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Influence of Wind Plant Ancillary Voltage Control on System Small Signal Stability

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***Abstract*—As a common tendency, large-scale wind farms are increasingly connected to the transmission system of modern power grids. This introduces some new challenges to the connected power systems, and the transmission system operators (TSOs) have to put some new requirements as part of the grid codes on the integration of wind farms. One common requirement to wind farms is the function of system voltage control which can be implemented in the grid-side convertor controller of a variable speed wind turbine. This ancillary voltage control provided by wind farms could have some influence on the system small signal stability. This paper implements an ancillary voltage control strategy on a direct-drive-full-convertor-based wind farm and studies its influence on the damping ratio values of the dominant oscillation mode within the connected power system. All the calculations and simulations are conducted in DIgSILENT PowerFactory 14.0.**

***Index Terms*—ancillary voltage control, direct-drive-full-convertor-based wind turbines, small signal stability**

I. Introduction

Large-scale wind power plants are increasingly integrated into the transmission system of modern power grids. The transmission system operators (TSOs) modified their grid codes to add specific technical requirements for wind farm integration. Some of these requirements in the grid codes include [1, 2]:

- Under normal conditions:
  - Frequency and voltage ranges
  - Active power regulation and frequency control
  - Reactive power regulation and voltage control
- Under disturbance conditions:
  - Voltage ride through
  - Reactive current injection

These requirements make sure that the wind farms maintain a satisfying performance under both normal and disturbance conditions. Furthermore, according to these requirements, wind farms ought to contribute some control functions to the connected grids as the conventional power plants do, e.g. frequency control and voltage control. These functions are termed as ancillary control.

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Ancillary voltage control is related to reactive power regulation. For variable-speed wind turbines which are connected to the power system through power electronic convertors, one advantage is that the output active power and reactive power can be controlled separately and this provides the flexibility of wind turbines contributing to voltage control. Ancillary voltage control strategies have been proposed for both direct-drive-full-convertor-based wind turbines in [3], [4] and doubly-fed induction generator (DFIG)-based wind turbines in [5]. Some technical issues such as wind farm reactive power capability and economical issues such as reactive power cost have been considered in [6], [7] and [8].

With regard to small signal stability, it is the ability of a power system to maintain synchronism among generators under small disturbances [9]. The main concern of small signal stability is the damping of electromechanical oscillations. Wind power integration in large scale can influence the small signal stability of the connected power system. The author of [10] which is a review of relevant literature, concluded that wind power plants based on constant speed wind turbines have positive effects on small signal stability, while the effects of wind power plants based on variable speed wind turbines are debatable.

Ancillary voltage control may introduce some new influence on small signal and the main objective of the present paper is to find this potential influence.

Some background knowledge of small signal stability is presented in section II. The utilized wind turbine model is briefly introduced in section III. The ancillary voltage control strategy is depicted in section IV. Simulation results are presented in section V and section VI gives the conclusions.

II. Small Signal Stability

Small signal stability is the ability of a power system to maintain synchronism among generators under small disturbances. It is the nature of a power system at a certain operating point and the main focus is the damping of electromechanical oscillation modes [9].

One way to study the small signal stability of a power system is modal analysis from which the eigenvalues of the system state equations are calculated in the form of a complex value as presented in (1).

$$\lambda = \sigma \pm j \cdot \omega \tag{1}$$

An oscillation mode always corresponds to two eigenvalues appearing as a conjugate pair. In this case, the real part of the conjugate pair, σ gives the information of the oscillation damping, while the imaginary part of the conjugate pair, ω stands for the oscillation frequency.

One common index to measure the small signal stability performance is damping ratio. It can be calculated from eigenvalues as shown in (2).

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{2}$$

The damping ratios of all oscillation modes should be positive so that the power system can be considered stable in the sense of small signal stability. In a power system, the operating point, which has larger damping ratios than others, is considered more stable than the others.

In DIgSILENT PowerFactory 14.0, modal analysis can be conducted at each calculated operating point, while afterwards eigenvalues and damping ratios are all available.

III. Wind Turbine Model and Control Schemes

The wind turbine model used in this paper is a direct-drive-full-convertor-based wind turbine modeled in DIgSILENT PowerFactory 14.0. Since the detailed description of this wind turbine model and its control schemes can be found in [11], only a brief introduction will be presented in this section.

A. Wind turbine model

To build a complete wind turbine model, it should include the wind speed model, the aerodynamic model, the mechanical models and the electrical models.

