A Simple Method for Analytical Evaluation of LVRT in Wind Energy for Induction Generators with STATCOM or SVC

Marta Molinas*, Jon Are Suul**, Tore Undeland*
* NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
Department of Electric Power Engineering, Trondheim, Norway
** SINTEF Energy Research, Trondheim, Norway
O.S. Bragstad plass 2E, 7491 Trondheim, Norway
Tel.: +47 7359 4237
Fax: +47 7359 4279
marta.molinas@elkraft.ntnu.no

Keywords

Abstract
Low Voltage Ride Through (LVRT) has emerged as a new requirement that system operators demand to wind turbines. E-ON Netz, the major German transmission operator has introduced a LVRT grid code that is receiving wide acceptance and being used as a template for similar requirements from nearly every country with wind generation. STATCOM and SVC are both good candidates for providing LVRT for wind turbines with induction generators. This paper provides a new analytical approach that allows using torque-slip curves to evaluate induction generator stability limits when having shunt reactive compensation such as STATCOM or SVC as the LVRT solution for the wind generation. This analytical approach is proposed as screening method to assess stability and/or to estimate the required rating of the reactive compensation that will ensure stability in a given system. Analytical and simulation results compared are in good agreement and both indicate the advantage in using a STATCOM since it gives an increased transient stability margin and consequently enhanced LVRT capability compared to SVC. The proposed method can easily and reliably be implemented by wind farm developers and the utilities after the validation by simulations presented in this paper.

Introduction
The transmission system operator in Norway is facing the possibility to integrate large amounts of wind power into their network. There is however a widespread reluctance to integrate such amount of wind power unless they are ensured that this step will not disrupt the stability of the whole power network. The development of the wind power technology could face the risk of being stopped if measures are not taken to ensure that there will be means to support stability and reliability of the power system. Today more than ever, utilities need electrical models of wind farms and methods of analysis that will help them to identify and cope with potential problems of grid stability.

Inspired by the E-ON Netz in Germany, Grid Codes have emerged in nearly every country with wind generation [1], [2],[3],[4]. By far, the most demanding requirement that the system operator grid code will impose to wind turbines and wind farms is the low voltage ride through (LVRT) capability. An example of such LVRT requirement by E.ON Netz is shown in Fig. 1. According to this requirement, tripping of wind turbines/farms is allowed below the red line. Without proper tools that can predict the behaviour of the wind farm under such severe voltage contingency, utilities are reluctant to integrate more wind power into the grid.
Wind farms using squirrel cage induction generators directly connected to the network will most acutely suffer from the new demands, since they have no direct electrical control of torque or speed, and would usually disconnect from the power system when the voltage drops more than 10-20 % below rated value [5]. In general, fulfilment of the LVRT demand for induction generators will require dedicated hardware, specific control strategies for pitching the blades of the turbine and/or extra support by controlled injection of reactive power [6],[7],[8].

Technologies that can improve LVRT capability of induction generators by controllable reactive current injection have been extensively reported in the literature [7]-[14] Transient stability margin studies related to the use of a STATCOM for LVRT have been reported by the authors in [10] and [12].

In order to evaluate the performance of STATCOM and SVC for LVRT, a wind turbine example is investigated using a simplified analytical approach that represents the turbine, the compensating device and the network. The purpose is to provide a simple tool for assessing transient stability by considering only relevant parameters that play a significant role in LVRT and that can determine the rating of the needed compensating devices to fulfil LVRT. The critical speed of the machine, considered as the speed at clearing of a fault before the generator looses its stability, is taken as the indicator of LVRT capability [15]. The transient stability margin is considered as time or speed margin to the stability limit for a specific fault. The presented analysis uses torque-speed curves for assessing transient stability limit, and it therefore neglects the flux transients of stator and rotor of the induction generator. Critical speed and critical clearing time (CCT) are calculated for different compensation levels of STATCOM and compared with the case of no compensation, ideal compensation (stiff voltage) and compensation with different sizes of SVC. The results obtained give advantage to the STATCOM when it comes to LVRT. Simulations performed with a system model implemented in the PSCAD/EMTDC simulation software [14], using the same parameters as for the analytical model, verify that the critical speeds obtained with the calculations are in good agreement with the ones observed in simulations. The deviations between calculations and the simulations are identified, and explained with reference to the simplifications made to derive the calculation method.

