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Enhancement of Transient Stability in Power Systems with High Penetration Level of Wind Power Plants

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Abstract—**Due to the power electronic converter based interface and maximum power control strategy, wind generators cannot directly respond to power system transients. This brings new challenges on power system transient stability. Taking wind turbine type 4 (WT4) as one example, this paper analyses its influence on transient stability with respect to locations, low voltage ride through parameters, wind power plant installation capacity and penetration levels. Based on the sensitivity analysis carried out for the influence of WT4, a supplementary transient stability control is proposed. The results on a 3-area system show that this supplementary control can improve transient stability of power systems with high penetration of wind power.**

Index Terms—**Low Voltage Ride Through, MIGRATE, Sensitivity Analysis, Transient Stability, Wind Turbine Control.**

I. INTRODUCTION

Nowadays, the share of wind generation in electricity supply is increasing considerably [1]. Due to different operation and control characteristics from synchronous generators, the integration of wind generators brings the new challenges to transient stability of power systems.

Transient stability means the ability of synchronous generators to remain in synchronism after being subjected to a large disturbance, for instance, a three-phase short circuit or a transmission line tripping [2]. When such a disturbance occurs, the equilibrium between the mechanical and electrical torques is significantly disturbed, which forces some synchronous generators to accelerate and others to decelerate. If the relative motions cannot be attenuated, transient instability occurs.

As a result, transient instability can lead to generator outages, load shedding, and even blackouts. So, it is significant to analyse the influence of wind generators (especially with increasing wind power penetration levels) on transient stability and further develop mitigation controls to maintain the secure operation of power systems.

The dynamic behaviour of the motion of synchronous generators is directly coupled to the dynamics of electromagnetic power at the terminal bus, via the internal flux linkage [2]. It enables the rotor to promptly respond to power fluctuations at the terminal bus, in the form of absorbing or releasing kinetic energy. This helps to balance the post-disturbance power flow and contributes to safeguard transient stability. However, the rotor response of wind generators is decoupled from power grid transients, because of maximum power pointing track (MPPT) control and power electronics interface [3], [4]. From this perspective, the replacement of synchronous generators by wind generators is expected to worsen the transient stability performance of power systems [5].

On the other hand, the underlying cause of transient instability is the electrical-mechanical torque imbalance, due to fluctuations of electromagnetic power at the generator's terminal bus. The electromagnetic power is influenced by all generation/load sources connected to the same transmission network. Therefore, there also exist some possibilities for wind generators to bring forth positive influences on transient stability. That is to say, regulating wind generator's power output may alleviate the torque imbalance of synchronous generator and in this way, the post-disturbance transient stability is probably improved [6], [7].

Recently, wind turbine type 4 (WT4) is getting increasing attention due to its flexibility in operation and control, good capability of providing ancillary service, and easy maintenance [8]. In this paper, the influence of WT4 on transient stability is investigated in terms of wind power plant location, parameters of low voltage ride through (LVRT), wind power plant installation capacity, and wind power penetration level. Based on sensitivity analysis, a supplementary control, which regulates adaptively LVRT, is proposed to improve the post-fault transient stability.

The rest of this paper is organized as follows. Section II first discusses the typical structure of WT4 and defines its mathematical model. Next, Section III shows the assessment, based on sensitivity analysis, of the influence of WT4 on transient stability, in terms of location, LVRT parameters, wind power plant installation capacity and wind power penetration level. The proposed supplementary control for transient stability is described and demonstrated in Section IV. Finally, conclusions and outline for future work are given in Section V.

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II. WIND TURBINE MODELLING

In this part, the used WT4 model is overviewed from the aspects of typical structure and mathematic formulation.

A. WT4 Structure

Fig. 1 shows the main components of investigated WT4: wind turbine (WT), gear box (GB), permanent magnet synchronous generator (PMSM), machine side rectifier (MSR), grid sider inverter (GSI). The MSR controller regulates the stator currents and thus controls the rotation speed of PMSM to regulate the extracted mechanical power. On the other hand, GSI controller is responsible to regulate the active power and reactive power injected to the grid.