Detailed wind speed model is not necessary for power system small signal stability study, so constant wind speeds are used in this paper.

The aerodynamic model is described by (3):

$$Tw = \frac{1}{2}\rho\pi R^3 v_{eq}^2 \frac{C_P(\theta,\lambda)}{\lambda} \tag{3}$$

where Tw is the aerodynamic torque extracted from the wind (Nm); ρ is the air density (kg/m^3); R is the wind turbine rotor radius (m); v_{eq} is the equivalent wind speed (m/s); θ is the pitch angle of the rotor (deg); $\lambda = \omega R / v_{eq}$ is the tip speed ratio; ω is the wind turbine rotor speed (rad/s); and C_p is the aerodynamic efficiency of the rotor.

As for the mechanical part, a two-mass model is constructed in this paper to represent the drive train.

The permanent magnet synchronous generator (PMSG) is modeled by the synchronous generator model in DIgSILENT PowerFactory library, with a constant excitation current setting.

To improve simulation speed, an average model without switchings is used to represent the PWM convertors [12].

B. Wind turbine control schemes

As a variable speed wind turbine, under low and moderate wind speed conditions, the electromagnetic torque is controlled to modify the turbine rotation speed so as to realize maximum power point tracking (MPPT) [13]. While under high wind speed conditions, a pitch controller is activated to maintain the output power at the rated value.

Vector control techniques have been well developed for PMSG using back-to-back PWM converters [14]. In this paper, two vector control schemes are designed respectively for the generator-side and grid-side PWM converters.

One advantage of variable speed wind turbine is that the output active power and reactive power can be separately modified. This provides the flexibility for system voltage control which is related with the reactive power output.

C. Wind farm aggregation

Interactions among individual wind turbines are not of concern in this paper. Therefore, the individual wind turbine's electrical and mechanical models are condensed into a single machine model to represent a wind farm.

IV. Ancillary Voltage Control

A. Danish grid code

According to [15], some control requirements have been put on wind farms with power capacity greater than 11kW. About reactive power regulation and voltage control functions, there are three alternatives, namely, reactive power control, power factor control and voltage control. These three functions are mutually exclusive. In other words, only one of them can be activated at a time.

In this paper, only voltage control function is considered and implemented as shown in the next subsection. The requirements for the voltage control range for wind farms with power capacity greater than 25MW according to [15] is illustrated in Fig. 1. These requirements are included in the voltage controller as a reactive power reference limiter with different limitations under different voltage values.

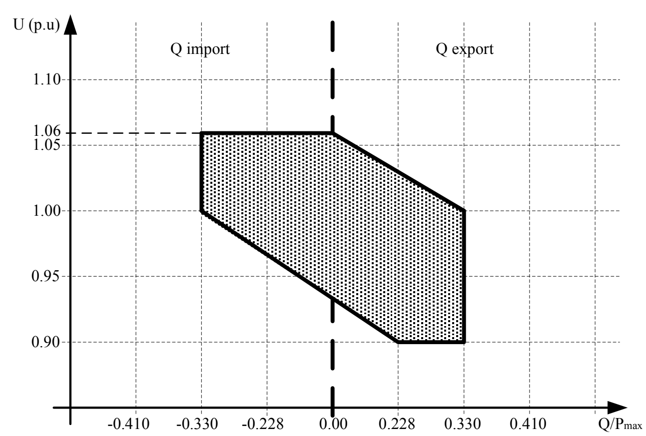

Fig. 1. The requirements for voltage control range for wind farms with output power greater than 25MW

B. Ancillary voltage controller

Fig. 2 illustrates the wind farm ancillary voltage controller used in this paper.

The voltage at the wind farm point of common coupling is to be controlled and the voltage difference from the reference value is then processed by a PI controller (K_p+K_i/s) with limitations described in the previous subsection. The output of this controller is sent to the grid-side convertor controller as the reactive power reference Q_{g_ref}.

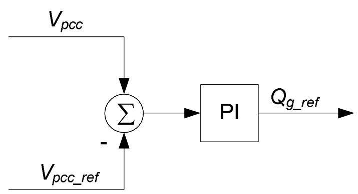

Fig. 2. Block diagram of the ancillary frequency controller

V. Simulation and Results

A. Test system

A two-area four-machine power system model as shown in Fig. 3 is used as the test system in this paper. The parameters of this test system can be found in [11]. Speed governors and exciters are modeled in each of these four synchronous generators. An aggregated full-converter-based wind farm as described in section III is connected to the grid in Area 1. The maximum output of the wind farm is assumed to be 500 MW, which can support 33% loads in the studied power system.