**Transient Stability Limit By Torque-slip analysis**

Figure 2 shows the schematic configuration of the system under consideration for reactive compensation. For this study it is assumed that the power system is subjected to a three phase fault at the point of connection of the reactive power compensation. No load compensation with fixed capacitors and controllable reactive power sources such as SVC and STATCOM are used for shunt reactive compensation in the study. The STATCOM is assumed to be a pulse width modulated voltage source converter controlling the voltage at its terminals by injecting a controlled reactive current, while the thyristor controlled SVC operates as controllable shunt impedance. The main advantage of the STATCOM over the SVC is that the compensating current does not depend on the voltage level of the connecting point and thus the compensating current is not lowered as the voltage drops [17]. This is an important feature now that new grid codes will require wind turbines dynamic supply of reactive current depending on network demand and actual highly fluctuating voltage level. Regarding LVRT, the paper investigates if there is any increased transient stability margin with the STATCOM compared to the SVC.
The transient stability of a directly connected induction generator is analysed using a simplified approach based on torque-slip characteristics, neglecting stator and rotor transients of the induction machine [18]. This leads to the use of a traditional per phase equivalent circuit representing the induction machine, and studying only the mechanical acceleration dynamics. This simplification will not be valid for dynamic phenomena dominated by the stator and rotor flux transients of the machine, but are considered reasonable for calculations of relevance to power system studies involving voltage stability and load restoration [19]. In the case of grid faults, this assumption is considered reasonable during balanced faults of long enough duration for the flux transients to be damped.

The equivalent per phase circuit of the system after a fault is shown in Fig. 3, where $v_g$, $v_1$ are Thevenin grid voltage and induction machine terminal voltage phasors, and $i_{g}$, $i_{\text{STATCOM}}$, $i_1$, $i_m$ and $i_2$ are line, STATCOM, stator, magnetizing and rotor current phasors. Grid impedance is $r_g + jx_g$ while $r_1$, $r_2$ are stator and rotor resistance and $x_1$, $x_m$, $x_2$ are stator, magnetizing and rotor reactance. During the fault and the first part of the recovery, it is assumed that the compensation device is not able to keep the voltage at the reference value of 1 pu. The STATCOM is therefore represented in the equivalent circuit by a current source given by the maximum current rating. The SVC controlled to its maximum capacitive compensation corresponds to a constant capacitor, and the SVC can therefore be represented in the same equivalent circuit by replacing the current source with a capacitor. Constant capacitor compensation at the machine terminals can also be included in the equivalent circuit in the same way. For the situation after a fault, both compensation by constant capacitors and SVC can be regarded as passive elements and treated in the same way as presented in [18].

**System equations with STATCOM**

For the case of the STATCOM, with the current directions indicated in Fig. 3, the relation between per phase grid voltage and STATCOM voltage will be given as:

$$v_g = v_1 + \left(r_g + jx_g\right)\left(i_1 + i_{\text{STATCOM}}\right)$$

(1)

The current $i_1$ will depend on the voltage $v_1$ and the slip, and can be expressed by (2), where $r_{eqr}$ and $x_{eqr}$ are defined by the slip dependent impedance of the parallel connection of the rotor branch and the magnetizing reactance in Fig. 3.

$$i_1(s) = \frac{v_1(s)}{r_1 + r_{eqr} + j\left(x_1 + x_{eqr}\right)}$$

(2)

Neglecting losses, the STATCOM current will be purely reactive, and always leading the voltage $v_1$ by 90°. The STATCOM current phasor can therefore be expressed by:

$$i_{\text{STATCOM}} = j\frac{v_1(s)}{v_1(s)}\left|i_{\text{STATCOM}}\right|$$

(3)
Fig. 3: Quasi stationary equivalent circuit for the system under study, consisting of the traditional induction machine equivalent, STATCOM as a current source or SVC as a fixed capacitance, and a grid equivalent.