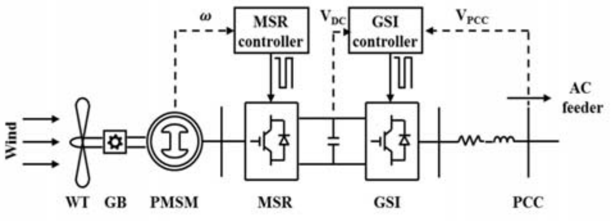

Figure 1. Wind turbine type 4.

B. Mathematic Formulation

The output of PMSM is expressed in the synchronous *d-q* reference system by the following equations [9]:

$$u_{sd} = -R_s i_{sd} - L_s \frac{di_{sd}}{dt} + L_s \omega i_{sq}$$
$$u_{sq} = -R_s i_{sq} - L_s \frac{di_{sq}}{dt} - L_s \omega i_{sd} + \omega \Psi f \tag{1}$$

where u_{sd}, u_{sq}, i_{sd} and i_{sq} are respectively the *d* and *q* axis stator voltages and currents; L_s and R_s are the stator inductance and resistance; Ψ_f is the flux; ω is the electrical angular speed of the rotor.

Next, the PMSM voltages and currents are rectified to charge the DC capacitor. The dynamics of machine side rectifier are defined as follows:

$$L_s \frac{di_{sd}}{dt} = u_{sd} - R_s i_{sd} - L_s \omega i_{sq} - d_{du} u_{dc}$$
$$L_s \frac{di_{sq}}{dt} = u_{sq} - R_s i_{sq} + L_s \omega i_{sd} - d_{qu} u_{dc} \tag{2}$$
$$C \frac{du_{dc}}{dt} = d_{di} i_{sd} - d_{iq} i_{sq} - i_{dci}$$

where C is the DC capacitance; u_{dc} is the DC voltage; d_{du}, d_{qu}, d_{di} and d_{qi} are the coefficients related to the average duty ratio of rectifier; i_{dci} is the current flowing from the DC capacitor to GSI.

i_{dci} is inverted into three phase AC currents through GSI, which are injected into the power system. The dynamics of GSI are represented by the following equations.

$$L_g \frac{di_{gd}}{dt} = -u_{gd} - R_g i_{gd} + \omega i_{gq} - d_{dg} u_{dc}$$
$$L_g \frac{di_{gq}}{dt} = -u_{gq} - R_g i_{gq} - \omega i_{gd} - d_{qg} u_{dc} \tag{3}$$

where u_{gd}, u_{gq} i_{gd} and i_{gq} are respectively the *d* and *q* axis voltages and currents on the grid side; d_{dg} and d_{qg} are the coefficients related to the average duty ratio of inverter.

The power injected into the grid is calculated by (4).

$$P = \frac{3}{2}(u_{gd} i_{gd} + u_{gq} i_{gq})$$
$$Q = \frac{3}{2}(u_{gq} i_{gd} - u_{gd} i_{gq}) \tag{4}$$

From (1) to (4), it can be seen that when i_{sd}, i_{sq} and ω vary following the wind speed, u_{sd}, u_{sq}, u_{dc}, i_{gd} and i_{gq} will change correspondingly. As the result, the powers injected to the grid, P and Q, are also changed. In such a way, wind generators will influence the post-disturbance power flow and further transient stability.

III. SENSITIVITY ANALYSIS FOR WT4 INFLUENCE ON TRANSIENT STABILITY

In this part, taking a 3-area system as an example [10], the influence of WT4 is discussed in items of locations, LVRT parameters, wind power plant installation capacity, and wind power penetration levels.

