IRP2016: Discussion of potential limits to variable renewable energy installations

Introduction

This technical paper serves as an input into the current discussion of the draft IRP 2016. It mainly focuses on build constraints of variable renewable energy (VRE, such as wind and solar generation) of specific IRP scenarios and presents an assessment whether these constraints can be justified on technical grounds.

The base case scenario of the IRP2016, which has been published for consultation in November 2016, foresees a mix of new coal fired power stations, VRE comprising PV and wind, gas generation plants (CCGTs and OCGTs), and from 2037 on nuclear power stations, for compensating load growth and the retirement of old coal-fired power stations.

The corresponding PowerPoint presentation of the DoE contains two additional scenarios considering stricter CO_2 emission constraints (carbon budgets) than the base case. The results of these scenarios show that when applying stricter CO_2 emission constraints, there will be fewer coal fired power stations constructed, and significantly more VRE (wind / PV) or nuclear.

The scenarios further show that compared to nuclear, wind and PV in combination with natural gas are by far the more economic option. It is only by introducing annual build limits of new PV and wind farms that nuclear becomes a competitive option.

As the economic implications of these annual build limits are huge (several billion ZAR per year), the reasons for introducing these constraints require careful analysis. However, the published base-case report does not provide any information on them.

Potential reasons, which have been communicated to GIZ during several meetings with relevant stakeholders, include the following:

1. Grid constraints: the transmission grid cannot be expanded quickly enough to accommodate more wind/PV.
2. Stability constraints: the amount of non-synchronous generation (wind and PV) is limited because of stability issues (some of them reported by other countries).
3. No technical reasons, the annual build limits are just imposed for reflecting the political will.

This document provides an assessment of the validity of the technical reasons given.

Grid constraints

It is unclear whether this concern refers to constraints at distribution level (e.g. 132kV connection of wind and PV farms) or at 275kV/400kV/765kV levels (where deep reinforcements are required). In both cases constraints resulting from the inability to sufficiently expand the grid can only be valid in the short term, as transmission expansion requires lead-times of around to 1-3 years at distribution level and 4-7 years at main transmission level, depending on the type of reinforcement / expansion. In the longer term, grid constraints cannot be a plausible reason for annual build limits of VRE because there would be sufficient time for planning and construction of the required reinforcements and expansions.

Therefore, when referring to generation expansion plans of other countries, it is common practice to consider grid constraints only for short-term planning (around 5-years ahead) and not for long-term planning. Since grid costs are typically lower than generation costs (at least one order of magnitude), the grid should ideally follow the most economic generation expansion plan, which will typically result in the most favorable overall economic solution. Only in densely populated countries (e.g. central Europe, various parts of U.S.), where there is a lot of resistance from citizens towards new transmission lines, grid constraints very often limit generation, or force planned generation to be reallocated.

Additionally, the TDP2014 of ESKOM shows that substantial transmission upgrades, including new 765kV transmission lines, are already planned for the Western Cape and the Eastern Cape[1]. These are required for accommodating relatively high levels of nuclear power in the Eastern Cape, which were foreseen by the IRP2010, but are not longer part of the base case scenario in the IRP2016. Considering that these new lines will also be available to accommodate wind and PV, particularly if nuclear is to be postponed or not required at all, there would be huge transmission capacity available in the Cape. Consequently, limited grid capacity at main transmission levels cannot be a plausible reason for introducing annual build limits of wind and PV.

Stability constraints

Some statements of Eskom highlight that power systems with very high levels of VRE (wind and PV) could suffer from stability constraints, and that the overall penetration level of VRE must be constrained for this reason. This argument does not relate to the variability of VRE, which is already accounted for by the IRP-methodology. However, the mentioned stability problems result from the fact that wind generators and PV modules are connected to the grid via power electronic converters and not via synchronous machines, as it is the case for thermal and large hydro power plants.

Additionally, wind and PV farms are typically connected to 132kV grids (and below) and not to the main transmission grid, which can also have an impact on power system stability.

These stability aspects must be carefully analyzed and considered when planning a power system with high wind and PV penetration. However, for each potential stability problem resulting from non-synchronous generation and distributed generation there exist several solutions. Therefore, these stability aspects can lead to some additional costs, but not to a restriction of the overall penetration level of wind and PV.

At the limit, it is even possible to operate a power system with 100% of non-synchronous generation. Every offshore wind farm with a HVDC connection[2] represents a power system with 100% non-synchronous generation which demonstrates the technical feasibility, even with today's technology.

