymbol{u}_0 + \Delta \boldsymbol{u}$$

(7)

$$\dot{\boldsymbol{x}} = \dot{\boldsymbol{x}}_0 + \Delta \dot{\boldsymbol{x}} = f\left[(\boldsymbol{x}_0 + \Delta \boldsymbol{x}), (\boldsymbol{u}_0 + \Delta \boldsymbol{u})\right]$$

(8)

As the perturbations are usually assumed to be small, express the nonlinear functions *f(x, u)* in terms of Taylor's series expansion as following:

$$\begin{aligned} \dot{x}_i = \dot{x}_{i0} + \Delta \dot{x}_i &= f_i\left[(\boldsymbol{x}_0 + \Delta \boldsymbol{x}), (\boldsymbol{u}_0 + \Delta \boldsymbol{u})\right] \\ &= f_i(\boldsymbol{x}_0, \boldsymbol{u}_0) + \frac{\partial f_i}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_n}{\partial x_n}\Delta x_n \\ &\quad + \frac{\partial f_i}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_r}\Delta u_r \end{aligned}$$

(9)

Therefore, the linearized forms are:

$$\begin{aligned} \Delta \dot{\boldsymbol{x}} &= \boldsymbol{A}\Delta \boldsymbol{x} + \boldsymbol{B}\Delta \boldsymbol{u} \\ \Delta \boldsymbol{y} &= \boldsymbol{C}\Delta \boldsymbol{x} + \boldsymbol{D}\Delta \boldsymbol{u} \end{aligned} \quad (10)$$

where

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \quad \mathrm{B} = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_r} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$
$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} \quad \mathrm{D} = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_r} \end{bmatrix} \quad (11)$$

Then, eigenvalue properties of the linearized equations (10) can be the judgement of system stability according to the Lyapunov's first method. However, when the eigenvalues have real parts equal to zero, it is not possible on the basis of the first approximation to say anything in the general [3]. Then the Lyapunov's second method could be investigated on the origin system. Through assessing the eigenvalue sensitivity or participation factor, the influences of oscillation modes and non-oscillation modes can be analyzed. The referred oscillation modes include local plant modes, inter-area modes, control modes and torsional modes.

In these papers, the outcomes shows that small signal stability has relationship with transient stability in increased wind power penetration systems because the modes with low damping could be excited by a large disturbance in a certain location.

In [4], considering stochastic nature of wind generation, a method combines probabilistic analysis and power system small-signal stability is proposed. The method can directly determine the system probabilistic stability by performing just once the proposed step-by-step probabilistic analysis which is very computationally efficient. In [27], the proposed approach is intended to evaluate eigenvalue sensitivity with respect to generator inertia. Using sensitivity coupled to inertia, the impact of increased penetration of DFIGs on electromechanical modes of oscillation can be revealed. It is shown that the increased installation of wind power based on DFIG may have both beneficial and detrimental impact. It is possible to identify them through sensitivity analysis with respect to inertia.

### *D. Stability Analysis Methods Comparison*

According to the classifications of stability issues, the corresponding analysis approaches and stable features of high wind penetration system are listed in table I.

TABLE I STABILITY ANALYSIS METHODS COMPARISON

| Stability Issues | Analyzing Method | Possible Problems with High Wind Penetration |
|---|---|---|
| Small Signal Stability | • Small-signal model<br>• Eigenvalue techniques | • Largely reduced inertia<br>• Beneficial and detrimental impacts coexist |
| Static Stability | • Power flow computation<br>• Voltage stability indices | • Stressed by reactive power generation requirement of wind farm<br>• Instability caused by power unbalancing |
| Transient Stability | • Bifurcation theory<br>• Time dominant simulation<br>• Equivalent model | • Extended time frame<br>• Excite the modes |

## IV. STABILITY IMPROVEMENT WITH HIGH WIND PENETRATION

### *A. Static Stability Improvement for High Penetration System*

The steady-state stability issues are mainly determined by the balancing of power generation and consumption. Due to the intermittent nature of wind, the wind fluctuation will cause great challenge to the balancing operation. The fluctuation and the voltage flicker are currently smoothed by appropriate configuration of ESS, STATCOM and SVCs. A considerable number of present papers pay attention to solve these problems with electric vehicles (EV), nevertheless, much more efforts are needed for popularizing EVs, studying the characteristics of EV usage and improving control strategies. When planning the wind farms, optimal configuration of ESS and STATCOM capacity and locus can improve the static stability margins and transient stability.

### *B. Transient Stability Improvement for High Penetration System*

Transient instability is mainly derived from the reduced inertia. It can be enhanced by configuring super capacitor or high rated power ESS facilities when planning the wind plant. For transient and voltage stability enhancement, SVC or STATCOM are usually configured in PMSG-based or DFIG-based wind farms to resist the severe faults. Active power control method is also used for transient stability improvement in wind turbine controllers. When utilize HVDC for wind farm integration, many strategies can be practiced on the inverter current regulator. Fuzzy control methods can be designed adaptively and efficiently [20]-[25].

To improve the transient performance like LVRT ability of the wind turbines, new topology combined with Super Capacitor or ESS are invented. For example, in [36], a solution for enhance inertial of a DFIG is provided.

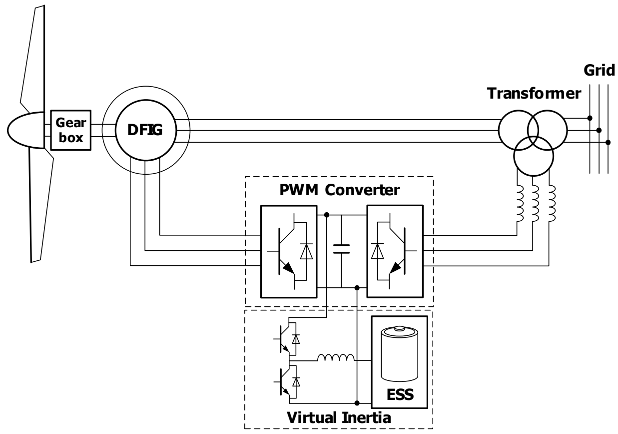

Figure 7. DFIG-based wind turbine with virtual inertia

### *C. Small Signal Stability Improvement for High Penetration System*

Small signal instability are determined by the damping torque component following a disturbance. Insufficient damping torque results in oscillatory instability which can be depicted by a small signal model.

Study shows that generator types used in wind turbines are irrelevant to power system oscillations. Rather, the penetration of wind power will have a damping effect due to reduction in size of synchronous generators that engage in power system oscillations. In HVDC connected wind farms, the PID or PI damping controller using the pole-placement technique is the first choice. In [32], the analysis shows that reactive power from wind generation can be used as a mitigation tool to ease the stress on synchronous generation and increase system security. In [37], the reason of power oscillation modes are investigated by small signal analyzing. Three types of controllers are proposed and compared to mitigate the forced wind power fluctuation.

## V. CONCLUSION

This paper presents the recently concerned issues about stability of modern power system with high wind power penetration. The different analysis approaches are discussed. According to different stability issues, corresponding solutions and enhancement strategies are introduced. For steady-state stability, wind power intermittence is the main concern. ESS or EV can be employed for a feasible solution. Transient stability can be enhanced by inertia emulation strategies using super capacitor and ESS. Novel control methods are used for mitigating small signal stability issues caused by wind turbine such as wind fluctuation, weak effect and tower effect. However, the ambitious plans to exploit wind energy haven't been realized yet. Hence, further efforts in theories and control techniques may be made to reveal factors which affect stability and stabilize the power system when wind penetration reaches an extra-high level.

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