Combining (2) and (3) with (1) gives:

\[
v_g = \left( i + \frac{r_g + jx_g}{r_i + r_{eq,r} + j(x_i + x_{eq,r})} + j \frac{r_g + jx_g}{v_1(s)} \right) v_1(s)
\]

(4)

The grid voltage \(v_g\) is the constant reference voltage, and for a given STATCOM current and a given slip, this equation can be solved to find the terminal voltage \(v_1\) as a function of slip or speed [20]. The corresponding stator current \(i_1\) is given by (2), and the per unit rotor current \(i_2\) and electromagnetic torque \(\tau_{em}\) are given as:

\[
i_2(s) = \frac{r_2 + j(x_2 + x_m)}{s}
\]

(5)

\[
\tau_{em}(s) = \frac{r_2}{s} |i_2(s)|^2
\]

(6)

Plotting the torque of equation (6) as a function of slip or speed for a specific STATCOM current rating, results in a corresponding torque-speed curve for the conditions after the fault. A critical clearing speed can be found as the intersection of the torque-slip curve with the mechanical torque. This is similar to what is previously reported for induction generators with only passive capacitor compensation [18]. Neglecting the flux transients of the machine, the critical clearing speed will in general not depend on the type of disturbance, since the stability of the induction machine depends only on the magnitudes of mechanical torque and reapplied electromagnetic torque after the disturbance [18].

The mechanical equation is given by

\[
T_a \frac{dn}{dt} = \tau_m - \tau_{em}(n)
\]

(7)

where \(T_a\) is the mechanical time constant, \(n\) is the speed, \(\tau_m, \tau_{em}\) are mechanical torque and electromagnetic torque. Assuming zero electromagnetic torque during a three-phase short circuit, and constant accelerating torque equal to mechanical torque, the critical clearing time (CCT) can be calculated from the critical speed and the initial speed, or the corresponding slip values as:

\[
CCT_{3-phase} = T_a \frac{n_{crit} - n_{init}}{\tau_m}
\]

(8)

**Torque-slip calculation example**

The given equations are used for an example calculation with machine parameters based on the 2 MW induction generators of the Smøla wind farm in Norway [21]. The parameters are listed in Table I, given in per unit values based on the total kVA rating of the machine. The resulting torque-slip characteristics for the uncompensated system, constant terminal voltage, 1 pu. STATCOM and 1 pu. SVC are given as torque-speed curves in Fig. 4, assuming a short circuit ratio (\(SCR=S_{sw}/P_n\)) of 10 and an \(X/R\) ratio of 10 for the grid. The curves are plotted together with torque-slip curves for no compensation and for constant terminal voltage (ideal compensation). Following the given assumptions, for the system to be stable after a fault, the speed at fault clearing must be lower than the speed at the intersection between the torque-speed curve for the specified system and the mechanical torque. Close to the stability limit, where the calculated torque of the generator equals the mechanical torque on the curves of Fig. 4, the flux transients that are not accounted for in this approach will determine whether the system is able to maintain stability or not.
During a fault, the generator is assumed to accelerate with zero remaining torque, and at fault clearing, the torque is assumed to be instantly re-established to the value corresponding to the specific speed at clearing and the given maximum rating of the compensation device. For a stable situation after fault clearing, the torque as function of speed will approximately follow the corresponding quasi-stationary torque-speed curve of Fig. 4 until the speed is reduced enough for the STATCOM to bring the terminal voltage back to its nominal value. Thereafter the torque-slip curve will be given by the constant voltage curve, which is the same as used to find the initial conditions. Calculated critical speed and CCT for the uncompensated system, and for the different types and ratings of reactive compensation are given in Table II assuming constant applied mechanical torque and zero electromagnetic torque during a three-phase short circuit as given by (8).

