Increasing the Share of Wind Power by Sensitivity Analysis based Transient Stability Assessment

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***Abstract*—The massive integration of wind power plants into the transmission system calls for a careful scrutinization of their dynamic behaviour and the interactions with the power system in the transient stability time-frame of interest.This paper presents a sensitivity analysis based approach to investigate the impact of full converter wind turbine generators on the transient stability of the interconnected power system. A combination of different fault ride through and voltage support mechanisms such as 1) low voltage ride through, 2) voltage-dependent reactive power injection, 3) current limitation strategy during grid faults, and 4) the application of inertia emulation capability are considered for the sensitivity analysis. Critical clearing times are used as the transient stability indicator. The implementation of the wind turbine models are according to IEC 61400-27-1 and the assessment is done through time domain simulations using DIgSILENT PowerFactory. The results on a modified version of the IEEE 9-bus system show that by more effective use of the existing controllers of wind turbines, the share of wind power plants can be increased substantially.**

***Index Terms*—full converter wind turbine generator, fault ride through, sensitivity analysis, transient stability**

I. Introduction

The significant share of wind power plants (WPP) brings new challenges in the operational and planning decisions of power systems [1]. In particular, their impact on power system dynamics in the transient stability time-frame needs to be studied [1], [2]. Large disturbance rotor angle stability known as transient stability refers to the ability of synchronous generators to remain in synchronism after being subjected to a severe grid fault [3]. When such a significant disturbance occurs, the electro-mechanical power imbalance is generated, which causes oscillations in speed deviations (and corresponding angle deviations) of generators in the system. If these oscillations cannot be diminished, transient instability occurs.

Full converter type wind turbine generators (FCWTG) are superior in terms of flexibility in operation and control, the capability of providing ancillary service, and easy maintenance [4]. FCWTGs contain power electronic converters fully decoupling the wind turbine generators from the grid. This, however, reduces the inertial response and short circuit power of the grid and consequently reduces the transient stability margin [5]. Moreover, unlike synchronous generators, FCWTGs do not intrinsically contribute to voltage support during a fault. This creates an extra electro-mechanical power imbalance at the synchronous generators' terminal bus and jeopardizes the transient stability [6]. Therefore, transmission system operators (TSOs) devise grid connection requirements for WPPs to remain connected for any contingency and provide ancillary services during faulted conditions [7]. Fault ride-through (FRT) and voltage support are examples of such requirements to ensure transient stability and grid security.

Transient stability enhancement methods of power systems containing FCWTGs can be based on: (1) addition of hardware components (e.g. crowbars/power-electronic interfaced resistors, FACTS devices, fault current limiter), or (2) modification or addition of control systems on the power electronics based grid interface.

Additional hardware-based methods [8][9] may involve substantial capital investments, which may not necessarily entail the technically desired effect. Therefore the modification or addition of control systems of wind generator's converters is the preferred approach in this paper.

Research efforts so far have been devoted to either modify the way current limitation occurs in the grid-side converter or to alter the way active and reactive power injection is performed by considering signals taken from the connection point of the wind generator with the power system. In [10], an active current reduction method is applied by adding a compensation torque signal depending on DC link current. A coordinated control scheme for active and reactive power delivery of an AC cable-connected WPP with FCWTGs has been proposed in [11]. An alternative vector current control is proposed in [12], which implements a decoupled and gain-scheduling controller on top of the grid-side converter logic. For weak grids, this tackles possible interactions in between active power and voltage control in case FCWTGs operate close to nominal power.

In the last 2 decades, significant research has been devoted to the tuning of existing wind generator controllers for transient stability enhancement, for instance by using special techniques like sliding mode control [13], model predictive control [14], and artificial intelligence [15]. These methods show great potential to adjust the settings of wind generator controllers in a near real-time context. Notwithstanding these efforts, their