A. Test system and methods

Fig. 2 shows the diagram of the 3-area benchmark system used in the study presented in this paper. The system consists of three meshed areas, 66 buses, 16 generators, 28 transformers, and 51 transmission lines. The loads are concentrated in Area C and the active power is transferred from Area A and Area B to Area C through two tie-lines. The worst case for transient stability of this system occurs when a three-phase short circuit fault on the tie line B-C occurs, which makes synchronous generators in Area B to lose transient stability. Therefore, the sensitivity analysis focuses on the transient stability of synchronous generators in Area B. WT4 will replace different numbers of synchronous generators at different locations. Besides LVRT parameters of WT4 and wind power plant installation capacity are also perturbed. In the current work, the sensitivity analysis is made respectively for different locations and parameters.

All simulations are carried out by using PowerFactory 2016 and an industrial-level WT4 model developed by Energynautics for the project MIGRATE [11], [12].

B. *WT locations*

There are 5 synchronous generators in Area B. Their power outputs are shown in Table I. After replacing them by WT4, one by one, the change of critical clearing time (CCT) is illustrated in Fig. 3. It can be seen that the CCT reduces the most if the synchronous generator B3G is decommissioned and replaced by WT4. By contrast, the influence is slight when replacing B2aG and B2bG by WT4.

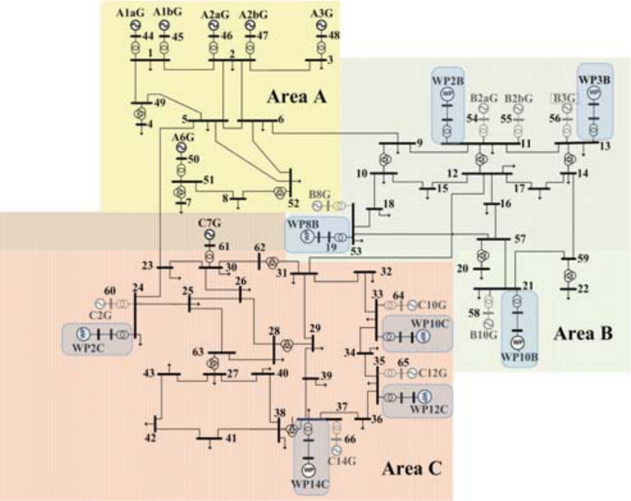

Figure 2. 3-area system [10].

TABLE I. Generator Power.

Generator	Active power (MW)	Reactive Power (MVar)
B10G	949	6.2
B2aG	1227	192
B2bG	1227	192
B3G	1399	17.3
B8G	966	24

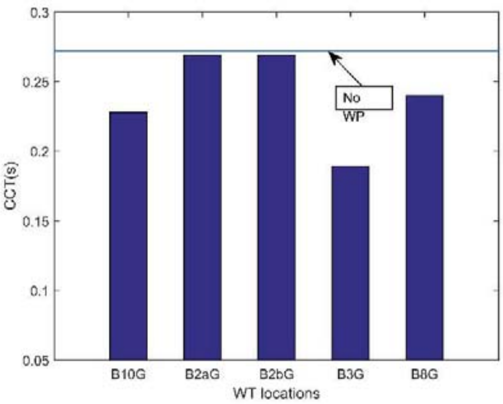

Figure 3. CCT when replacing different synchronous generators.

In order to explain this difference, the changes of power flow when decommissioning B2aG and B3G are compared in Fig. 4 and Fig. 5. If decommissioning B3G, the reactive power support from WP3G is considerably reduced during the fault (the lower plot of Fig. 4). In particular, from second 1 to second 1.5, the reactive power of WP3G (the red line) is apparently less than that of B3G (the blue line). This causes the lower bus voltages during the fault and prevents the voltages restoring after the faults, as shown in the lower plot of Fig. 6. As a result, transient instability occurs. By contrast, the reactive power support from WP2aG is similar to that of B2aG. Hence, when replacing B3G by WT4, the limited contribution of WT4 to the post-disturbance reactive power causes low voltages at the terminal buses of remaining synchronous generators, which alters the electric power output and aggravates the imbalance between the mechanical torque and the electromagnetic torque. As a result, the remaining synchronous generators will lose transient stability more easily after decommissioning B3G. Furthermore, for the same fault in the tie line B-C, which lasts 0.2 seconds, the system is stable after decommissioning B2aG, but unstable after decommissioning B3G, as indicated by the generator terminal bus voltage magnitudes shown in Fig. 6.