### Table I: Main parameters of investigated system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine rated power</td>
<td>$P_n = 2.0 \text{ MW}$</td>
</tr>
<tr>
<td>Rated apparent power</td>
<td>$S_n = 2.2 \text{ MVA}$</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>$V_{LL,n} = 690 \text{ V}$</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$r_s = 0.010 \text{ pu}$</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>$x_s = 0.179 \text{ pu}$</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>$r_r = 0.008 \text{ pu}$</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>$x_r = 0.074 \text{ pu}$</td>
</tr>
<tr>
<td>Magnetizing reactance</td>
<td>$x_m = 4.376 \text{ pu}$</td>
</tr>
<tr>
<td>Grid reactance</td>
<td>$x_g = 0.11 \text{ pu}$</td>
</tr>
<tr>
<td>Grid resistance</td>
<td>$r_g = 0.01 \text{ pu}$</td>
</tr>
<tr>
<td>Mechanical time constant</td>
<td>$T_a = 6 \text{ s}$</td>
</tr>
<tr>
<td>Mechanical damping (simulation)</td>
<td>$D = 0.008 \text{ pu}$</td>
</tr>
</tbody>
</table>

### Table II: Calculated results for a three-phase fault with different compensation ratings

<table>
<thead>
<tr>
<th>Reactive Compensation</th>
<th>Critical speed</th>
<th>CCT$_{3\text{-phase}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No compensation</td>
<td>1.053 pu</td>
<td>0.257 s</td>
</tr>
<tr>
<td>0.25 pu fixed capacitor</td>
<td>1.057 pu</td>
<td>0.287 s</td>
</tr>
<tr>
<td>0.5 pu STATCOM</td>
<td>1.062 pu</td>
<td>0.320 s</td>
</tr>
<tr>
<td>1.0 pu STATCOM</td>
<td>1.071 pu</td>
<td>0.370 s</td>
</tr>
<tr>
<td>1.8 pu STATCOM</td>
<td>1.085 pu</td>
<td>0.457 s</td>
</tr>
<tr>
<td>1.0 pu SVC</td>
<td>1.067 pu</td>
<td>0.352 s</td>
</tr>
<tr>
<td>2.0 pu SVC</td>
<td>1.084 pu</td>
<td>0.451 s</td>
</tr>
</tbody>
</table>

Fig. 4: Torque-speed curves for uncompensated system, for different STATCOM and SVC current ratings, and for constant terminal voltage.
Transient Stability Limit by Simulation

In order to investigate the validity of the calculation method, the schematic configuration shown in Fig. 2 is implemented in PSCAD/EMTDC [14]. Simulations are performed replicating the conditions assumed in the analytical approach, with the objective of comparing the simulation results with the results of calculations presented in Table II. For the case of STATCOM, the control strategy implemented is based on the vector control principle for independent control of reactive current and DC-link voltage [22], [23]. The reactive current injected is controlled by a PI-controller so as to obtain the rated 1 pu grid voltage before and after the fault. During the fault, the reactive current injection will be given by the maximum compensation possible within the specified current limits. The implemented SVC has equal inductive and capacitive rating, and can therefore be controlled in the range from zero compensation to the maximum reactive compensation corresponding to the rating of the capacitors. The effective shunt impedance of the SVC is controlled by a simple PI controller that will regulate the firing angle of the thyristor controlled inductance (TCI) to bring the voltage to its reference value.

The validity of the analytical approach should be concluded by comparing the critical speed for all the cases that are investigated in both simulation and by the calculation method. The critical speed corresponding to the stability limit in simulations, defined strictly as the exact speed at clearing, is given in Table III. Comparing these numbers with the results of Table II, it is clear that the critical speed at clearing given by simulation is for all cases lower than the critical speed given by the calculation method. The main reason for this is that the machine does not build up the torque instantly after fault clearing as considered in the calculation method, but needs some time before the flux of the machine is re-established and the transients of the fault clearing are damped. This can also be observed by point 2 in the red curve of Fig. 7, which is provided to illustrate the sequence of a fault and show how the simplified analytical treatment relates to the detailed time domain simulation. Fig. 7 shows the simulated torque-speed trajectory at the stability limit with a STATCOM of 1 pu maximum current rating together with the calculated torque-speed curves with constant terminal voltage and with maximum injection of reactive current from the 1 pu. STATCOM.