There are three electromechanical oscillation modes in the test system, i.e. two intra-area oscillation modes (with close frequencies around 1.0Hz and close damping ratio values around 14%) and one inter-area oscillation mode (around 0.6Hz with damping ratio of 4.8%). Due to the low damping ratio values, the inter-area mode is the dominant mode in the test system.

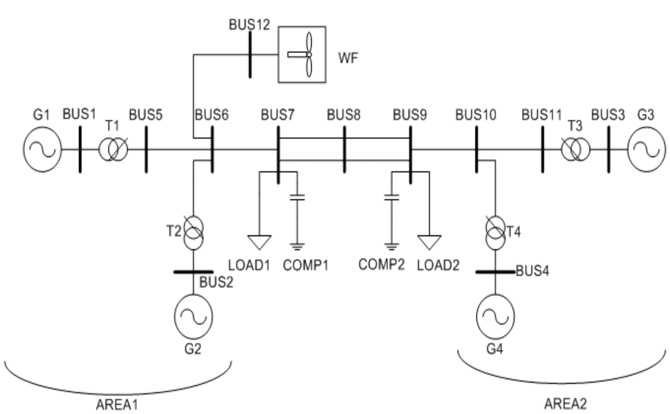

Fig. 3. The two area test power system with a large wind farm

When studying the influence of wind farm integration and its ancillary voltage control, the integration of the wind farm is implemented in such a way that the power flow in the transmission tie line between area 1 and area 2 is kept unchanged. This means that if the wind farm output power increases, the output of the two synchronous generators in area 1 should decrease by an equivalent amount and vice versa.

B. Performance of ancillary voltage control

The wind farm ancillary voltage controller is mainly a PI controller as described in the previous section. There are mainly two parameters, i.e. K_p and K_i. In the following study, these two parameters will be set to different values in a series of study cases as shown in Table I, in which case 1 is the base case without ancillary voltage control.

TABLE I
Ancillary Voltage Controller Parameter Settings in Different Study Cases

Study cases	K_p	K_i
CASE 1	-	-
CASE 2	5	0
CASE 3	10	0
CASE 4	100	0
CASE 5	0	5
CASE 6	0	10
CASE 7	0	100
CASE 8	5	5
CASE 9	10	10
CASE 10	100	100

Fig. 4 and Fig. 5 compare the performance of the wind farm ancillary voltage controller with different parameters in case 1, case 8, case 9 and case 10, respectively under a moderate wind speed (8m/s) condition and a high wind speed (16m/s) condition. A 10% step increase in load 1 (both active and reactive power) occurs at 10s, and then the voltage at the wind farm point of common coupling starts falling.

As shown in Fig. 4 and Fig. 5, under both wind speed conditions, when there is no ancillary voltage control in the wind farm (case 1), no reactive power will be output after the disturbance and the voltage will stabilize at a value lower than the pre-disturbance value. While when the ancillary voltage control is used (case 8, case 9 and case 10), an amount of reactive power is output from the wind farm after the disturbance and the controlled voltage will be restored to a value very close to the pre-disturbance one. In all these three cases, the reactive power output reaches the upper limitation defined by the grid code presented in the previous section.

On the other hand, it can also be seen in Fig. 4 and Fig. 5, with the parameters of the ancillary voltage controller increasing, the reactive power response is faster, but the voltage response is not necessarily better, on the contrary, when the parameters are considerably large (e.g. 100 in case 10), the voltage experiences a more obvious oscillatory transient at the dominant inter-area mode frequency (around 0.6 Hz).