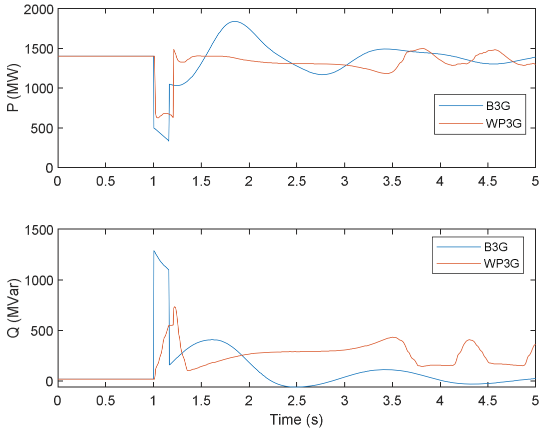

Figure 4. Power change after decommissioning B3G.

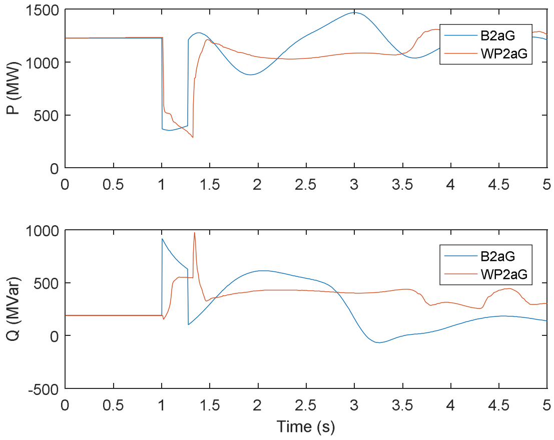

Figure 5. Power change after decommissioning B2aG.

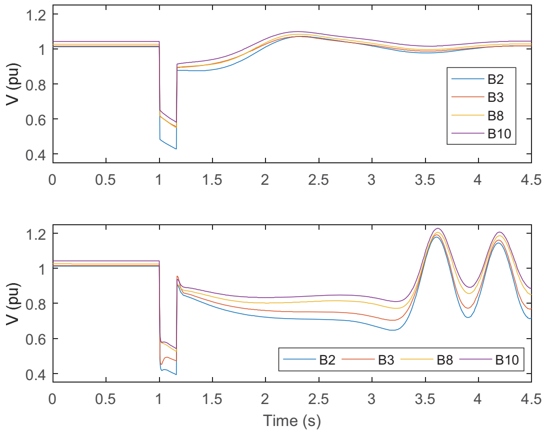

Figure 6. Magnitude of generator terminal bus voltages after decommissioning B2aG (upper plot) and B3G (lower plot).

Therefore, B3G is considered as the critical generator, and, from transient stability point of view, it should be the last conventional thermal generator to be decommissioned, to avoid worsening transient stability (i.e. the most dramatic reduction of CCT). In the next subsection, the investigation of the impact of LVRT parameters, wind power plant installation capacity, and wind power penetration level, focuses on the replacement of synchronous generator B3G by a wind park WP3G, since it constitutes the worst case.

C. LVRT parameters

Grid codes require wind generators to remain connected and support the grid during and after a fault, to provide support such that the PCC voltage is above the pre-determined voltage-time profile, like the example shown in Fig. 7 [13]. This is the LVRT function of wind generators. In Fig. 7, Udb1 is the lower limit of LVRT dead band. The bigger Udb1 is, the more reactive power WT4 will provide. As discussed in Section III.B, more reactive power is helpful to restore the post-disturbance voltage, which can increase the electromagnetic power outputs of synchronous generators to improve transient stability. Fig. 8 compares CCTs corresponding to different values of Udb1. It can be seen that the larger Udb1 brings the larger CCT.