The sequence of the torque trajectory in Fig. 7 can be explained by the different sections indicated in the figure between the marked points. Immediately after the short circuit occurs, there are severe torque transients caused by the short circuit current of the machine. These transients are damped as the flux of the machine decays. When the machine is demagnetized it accelerates with almost negligible remaining torque independent of the compensation device, and with the speed increasing almost linearly with time if the applied mechanical torque is constant. When the fault is cleared, at point 2 in Fig. 7, the machine starts to re-magnetize, leading to a torque transient before the flux settles at a quasi-stationary value at a specific torque given by the speed and the rating of the reactive compensation as marked by point 3 in the figure. This point determines if the machine is stable, because a quasi-stationary torque above the mechanical torque will lead to a slow deceleration of speed, while a torque below the mechanical torque will result in further increase of speed and the loss of stability. It is important to note that the values for speed at this point coincide almost exactly with those from the simplified calculations at the stability limit. When stability is ensured, the machine will decelerate back to the initial speed. At first, deceleration is slow, and the torque-speed trajectory follows the stationary curve almost exactly. As the torque increases, the deceleration of the machine will be faster, causing transients that will make the torque-speed trajectory of the dynamic simulation deviate from the stationary torque-speed characteristic because of the time needed to increase the flux level and the corresponding torque capability of the machine.

### Table III: Simulation results for a three-phase fault with different compensation ratings

<table>
<thead>
<tr>
<th>Reactive Compensation</th>
<th>Critical speed (point 2)</th>
<th>Maximum speed</th>
<th>Speed after transient (point 3)</th>
<th>CCT (_{3\text{-phase}}) SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>No compensation</td>
<td>1.046</td>
<td>1.056</td>
<td>1.054</td>
<td>0.229 s</td>
</tr>
<tr>
<td>0.25 pu fixed capacitor</td>
<td>1.050</td>
<td>1.061</td>
<td>1.057</td>
<td>0.259 s</td>
</tr>
<tr>
<td>0.5 pu STATCOM</td>
<td>1.056</td>
<td>1.066</td>
<td>1.062</td>
<td>0.310 s</td>
</tr>
<tr>
<td>1.0 pu STATCOM</td>
<td>1.067</td>
<td>1.076</td>
<td>1.072</td>
<td>0.375 s</td>
</tr>
<tr>
<td>1.8 pu STATCOM</td>
<td>1.083</td>
<td>1.090</td>
<td>1.086</td>
<td>0.473 s</td>
</tr>
<tr>
<td>1.0 pu SVC</td>
<td>1.062</td>
<td>1.071</td>
<td>1.067</td>
<td>0.346 s</td>
</tr>
<tr>
<td>2.0 pu SVC</td>
<td>1.081</td>
<td>1.088</td>
<td>1.084</td>
<td>0.459 s</td>
</tr>
</tbody>
</table>
At point 4, the sequence is completed returning to the initial conditions. Torque trajectory and fault sequences close to the stability limit are similar for all the investigated compensating devices and ratings presented in Table II and Table III.

The maximum speed observed in simulations at the stability limit is also given in Table III, and it can be observed that these numbers are slightly higher than the critical speed of the calculation method. This is because of the torque transients during the re-magnetization of the machine. The speed of the recovery process at point 3 in Fig. 7 is also given for the different compensation levels in Table III, and it almost coincides with the calculated critical speeds from Table II. A trend of increased accuracy for higher rating of reactive compensation is observed in Table III. This can be explained by the faster re-magnetization of the machine when there is more reactive power available.

Table III also lists the CCT observed in all the simulations performed. These values of CCT compared to those in Table II indicate that the simulations results give lower CCT for the lower rating of reactive compensation, and higher CCT than those obtained with the calculation method for the higher ratings. The lower critical clearing times can be explained by the fact that for shorter fault conditions, the influence of the flux transients will dominate during most of the fault and recovery process. However, for longer faults and correspondingly higher compensation levels, the torque transients during the first part of the fault will contribute to limit the acceleration of the machine. In the simulations there is also a small influence from mechanical damping, and for the STATCOM control to be able to operate during the fault there is a small remaining voltage giving a small remaining torque during the fault. Then, the sum of these effects is larger than the influence of the flux transient recovery, and therefore the resulting CCT in simulation are larger than the calculated values. From these results it can be concluded that the stability of an induction generator is determined by the quasi-stationary torque capability of the machine as represented by the torque-speed characteristics, and by the flux transient with corresponding torque transients after the fault clearing. If a correction factor taking into account the torque transients is introduced, then the given procedure will be an efficient way of estimating the critical speed of a wind turbine or a wind farm and a relevant tool for screening different compensating devices with different ratings.
Calculation of required rating for STATCOM and SVC