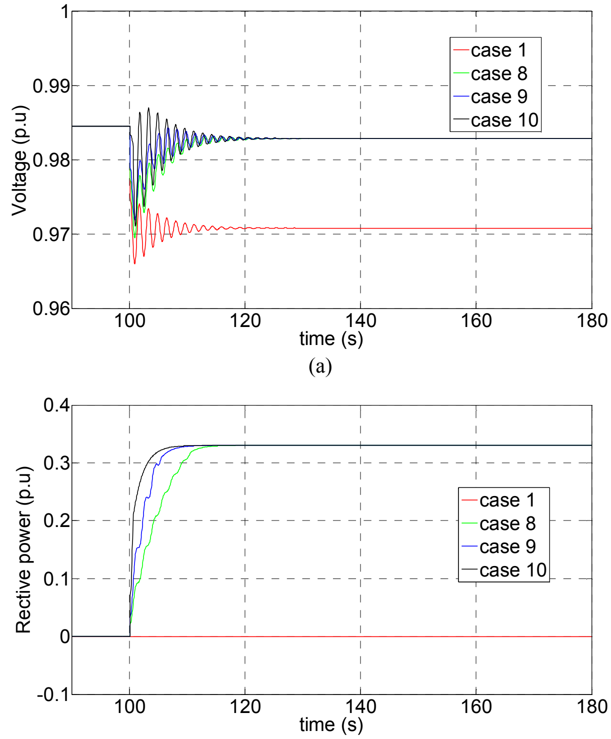

Fig. 4. Ancillary voltage control performance at wind speed 8m/s. (a) Voltage at wind farm point of common coupling. (b) Reactive power output from the wind farm

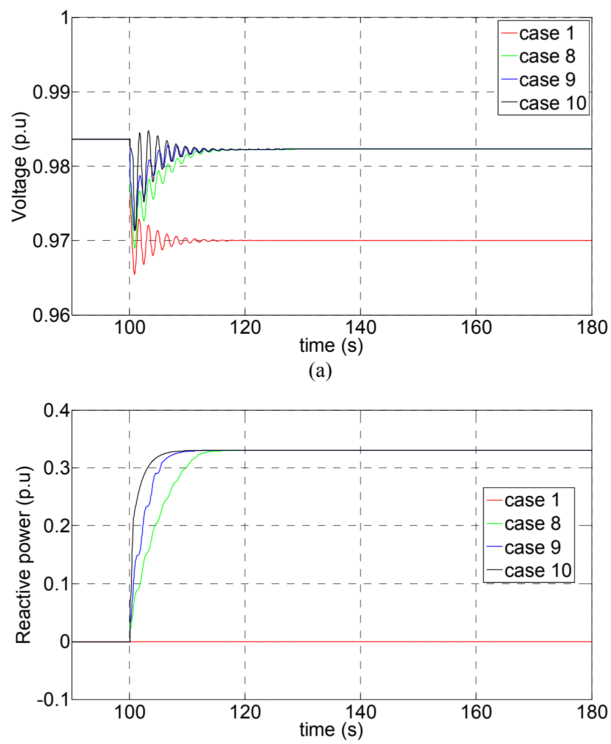

Fig. 5. Ancillary voltage control performance at wind speed 16m/s. (a) Voltage at wind farm point of common coupling. (b) Reactive power output from the wind farm

C. *Influence of wind power integration*

The influence of wind farm integration without ancillary voltage control on small signal stability should be considered so that the influence of ancillary voltage control can be distinguished from it. Fig. 6 illustrates the influence of wind farm integration on the three electromagnetic oscillation modes in the test power system. A detailed description of this influence can be found in [11]. For the same consideration as in [11], only the dominant mode (mode 3) is taken as the target mode in the following subsection.

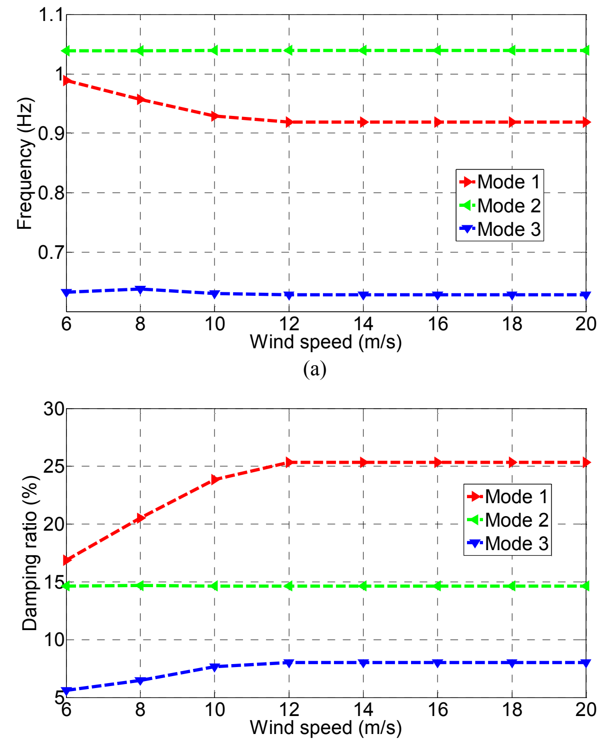

Fig. 6. Influence of wind power integration on system electromechanical oscillation modes. (a) Oscillation frequency. (b) Mode damping ratio

D. *Influence of wind farm ancillary voltage control*

The influence of ancillary voltage control is studied by comparing the calculated oscillation frequency and damping ratio values of the dominant mode in different cases with different controller parameter settings defined in Table I.