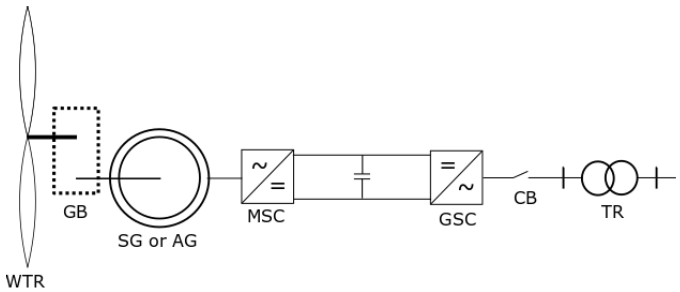


Fig. 1: Main components of full convert wind turbine

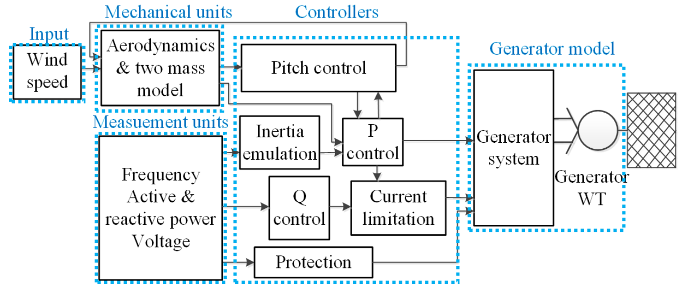


Fig. 2: Control structure of the full converter generator interfaced wind turbine

sensitivity to factors like grid operating conditions, network topology, and disturbances are commonly disregarded in the training or application of these methods, and hence remain an open research gap.

In this paper we present a sensitivity analysis-based study to investigate the impact of FCWTGs on the overall transient stability of the interconnected power system. The FRT and voltage-support requirements are thereby taken as starting points. The sensitivity analysis determines key factors of wind turbine controllers, which will then be applied to tune the dynamic behaviour for FRT conditions and voltage support during a large disturbance.

The paper is organized as follows. We start with introducing the FCWTG model and its overall control scheme. Section III deals with the methodology for sensitivity analysis. Then the approach is applied to a case study comprising a modified IEEE 9-bus system. The paper ends with conclusions.

II. Full Converter Generator Wind Turbine Dynamic Model

Fig. 1 shows the main components of investigated FCWTG, which is developed based on [16]: wind turbine rotor (WTR), gear box (GB), synchronous generator or asynchronous generator (SG or AG), machine side converter (MSC), grid side converter (GSC), circuit breaker (CB) and transformer (TR).

Fig. 2 illustrates the overall structure of the wind turbine control [17],[18]. The main features of the model are:

- In the measurement part of this model, the blocks *Frequency, Power, and Voltage Measurement* are connected directly to the terminals of the wind turbine and provide the corresponding calculated quantities.
- The *generator* block contains the PowerFactory model *Static Generator* and operates as a Norton current source.
- The mechanical part is represented by the *Aerodynamic* block, which calculates the mechanical torque and corresponding power of the turbine based on the *wind* block, the two-mass shaft model, and maximum power point tracking.
- The control part consists of the blocks *P control* for active power control, the *Pitch angle* control, *inertia emulation*, *Q control* for reactive power control, *current limitation*, and *grid protection*, which includes protection logic against over and under voltage and frequency.

III. Sensitivity Based Approach for Transient Stability Enhancement

Fig. 3 shows the proposed approach for sensitivity analysis. The procedure starts with the overall dynamic model preparation. The input is a given power system with several WPPs with a given rating and an initial set of control parameters. The WPPs are represented aggregatedly by a single FCWTG. After the preparation of the model, the second step is to find a critical wind turbine for further investigation. Every synchronous generator in the system is replaced by a FCWTG of equal dispatch rating by considering efficiency of wind turbines, one by one, and then a selected disturbance (e.g. a 3-phase bus short circuit) is applied. The critical clearing time (CCT) is then used as a transient stability indicator. The CCT is the maximum time it may take to clear the fault without the system going out of synchronism. That is, one of the remaining synchronous generators exhibiting a pole slip or similar. An iterative process (implemented via Python scripting) is performed to calculate the CCT, which is shown in Fig. 4. The critical wind turbine is selected as the one that gives a minimum amount of CCT of all replaced synchronous generators. After that, sensitivities to different FRT factors are applied for the selected critical WPP. Five different and independent control factors are considered:

- the per unit reactive current boosting gain k;
- the fault-induced voltage control dead band threshold $u_{\mathrm{db,low}}$;
- the current limiting precedence during disturbances (i.e., active or reactive);
- the maximum allowable current of the wind turbine $I_{\max}$; and
- the application of inertia emulation capability (i.e., on/off).

After identifying the key factors influencing the transient stability and their effective values, the penetration level of the wind power generation is increased to assess the maximum share of wind given the observed CCTs.