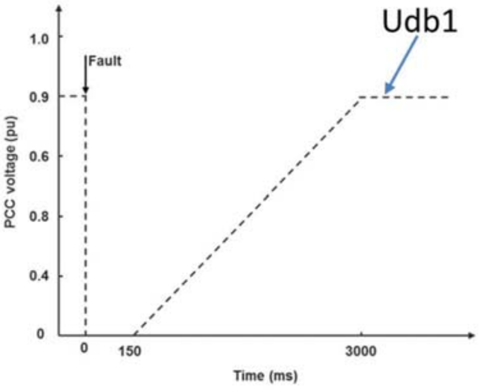

Figure 7. LVRT voltage time profile.

Besides, grid codes also require wind turbines to supply the reactive current based on the depth of voltage dip, in order to support voltage recovery and limit the geographical low voltage [13], as shown in Fig. 9. A larger ratio of $\Delta I/I_N$ to $\Delta U/U_N$, namely k_{qv}, means that wind generators will supply the larger reactive current for a same voltage dip, which is helpful to restore faster the post-disturbance voltage, and thereby improve transient stability. Fig. 9 shows that CCT increases when k_{qv} increases.

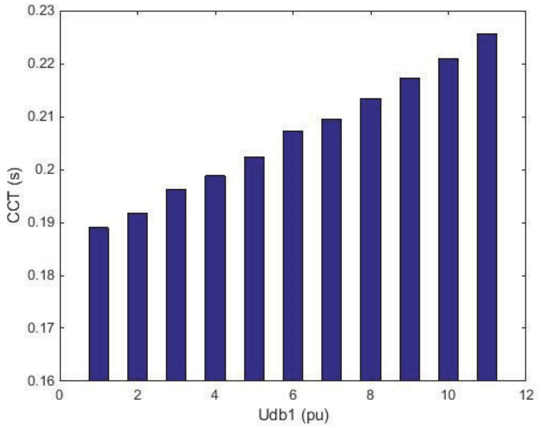

Figure 8. CCT corresponding to different values of Udb1.

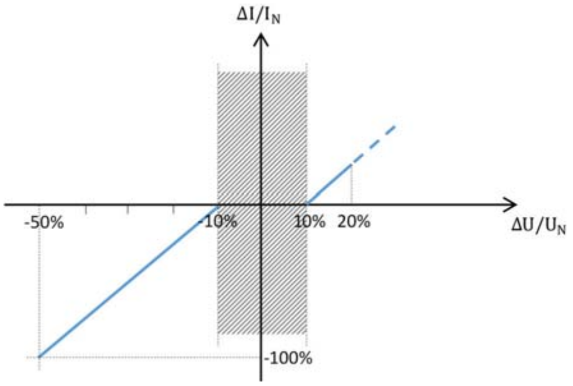

Figure 9. LVRT reactive current vs voltage dip.

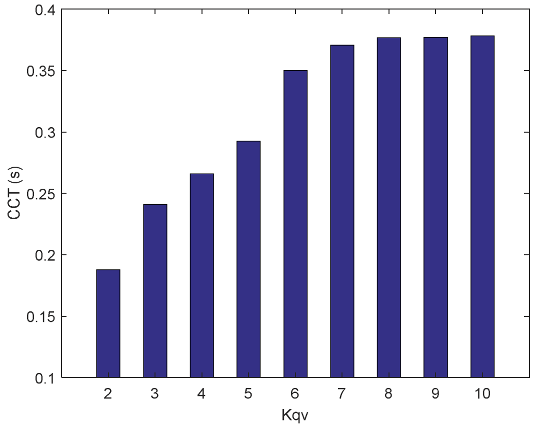

Figure 10. CCT corresponding to different k_{qv}.

D. *WT4 park installation capacity*

So far, a synchronous generator was replaced by a wind power plant of comparable installation capacity. However, in practice, the output of wind generator rarely reaches the rated power due to the limit on wind speeds. Therefore, in order to produce the same power output as synchronous generators, a larger installation capacity of the wind power plant should be considered in the simulations. The larger installation capacity means the larger short circuit capacity, which enables wind park to inject more reactive power to restore more effectively post-fault grid voltages. This is helpful to maintain transient stability.