With case 1 being the base case in which no ancillary voltage control is used, Fig. 7 illustrates the influence of the parameter K_p that is increasing case by case in case 2, case 3 and case 4, while the other parameter K_i is kept at 0 in these cases. It can be seen that with ancillary voltage control implemented, the oscillation frequency is decreased from the base case by a small value under all the wind speed conditions and this influence changes little when K_p changes. Under low wind speed conditions, the damping ratio values in those cases with ancillary voltage controller are higher than those in the base case. Under moderate and high wind speeds, the curves in Fig. 7 (b) share the same pattern and the damping ratio values are increasing with K_p, although these values are still not far from the base case.

Fig. 8 illustrates the influence of the parameter K_i which is increasing case by case in case 5, case 6 and case 7, while K_p is kept at 0 in these cases. Generally, the influence of the ancillary voltage controller with only K_i also leads to a decrease in oscillation frequency, which is similar to the influence with only K_p, although the frequency change with K_i is more violate under low wind speed conditions. The influence of K_i on damping ratio values is more different from K_p. Under low wind speed conditions, ancillary voltage control with only K_i leads to higher damping ratio values than the base case, while under moderate and high wind speed conditions, the damping ratio values are lower than the base case. When K_i is small (case 5 and case 6), the damping ratio values are far from the base case. While when K_i is large (case 7), the damping ratio values are close to the base case except for the low wind speed situation.

Then the influence of a more practical ancillary voltage controller with both K_p and K_i increasing case by case in case 8, case 9 and case 10, is illustrated in Fig. 9. An interesting finding in Fig. 9 is that the curve patterns are similar to those in Fig. 7. This means that the influence of ancillary voltage control with a practical PI controller on small signal stability of the connected power system is mainly dependent on K_p other than K_i. In this paper, this influence leads to a slight decrease in the oscillation frequency. The damping ratio values are slightly influenced as well, but they will increase with K_p. This is verified in the time simulation results shown in Fig. 4 and Fig. 5. Although the post-disturbance oscillation (around 0.6Hz) in case 10 is larger in the first few cycles than in case 8 and case 9, it is damped out almost the same time as in case 8 and case 9, which is to say that the damping ratio of the 0.6Hz mode is higher in case 10 (with Kp =100) than in case 8 (with Kp =5) and case 9 (with Kp =10).

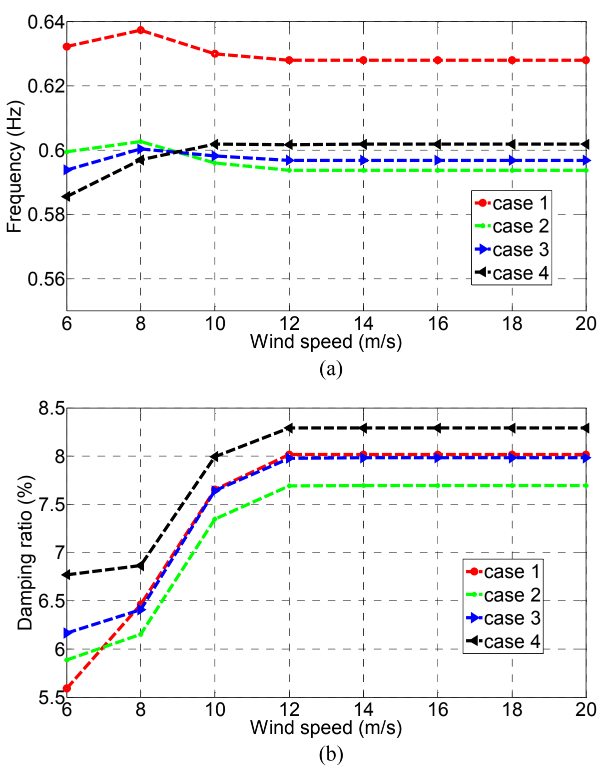

Fig. 7. Influence of wind power ancillary voltage controller parameter K_p on system inter-area mode. (a) Oscillation frequency. (b) Mode damping ratio