The dynamic study is conducted under the assumption that 1) the loading conditions are equal and will not change in the time-frame of interest, 2) the WPP can be represented by an aggregated dynamic model of a FCWTG, 3) the wind speed remains constant during the time-frame of interest, and

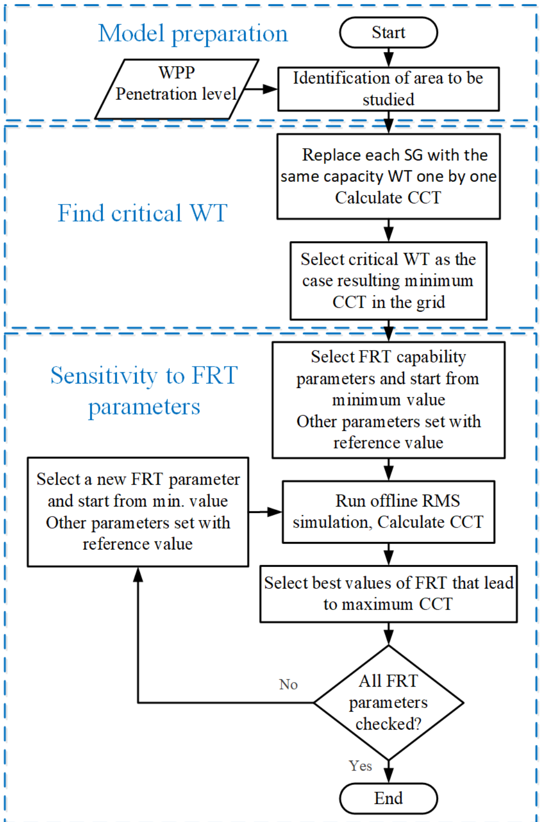


Fig. 3: Procedure for sensitivity analysis

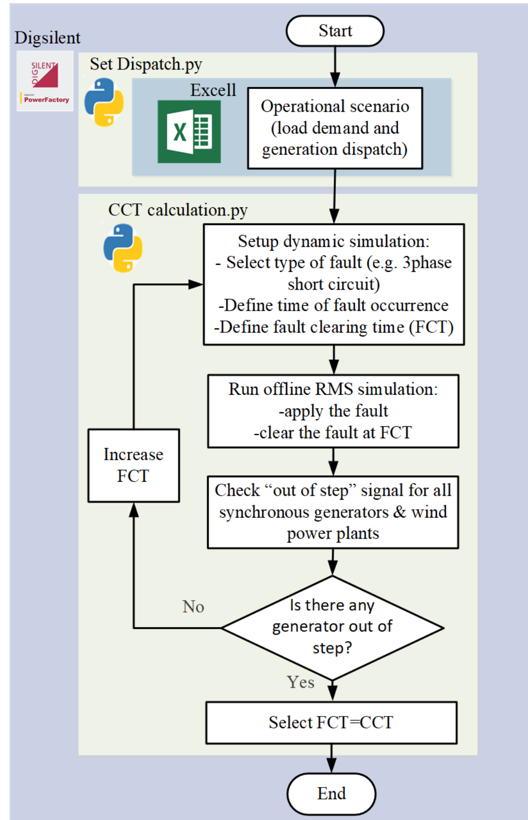


Fig. 4: Procedure for calculation of CCT

4) the controls of the governing and excitation systems of the synchronous generators remain unaltered.

IV. Results and Discussions

The procedure defined in Section III is applied to a modified version of the IEEE 9-bus system [19], the single line diagram of which is shown in Fig. 5. The main modifications comprise the inclusion of three WPPs to create different penetration levels. After a fault screening, a three-phase short circuit on bus 1 is considered as the severest type of fault in terms of transient stability. The total demand for the system is 315 MW and it is fixed for all scenarios. Table I shows initial conditions of synchronous generators and WPPs as the original model, referred to as *original case*, and the *base case study with WPPs*. The share of WPPs is defined as the ratio between total wind power generation and the total demand. It is calculated as 57% for the base case study with WPPs.

