Integrating a wind farm into a transmission or distribution system

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With South Africa implementing a renewable energy independent power producer program (REIPPPP) there has been keen interest in independent power producers (IPPs). A large numbers of these IPPs are wind energy facilities (WEF) [1]. Integrating a WEF into a transmission or distribution network not only requires good engineering practices but also conformance to the NERSA grid connection code. This article considers some of the requirements of the grid connection code.

Poorly integrated WEF can degrade the quality of supply in the network resulting in inconvenience to existing customers and an embarrassment to the utility. To prevent this happening, a grid connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa (SAGCRPP) has been developed which recognises this fact and requires a detailed analysis of the situation and a careful appraisal of possible connections [2]. This grid connection code clearly states the conditions to which every WEF should adhere.

This article relates to WEFs which utilise fully converter coupled wind turbine generators (WTG) and covers ride-through large frequency deviations, system faults and the capability of the WEF to conform to the SAGCRPP under various voltage, active power and reactive power conditions.

The SAGCRPP specifies the minimum technical and design grid connection requirements for all types of RPPs. This article examines the basic operation of fully converter coupled wind turbine generators in a wind farm and the problems that can be expected in meeting the grid connection code from the following aspects:

- The ability of the WEF to ride through large frequency deviations
- The ability of the WEF to ride through system faults
- The capability of the WEF under various voltage, active power and reactive power conditions

A typical full converter coupled wind generator layout is shown in Fig. 1. The generator output, which is AC with a frequency determined by the rotor speed, is rectified and the DC voltage inverted to a 50 Hz AC voltage; this completely decouples the speed of the generator from the 50 Hz frequency of the grid. Fig. 2 shows the basic control system of the converter.

The inversion of the DC voltage from the generator is achieved using pulse width modulation (PWM) technology as opposed to the older technology that varied the firing of thyristors. This has advantages, not the least of which, is the ability to control active power and reactive power independently of each other.

Wind farm layout

A wind farm consists of a number of wind turbines and their inverters connected to a substation where the outputs of the wind turbines are combined. The choice of cable run and the number of wind turbine units is usually based on the economics of cable cost and losses. The single line diagram of a typical wind farm is shown in Fig. 3.

Overall power plant controller

The system operator (SO) is only interested in the wind farm as far as the voltage and power at the point of connection (POC) are concerned. The voltages and power at the individual WTGs are of no concern to him. An important aspect of the SAGCRPP is to ensure the wind farm can meet the needs of the SO with its units working together in a co-ordinated manner. This is achieved by the power plant controller, PPC.

Compliance with the grid code frequency requirements

The integrated Southern African grid is relatively small compared with the integrated grid in Europe or North America. As a result larger frequency deviations can be expected. It is undesirable to have any generation, be it WEF generation or Eskom generation tripping during or following a frequency deviation from 50 Hz and a wind farm or any other IPP is required to meet the frequency versus duration requirements shown in Fig 4. Thus it is important to ensure that the equipment for a local WEF can comply with South African conditions.

The WEF supplier might offer generic equipment, which is suitable for European conditions but may not be suitable for operation in the South African environment. It is thus important to check compliance of WEF equipment as inverter settings may need to be adjusted for South African Standards. The red dotted line shows typical frequency limits that could be expected from a wind turbine that was developed for Europe.
settings the wind turbine will not conform to the requirements stipulated in the SAGCRPP.

The frequency versus time requirements of the code are best validated by a dynamic study. The wind farm model and the computer package need to be able to represent frequencies other than 50 Hz [3]. The graph in Fig. 5 shows the low frequency condition as stipulated by the SAGCRPP applied at the POC.

To check for code compliance the active power of the individual wind turbines is monitored. From Fig. 6 it can be seen that the wind turbines have disconnected at 0.1 s due to the frequency dipping below 47.6 Hz, thus not complying with the South African SAGCRPP.

A similar approach is taken for the high frequency condition.

**Transient voltage requirements**

Similar to the frequency versus time requirements, there is an equivalent requirement for voltage. In this instance voltage versus time requirement refers to the voltage at the POC following a particularly onerous fault. The representation of zero voltage is easily achieved. The ramp up of voltage from zero to 85% voltage will require a specially developed voltage source model. This model can then be used to represent any voltage profile at the POC. The SAGCRPP specified voltage conditions at the POC are shown as a blue dotted line shown in Fig. 7 and all wind turbine units are required to remain connected to the grid during these conditions. The typical voltage ride through characteristics required for a European WEF are shown as the red lines in Fig. 7.
Fig. 8 shows the active power and the reactive power during a low voltage ride through condition. The active and reactive power outputs of all the WTG are the same and thus only show up as one line in Fig. 8. As a fault is applied and the voltage goes to zero, the active power from the individual generators drops almost to zero, the difference from zero being the resistive power loss in the cables to the POC. There is a similar reaction from the reactive power. At 0.25 s the WEF terminal voltage ramps up. The active power remains at approximately zero while the reactive power starts to ramp up. The reaction of the reactive power to the voltage dip is shown in Fig. 9. In this instance, the response given in Fig. 9 does not meet the requirements of the SAGCRRPP. Control setting changes will be required so that the WEF produces maximum IQ when the voltage reaches 50%.