Based on the results presented in the previous section, the same simplified approach based on torque-speed calculations is suggested for direct estimation of required rating of STATCOM or SVC for LVRT fulfilment. By further manipulation of the presented equations and solving them for the compensation current, a generalised calculation method for estimation of required reactive compensation as a function of the system parameters and the speed at fault clearing can be obtained.

For the system to be stable at a specified speed, the braking torque of the machine must be larger than the applied mechanical torque, and this will be the criteria for specifying the torque requirement at a certain speed. In addition to rotor current calculated from the required torque, the magnitude of the voltage source of the grid equivalent is assumed to be known. From this starting point, the circuit of Fig. 3 can be solved to find the necessary STATCOM current or the corresponding impedance of SVC. The required current can be found as presented in [20] by a second order equation as given in (9), where $b$ and $c$ are dependant on the system parameters and can be evaluated by solving the circuit of Fig. 3 for the STATCOM current.

$$\left|i_{\text{STATCOM}}\right|^2 + bi_{\text{STATCOM}} + c = 0 \quad (9)$$

Solving this equation, the minimum solution gives the required capacitive STATCOM current rating to maintain stability for a specified speed/slip at fault clearing. From this current rating and the voltage required at the connection point to achieve the specified torque, also per unit capacitance of a SVC can be calculated.

Figure 8, shows the required current rating of the STATCOM and capacitive impedance rating of the SVC as a function of speed at clearing for various values of Short Circuit Ratio (SCR) and $X/R$. For all values of SCR in the speed range of interest, the required STATCOM rating is bit lower than required SVC rating with the machine parameters of Table I. The stronger the grid becomes, the lower the required STATCOM and SVC rating to ensure stability, since the grid is more able to supply large amounts of reactive power to the induction generator. To the right of the point were curves for STATCOM and SVC intersects, which corresponds to 1 pu voltage, the required SVC rating is lower than the STATCOM rating since stability can not be ensured without increasing the voltage beyond its nominal value. To the left of the figure, all the curves go to zero, meaning that for lower speeds at fault clearing the generator will be stable without any compensation.

Table IV lists the required ratings of STATCOM and SVC to ensure stability obtained by trial and error simulations. This was done with the purpose of verifying the calculated values in Fig. 8. For lower speeds at clearing the required rating from calculation is significantly lower than the ones obtained from simulations ($\nu=1.06, 1.07$). When the speed at clearing becomes higher the difference between the two methods becomes smaller.