TABLE I: Initial conditions of original and base case

	Original case	Base case with WPPs
G1 (MVA)	247,5	247,5
G2 (MVA)	192	100
G3 (MVA)	128	—
WPP01 (MVA)	—	72
WPP02 (MVA)	—	36
WPP03 (MVA)	—	72
CCT (ms)	180	120

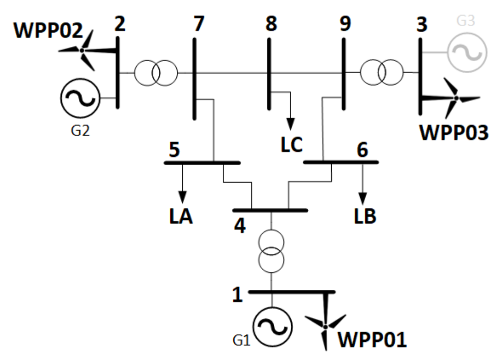


Fig. 5: Modified IEEE 9-bus system single line diagram

Subsequently, the five identified control factors that are presumed to affect transient stability are investigated. After successively replacing the synchronous generators by the WPPs, it was found that the CCT reduces the most if synchronous generator G3 is decommissioned and replaced by WPP03. Therefore, WPP03 is selected as the critical wind turbine generator for the following analysis.

A. *Reactive power boosting gain (k-factor)*

Wind power plants shall provide voltage-dependent reactive power support during grid faults [7]. The additional reactive current injection is given by the following equation:

$$\triangle i_{\mathrm{Q}} = k.(u_{\mathrm{db,low}} - u_{\mathrm{WT}}) \quad (1)$$

Here k is a proportional gain that is called K-factor [20], u_{WT} is the grid connection point voltage and $u_{\mathrm{db,low}}$ is the lower limit of the voltage dead-band threshold. The k-factor could vary between 0 and 10 for wind power generation units [20]. A larger k-factor implies that wind turbines will supply a higher reactive current during faults. This targets faster restoration of the post disturbance voltage and thereby improving transient stability. The K-factor is accessible through the Q control block . We start with no voltage deadband, i.e., $u_{\mathrm{db,low}} = u_{\mathrm{WT}}$, a current limit of 1.6 per unit and no additional inertia emulation. Fig. 6a shows how the CCT increases when a larger K factor is employed. The response of the WPP03 terminal voltage for $k = 1$ and $k = 10$ during a 3-phase short circuit at bus 1 are shown in Fig. 6b. A comparison of different k-factors shows that for $k < 5$, a significant decrease in voltage support and hence larger voltage excursions are experienced.

It can be seen that a higher K-factor result in a shallower voltage dip during faults. This significant positive effect can be seen in Fig. 6c too, which shows that a higher k yields a higher injection of reactive power during the fault.

B. The Effect of the Dead-Band Threshold Voltage

Next, the choice of the dead-band $u_{\mathrm{db,low}}$ in eq. 1 for the provision of fast reactive current is investigated. Based on the previous case study, $k = 10$ is chosen as the reactive current gain. Fig. 7 shows the reactive power injection of WPP03 when a dead-band of 10% is applied compared to a case without a dead-band. It can be observed that the deactivation of $u_{\mathrm{db,low}}$ results to a better fault response due to the fact that the reactive power injection mechanism of the wind turbine is engaged immediately at fault ignition.

C. The Effect of Active or Reactive Power Precedence

With $k = 10$ and no deadband on the reactive current controller, we now assess the effect of the current limitation strategy. Typically, the reactive current is given priority and therefore active power limitation is applied according to the following equation:

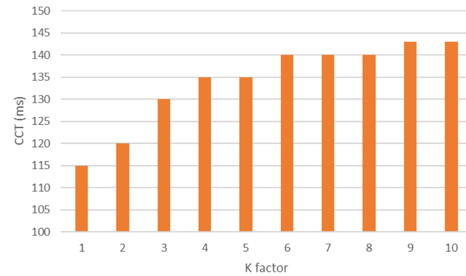
$$i_{\mathrm{P,max}} = \sqrt{{I_{\mathrm{max}}}^2 - {i_{\mathrm{Q,ref}}}^2} \quad (2)$$

in which I_{max} is the maximum allowed current of wind turbine and $I_{\mathrm{Q,ref}}$ is the reactive current reference value from the turbine controller. The reactive current is limited by the maximum allowed reactive current:

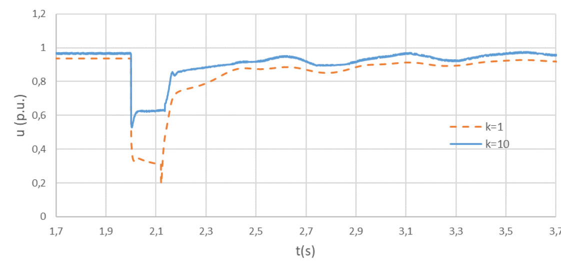
$$i_{\mathrm{Q,ref}} = I_{\mathrm{Q,max,ref}} \quad (3)$$

In some countries with stability concerns, however, active power limitation is not allowed and wind turbine shall provide active power in proportion to the voltage dip depth[21].