**Wind energy farm traditional capability diagram**

A typical wind turbine capability curve could look like Fig. 10. At rated power output and 0.95 power factor leading or lagging, there can be a limitation due the maximum current carrying capacity of the inverters, especially the inverter semiconductor switches. As the SAGCRRPP requires rated power at 0.95 pf, the WEF needs to recognise reduction in output. IR losses in the collector network also reduce the WEF output and need to be considered when determining the overall output of the WEF.

**Reactive power**

At the POC, there are limitations on the reactive power output, which are more pronounced than those on active power. The MV step-up transformers consume reactive power as does the collector network, which generally absorbs more reactive power than it generates. Thus the WEF will not operate at 0.95 power factor in the capacitive range, when the individual generators are at 0.95 leading. With the individual generators at 0.95 power factor lagging the WEF network absorbs more reactive power than the combined individual generators. The capability diagram will tend to look like Fig. 11.

**Reactive power requirements from $U_{MIN}$ to $U_{MAX}$**

Besides the reactive power requirement at
Un there are requirements at voltages from 110% $U_n$ to 90% $U_n$, as shown in Fig. 12.

The resistance of the wind farms MV collector network causes a voltage rise between the POC and the individual generators. This means that the voltages at the wind turbines will exceed 110% $U_n$ if the voltage at the POC is 110%. This has an implication as far as the MV insulation requirements of the individual wind turbines are concerned. This problem is illustrated by the simple wind farm example in Fig. 13 [4].

For example, with the POC at 110% and the WEF operating at unity power factor the highest overvoltage could be 113% of rated voltage in the LV (315 V) and 112% in the 22 kV MV.

The 315 V equipment can usually be operated at voltages up to 115% of $U_n$ from an insulation and inverter point of view, however transformer manufacturers indicated that saturation effects could be an issue above 110% voltage. There are different solutions to solve the overvoltage problem.

These include:
- Tapping of the 22/0.315 kV transformer
- Installing shunt compensation
- Reducing active power output
- Installing a 1:1 transformer

Possible remedies for non-compliance include:

**Tapping of 22/0.315 kV transformer**

This remedy can be effective when the problem is at 0.315 kV. However tapping the 22/0.315 kV transformers has no effect on the MV network. It should be noted that this remedy can result in undervoltage conditions in the WEF network when the POC is operated at 90% voltage and at unity power factor. Thus tapping the 22/0.315 kV transformers is not a solution.

**Tapping of 22/0.315 kV transformer and installing a reactor**

If the 22/0.315 kV transformers are tapped and a reactor is installed at the point, where the two feeder cables are connected to the cables running to the switching station Collector Station shown Fig. 3), then the under voltage condition at the inverters can be rectified but the over voltages are still seen throughout the MV network. However the situation, when operating the POC at its upper voltage limit is the same as without the reactor. This comes about as voltage at the reactor needs to be the same as if the reactor was not there.

**Installing a capacitor bank**

With the MV/0.315 kV transformers left on nominal tap and an 11 Mvar capacitor installed at the ring main unit, the overvoltages at the inverters are eliminated. However, with the POC at 110% (unity power factor) an overvoltage of 112% is still seen in the 22 kV WEF network. To get to a satisfactory solution using a shunt capacitor, it would be necessary for the capacitor to be larger than 27 Mvar and be installed at the POC. A capacitor of this size would overload the inverters from a reactive power aspect and most probably require the 22 kV cables to be up to 50% larger. This is not a suitable solution.

**Installing a 1:1 transformer**

With a 1:1 on-load tap changing transformer installed at the POC, the WEF will conform to the Grid Connection Code requirements. With the POC at 110% the transformer can tap and the WEF farm can operate at less than 110% for example 109%. At this voltage all 22 kV voltages in the WEF are within required limits.

**Reducing power output**

Reducing the active power output will not solve the problem as overvoltages will still exist.

With the POC at 110%, and the active power reduced to 50%, MV voltages of 110.2% are still experienced. Thus this is not a feasible option.

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### References


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