In Fig. 11, CCTs are calculated at different dispatching levels. The dispatching level is defined as the ratio of actual wind power plant active power output to the installation capacity. For a given active power output, a lower dispatching corresponds to a larger installation capacity and a larger short circuit capacity. It is shown in Fig. 11 that CCT becomes larger as the installation capacity increases.

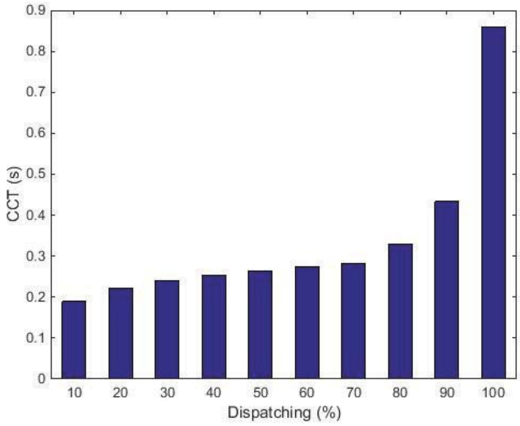

Figure 11. CCTs corresponding to different dispatching levels.

E. *Different penetration levels*

Lastly, the evolution of the CCT at different penetration levels is investigated, as shown in Fig. 12. It can be seen that with the increase of penetration levels, the CCT reduces gradually (blue bars). When the penetration level is larger than 20%, CCT is below 200 milliseconds, which means the large risk of transient instability. Therefore, mitigation measures should be developed to ensure transient stability and at the same time increase the penetration level.

Based on the analysis in Section III.C, a natural idea is to increase the post-fault voltage support from wind generators. For example, let's consider Udb1=1.0 and k_{qv}=10. The new CCTs are shown by the yellow bars in Fig. 12. Transient stability is improved significantly. So, in Section IV, a supplementary control scheme is proposed to regulate adaptively LVRT parameters after a disturbance, in order to ensure transient stability of power systems with high penetration of wind power.

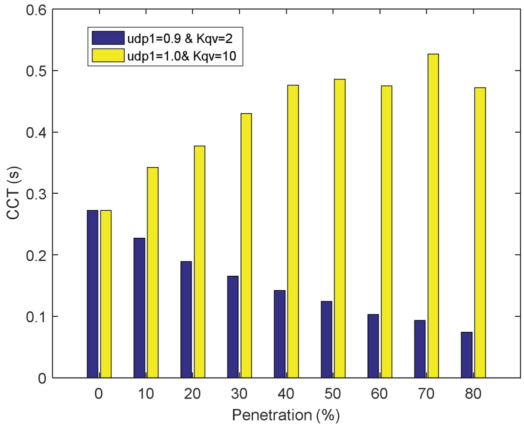

Figure 12. CCT under different penetration levels

IV. SUPPLEMENTARY TRANSIENT STABILITY CONTROL

The framework of proposed supplementary control is described in Fig. 13. After detecting a fault, the fault characteristics (fault locations and voltage dip) are compared with the pre-determined threshold values (voltage threshold of tie lines in this paper) to decide if the supplementary control will be started or not. If yes, based on the pre-stored knowledge, the supplementary control will select the new Udb1 and k_{qv} for LVRT in order to regulate the reactive power injected by wind generators. The pre-stored knowledge is the mapping from the current operation conditions (power flow, topology, etc.) to the values of Udb1 and k_{qv}, which can be obtained from off-line simulations or historic operation data of power systems.

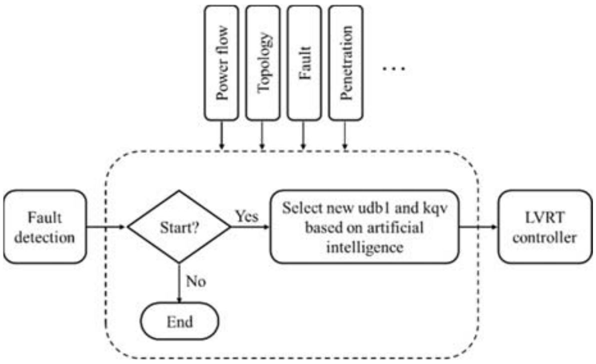

Figure 13. Supplementary transient stability control.