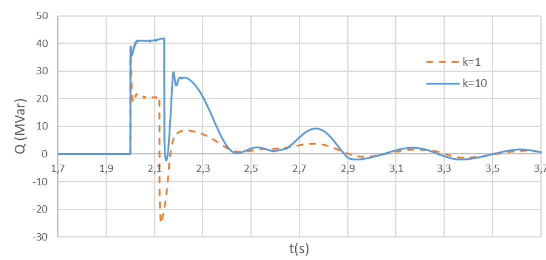
The difference between the applied current limitation strategy (active power versus reactive power priority) during a grid fault can be seen in Fig. 8. It shows slightly better reactive power support during the fault when precedence is given to the reactive part of the current reference.



(a) CCT corresponding to different k-factor



(b) Terminal voltage of the WPP03



(c) Reactive power injection of the WPP03

Fig. 6: The effect of different k-factor

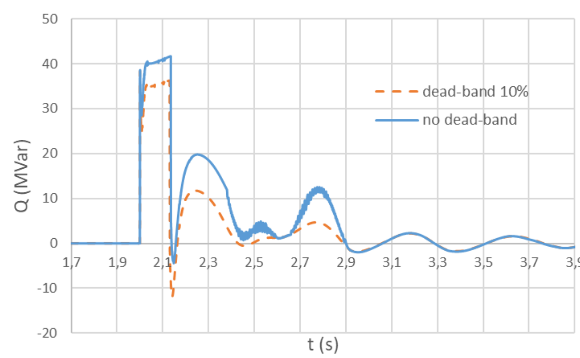


Fig. 7: Reactive power injection of WPP03 with 10% dead-band (red, dashed) and deactivation of the dead-band (blue, solid)

D. Maximum Allowable Current of the Wind Turbine

The maximum current injection of a FCWTG during experienced voltage dips is limited to the maximum fault current capacity given by I_{max} in eq. 2. Previously, FCWTGs were

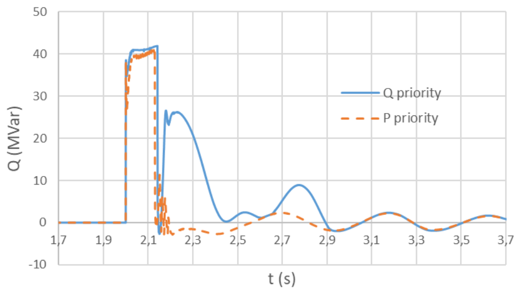
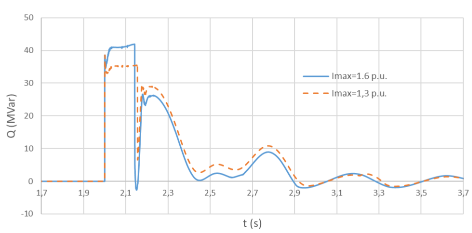
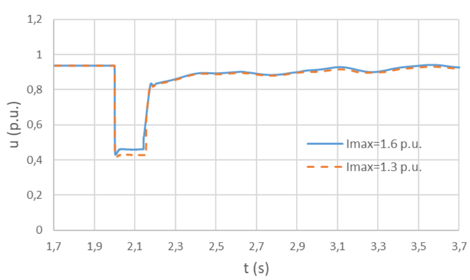


Fig. 8: Reactive power injection of WPP03 with active (dashed, red) and reactive (solid, blue) power priority respectively

defaulted to 1.6 p.u. as the maximum allowed current during a grid fault. In order to analysis the affect of I_{max} on transient stability, the value is decreased $I_{\text{max}} = 1.3$ p.u. while keeping $k = 10$, no deadband for reactive current support, and reactive current precedence. The response of WPP03 for two different values of I_{max} is presented in Fig. 9a and 9b. It can be seen that, as expected, the higher value of I_{max} results in lower voltage drop.