<table>
<thead>
<tr>
<th>Speed at fault clearing</th>
<th>Needed rating from simulation</th>
<th>Needed rating from calculation</th>
<th>Speed after transient (point 3)</th>
<th>Needed rating from post transient calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.06</td>
<td>0.59</td>
<td>0.24</td>
<td>1.066</td>
<td>0.58</td>
</tr>
<tr>
<td>1.07</td>
<td>1.09</td>
<td>0.81</td>
<td>1.075</td>
<td>1.09</td>
</tr>
<tr>
<td>1.08</td>
<td>1.58</td>
<td>1.37</td>
<td>1.083</td>
<td>1.54</td>
</tr>
<tr>
<td>1.09</td>
<td>2.07</td>
<td>1.92</td>
<td>1.093</td>
<td>2.08</td>
</tr>
<tr>
<td>1.10</td>
<td>2.56</td>
<td>2.43</td>
<td>1.102</td>
<td>2.55</td>
</tr>
<tr>
<td>1.12</td>
<td>3.56</td>
<td>3.46</td>
<td>1.123</td>
<td>3.61</td>
</tr>
<tr>
<td>1.06</td>
<td>0.75</td>
<td>0.31</td>
<td>1.066</td>
<td>0.74</td>
</tr>
<tr>
<td>1.07</td>
<td>1.31</td>
<td>1.01</td>
<td>1.074</td>
<td>1.27</td>
</tr>
<tr>
<td>1.08</td>
<td>1.85</td>
<td>1.63</td>
<td>1.083</td>
<td>1.81</td>
</tr>
<tr>
<td>1.09</td>
<td>2.39</td>
<td>2.19</td>
<td>1.093</td>
<td>2.34</td>
</tr>
<tr>
<td>1.10</td>
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<td>1.102</td>
<td>2.77</td>
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<tr>
<td>1.12</td>
<td>3.75</td>
<td>3.51</td>
<td>1.122</td>
<td>3.58</td>
</tr>
</tbody>
</table>
low accuracy for lower speeds at clearing is originated by the neglected transients in the calculation methods. The same explanation holds as it was given in the previous sections for the critical speeds. To verify this, the speed after the flux transient for the simulation on the stability limit is additionally given in Table IV in column 4, and used to find the corresponding required rating from Fig. 8. These calculated current ratings for the speed after the flux transient at fault clearing coincide almost exactly with the required rating found from the trial and error simulations. This demonstrates clearly that the estimation method is valid, when the influence of the transient is small. The inaccuracy is high for lower ratings or short faults and should not give more than a rough estimate. The duration of the main flux transients will depend on the machine parameters and on the grid. When estimating required rating for a specific length of fault, it would therefore be relevant to improve the performance of the analytical method by introducing a correction factor that quantifies the speed increase from the clearing of a fault until the transients are damped and the machine has settled in a quasi-stationary condition that makes the simplifications of the calculations valid. This will be subject of further investigations, and will give higher accuracy to the calculated required ratings for the whole range of critical speed.

With the information of specified Grid Code requirements of CCT expressed as speed at fault clearing, including correction for the transient at fault clearing, Fig. 8 can be used for estimating required rating of STATCOM or SVC to ensure LVRT for screening possible solutions. This method can give a first indication before proceeding to further investigation of the most interesting cases for instance by detailed simulation studies. Plotting calculated results in curves like presented in Fig. 8 can also illustrate the sensitivity of the system to different conditions. From Fig. 8, it can be seen how the difference in required rating of a STATCOM and an SVC is larger for a lower SCR of the grid.

This rating calculation method will be an important tool for wind farm developers to help them fulfil the requirements of the Grid Codes and to the utilities to investigate the impact that a planned wind farm would have on the network.

**Conclusions**

A simplified theoretical approach to investigate transient stability limits of induction generators with reactive compensation, and to estimate the required rating of reactive compensation for LVRT fulfillment is presented. An estimate for the increase of critical speed and corresponding CCT for different STATCOM and SVC ratings after a three phase fault is calculated. Further on, a generalized method for estimating required rating of STATCOM and SVC for LVRT fulfillment, with given system and generator parameters, is suggested on basis of the same simplifications.

In order to validate the proposed simplified calculation method, simulations were performed to compare the critical speeds and CCT with those of the calculation method. Deviations between the estimated values and results from detailed simulation are discussed in light of the simplifications made for the analytical approach. For this purpose, critical speed seems to better indicate the stability limit for any given system and fault because its dependence on contingency characteristics is lower than in the case of CCT. It is also seen that there is better agreement around the values of critical speeds from calculation and simulation results and that it is this value that will determine stability. For the simplified calculations to be valid, the fault must be long enough to allow the first severe transients to be well damped. In general, calculation and simulation values are in good agreement, and the method can be used as a powerful screening tool as long as the influence of the given simplifications is well understood.

The value of the proposed method lies on the fact that this new tool can be implemented in a simple and reliable manner by both wind farm developers and utilities in order to fulfil the demands of the Grid Codes and to investigate the impact of new wind farms in the stability of the network. Providing such an analysis tool for the case of induction generators directly connected to the network with shunt reactive compensation, will widen the possibilities for a more economical solution for induction generators in wind energy.

To generalize the rating calculation method for all fault durations, a correction factor should be introduced for quantifying the speed increase from the clearing of a fault until the transients are damped. This topic will be subject of further investigations.
References