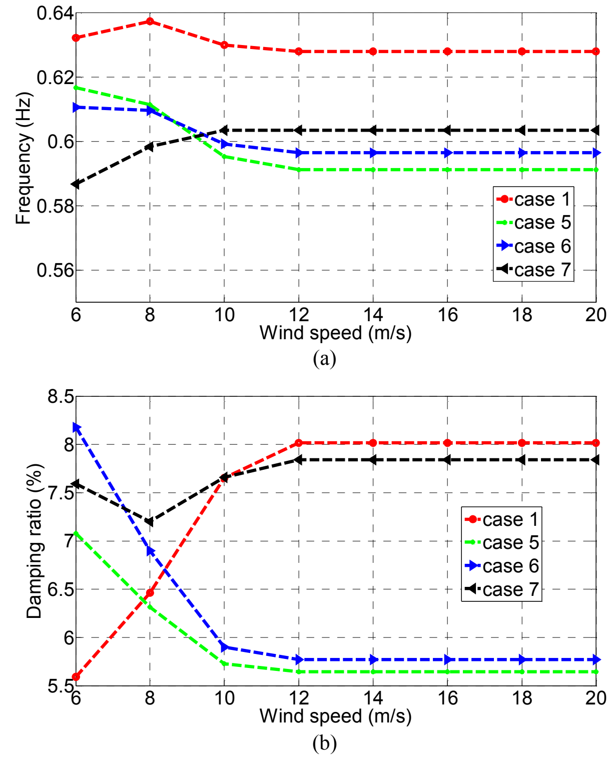

Fig. 8. Influence of wind power ancillary voltage controller parameter K_i on system inter-area mode. (a) Oscillation frequency. (b) Mode damping ratio

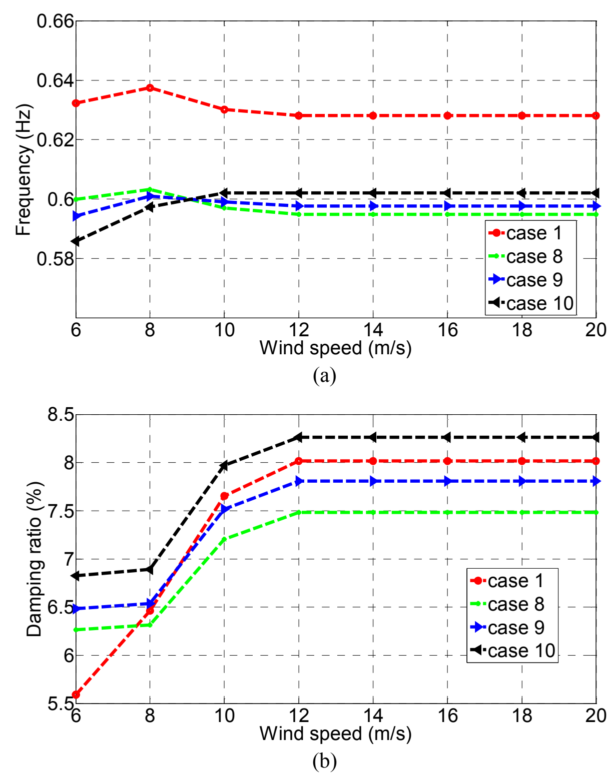

Fig. 9. Influence of wind power ancillary voltage controller on system inter-area mode. (a) Oscillation frequency. (b) Mode damping ratio

VI. CONCLUSIONS

This paper implemented an ancillary voltage control strategy in a direct-drive-full-convertor-based wind farm model. A two-area 12-bus power system model is used as the test system. The ancillary voltage control used in this paper consists of a PI controller with two parameters K_p and K_i.

Using the modal analysis function in DIgSILENT PowerFactory, the influence of these two parameters on the small signal stability of the connected system is respectively studied. It is found that the influence of these two parameters is similar on the oscillation frequency, but different on the oscillation damping ratio. However, when both K_p and K_i are implemented, the influence of K_p is dominant. The frequency decreases from the case without ancillary voltage control and the damping ratio values are close to the case without ancillary voltage control but will increase with increasing K_p.

For future work, the conclusion from this paper should be further verified in more power system topologies with different electromagnetic oscillation modes and the parameters may be considered within a wider range. The mechanism of this influence of the wind farm ancillary voltage control on small signal stability should be further studied.

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VIII. BIOGRAPHIES

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His research areas are power systems, power electronics and electric machines; and his main current research interests are wind energy and modern power systems. He has more than 260 publications in his technical field.
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