(a) Reactive power injection of the WPP03

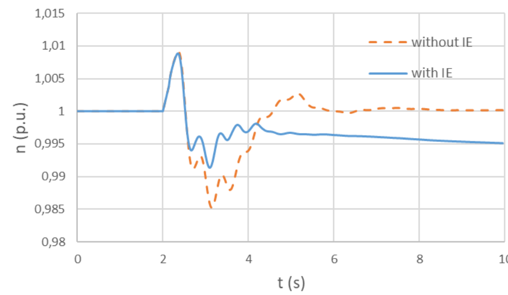


(b) Terminal voltage of the WPP03

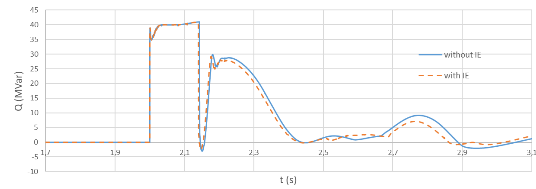
Fig. 9: Responses of the WPP03 to $I_{max} = 1.6$ p.u. (solid, blue) and $I_{max} = 1.3$ p.u. (dashed, red)

E. Inertia emulation (IE) capability

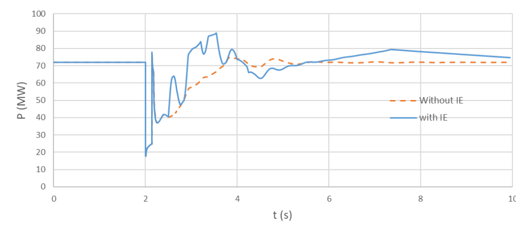
The droop-based fast active power injection as inertia emulation control for wind turbines is implemented based on a modified version of [22]. The results are shown in Fig. 10a to 10c. Fig. 10b and 10c demonstrate the reactive and active power injections of WPP03 respectively. As expected the inertia emulation mainly impacts the active power regime of the FCWTG. It can be seen in Fig. 10a that inertia



(a) Speed of synchronous generator G1



(b) Reactive power injection of WPP03



(c) Active power injection of WPP03

Fig. 10: The inertia emulation capability effect

emulation considerably aids in damping speed oscillations of synchronous generator G1. It is not measurably beneficial for the transient stability: the CCTs improved in the ms range, just above the calculation precision.

F. Increasing share of WPPs

Finally we increase the share of WPPs by adopting the optimal factor levels found previously. That is, $k = 10$, the dead band is deactivated, the reactive power priority is used, $I_{max} = 1.6$ p.u., and the inertia emulation block is off. A fault of 3-phase short circuit at Bus 1 is considered and the share of FCWTGs is gradually increased. Taking the 120ms of Table I (with default values of the FRT and voltage control parameters) as the basis, we now apply the more favourable factor levels from above (CCT equals 145ms) to see how the share of wind power can be increased until the transient stability level of the base case is at least maintained. As a result the share of FCWTGs can be increased from 57% to 78% without jeopardizing transient stability. Fig. 11 shows the stable transient responses of the investigated system for 78% share of FCWTGs.

V. Conclusion and Future Work

The increasing share of wind generation gradually changes the dynamic behaviour of our power system. This paper inves-

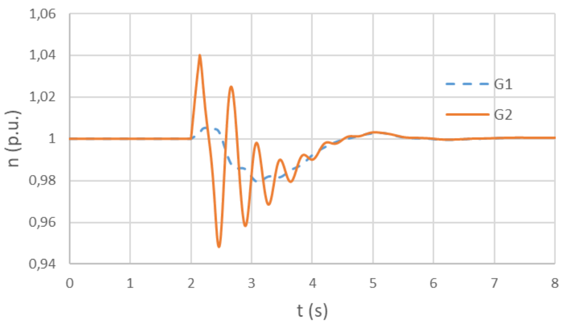


Fig. 11: Speed responses of synchronous generators G1 and G2 for the case of 78% share of FCWTGs

tigates the effect of full converter wind turbines on transient stability. It proposed a sensitivity based method to tune wind turbine controllers as a mitigation measure to increase the penetration level of wind generation.

The results show how the influence of wind turbines on transient stability depends on different FRT control parameters. The deactivation of the reactive current control dead-band and increasing the maximum allowed current of the wind turbine can enhance transient stability; however, the reactive current boosting gain, k, is the most effective factor.

The transient stability is also improved by setting reactive current priority during the faults. Although the *inertia emulation* option has a positive effect on the damping of oscillations, its benefit to transient stability could not be shown in our case studies. Finally, the results show that by more effective use of the existing controllers of wind turbines, the share of WPPs can be increased substantially.

During faulted conditions both active and reactive power interact very closely and their relationship becomes very complex. Therefore, the improvements in transient stability margin that can be brought by wind turbine controllers without jeopardizing the maximum allowable frequency deviation, should be investigated by a multi-variable optimization-based sensitivity analysis approach.

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