Like in the sensitivities computed in Section III, considering a three-phase short circuit to ground fault in tie-line B-C, which lasts 0.2 seconds, the transient responses of investigated 3-area system are shown in Fig. 14 and Fig. 15. With the designed supplementary control, Udb1 is regulated automatically from 1 to 0.9 after the fault. It can be seen in Fig. 14 that the supplementary control increases the reactive power output of wind generators during the fault period. As a result, the 3-area system is kept transient stable. The rotor angle of a representative generator (B2aG) is shown in Fig. 15.

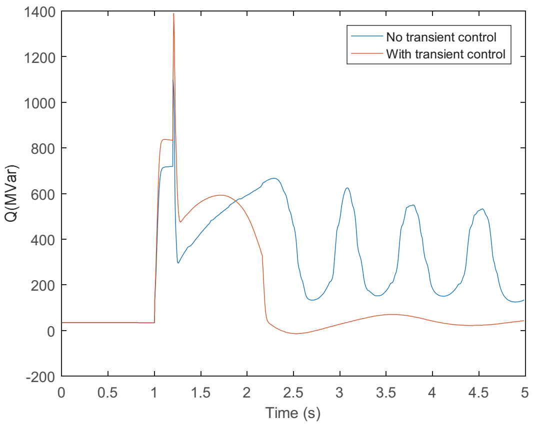

Figure 14. Reactive power WP3G.

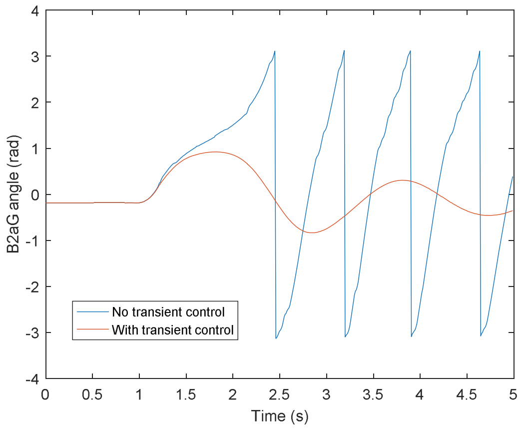

Figure 15. Rotor angle of B2aG.

V. CONCLUSIONS

The integration of wind generators is changing the operation and control schemes of power systems. Taking WT4 as one example, this paper analyzes the influence of wind generators on transient stability and designs the initial mitigation measure to increase the penetration level of wind power.

The influence of wind generators depends on locations, controller parameters, wind power plant installation capacity, and wind power penetration levels. The synchronous generator which has the biggest contribution to transient stability is considered as the critical generator (in case of phase out). It is suggested to replace such a generator at last to avoid considerably worsening transient stability. The reactive power support provided by LVRT helps to restore the post-disturbance voltage and increase the electromagnetic power output of synchronous generator, which can bring positive influence on transient stability. The larger wind park installation capacity brings the larger short circuit capacity, which is also helpful to improve transient stability.

With the increasing of wind power penetration, transient stability worsens. So developing the necessary mitigation measures is crucial to allow larger penetration levels of wind power. The proposed mitigation measure is able to regulate the reactive power output of LVRT according to the disturbance and the operation condition of power system. The obtained results on a benchmark system show that this mitigation measure improves conspicuously transient stability.

However, in order to make this mitigation measure feasible and viable, the knowledge about the mapping from the operation condition (like power flow or penetration levels) to the starting threshold (voltage dip of main transmission lines) and LVRT parameters must be extended to cover more fault scenarios which may appear. In addition, this mitigation control will also be tested and improved further based on software-based simulations with larger and real power systems.

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