The most important potential stability issues resulting from non-synchronous generation and distributed generation are the following:

a. Reduced inertia (frequency stability)

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[1] http://www.eskom.co.za/Whatweredoing/TransmissionDevelopmentPlan/Pages/Transmission_Development_Plans.aspx

[2] *HVDC: High Voltage Direct Current. Several offshore wind farms in the German Northern Sea are interconnected via HVDC*

b. Reduced synchronizing torque (transient stability, oscillatory stability)

c. Reduced voltage support (reactive power/voltage control)

d. Reduced contribution to short-circuit currents

All these aspects are very often expressed as “short circuit level” or “short-circuit power” because in systems with synchronous generation, a high short-circuit level is equivalent to high inertia, high synchronizing torque, high voltage support and high contribution to short circuit currents. However, in the case of non-synchronous generation, each of these stability aspects must be discussed separately and it is not possible to characterize the stability of a system by the term “short-circuit-level” any more. Numerous international working groups (e.g. CIGRE, IEEE etc.) are in the process of updating the definition of “short-circuit level”, regarding power system stability.

The following sections describe the individual stability issues in more detail and discuss technical solutions to overcome them.

a. Reduced inertia (frequency stability):

Conventional synchronous machines store a small amount of energy in their rotating masses (shaft inertia, turbine inertia, generator inertia), which they naturally make available to the system in the case of a frequency change (without any control action). The higher the overall inertia of a power system (sum of the inertia of all generators in the system), the lower the initial frequency gradient and the larger is the available reaction time for control actions like primary control of thermal power stations or load shedding. Sometimes, system inertia is also named “instantaneous reserve” or “second-reserve”.

In the case that system inertia is too low, there is a risk of a very deep transient frequency excursion triggering load shedding or, in the case of extremely low inertia, it can even happen that frequency drops so rapidly that load shedding relays can’t react quickly enough and the system is driven into a black-out[3].

PV modules are coupled to the grid through inverters without any storage. Therefore, PV farms don’t contribute to system inertia and a substitution of synchronous generators by PV generation results in a reduction of overall system inertia.

Wind turbine generators (WTGs) contain rotating masses and have similar inertia as synchronous machine power plants. However, because most WTGs (IEC type 3 and ICE type 4) are variable speed generators, the inertia of a WTG is decoupled from the frequency of the grid and therefore, a reduction of electrical frequency doesn’t result in a reduction of rotational speed. Because electrical frequency and mechanical speed is decoupled in a variable speed WTG, energy stored in the rotating masses of a WTG is not made available to the system in case of a frequency drop and therefore, there is no contribution to system inertia. This is similar to PV farms which are inverter connected, without any rotating components at all, and thus no stored energy.

Note that concentrating solar power (CSP) generators and biomass/biogas generators are not the same as PV, as the solar energy is used to produce steam which is converted to electricity using a turbine and synchronous generator – therefore CSP, biomass and biogas power plants add inertia to the system in the ‘traditional’ way.

[3] *As it has recently happened in South Australia*

How to resolve the problem of reduced system inertia?

For resolving the issue of reduced inertia, several options are available with today's technology:

Artificial inertia: Artificial inertia, which is sometimes known as 'synthetic inertia', relates to a special control function, which is available as an option for many WTGs today. Artificial inertia automatically increases the active power output of a WTG in proportion to the rate of change of frequency (df/dt-control). Effectively, this control function overcomes the problem that results from the decoupling of mechanical speed and electrical frequency and makes the energy stored in the rotating masses of a WTG available to the system in the case of a frequency drop. However, reducing the speed of a WTG can have a negative impact on its aerodynamics. Therefore, the positive impact of artificial inertia on frequency stability is rather limited.

Fast primary control: Wind- and PV-farms can provide very fast frequency control if their active power output is artificially constrained during normal operation. In contrast to a thermal power plant, in which relevant time constants depend on thermodynamic processes, a wind farm or PV farm can increase its active power output almost instantaneously and can therefore react much quicker to a frequency drop than a thermal power plant. For this reason, a new ancillary service, named "fast frequency control" is currently discussed by many international TSOs (e.g. National Grid/U.K.), which basically behaves like "primary control" (additional active power output in proportion to a frequency deviation) but which acts much faster.

Short-term storage: The participation of wind and PV farms in frequency control requires them to limit their active power output during normal operation. This is very costly because the "fuel" of wind and PV is for free. For this reason, it is more economic to deliver short-term frequency support (inertia and primary control) by additional storage systems (e.g. battery storage or flywheels). These devices can be relatively small in terms of their energy storage capacity because they must store energy only for a very short time frame of a few minutes. These batteries can, for example, be integrated into the tower of a WTG, where they can be linked to the communication network of a wind farm avoiding the need for additional communication systems for controlling the batteries. The British system operator National Grid has just started a competitive tender program for battery storage for "enhanced frequency control" (see http://www2.nationalgrid.com/Enhanced-Frequency-Response.aspx)

Synchronous condensers: When retiring large thermal power stations, the actual generator can be retained and can still be used in synchronous condenser mode. This means that it continues to provide ancillary services like inertia, synchronizing torque, voltage control and short circuit currents. In order to enhance its inertia (without any turbine connected, its inertia is substantially reduced) additional masses can be mounted on the turbine shaft.

Wind Turbine Generator technology: There are technologies available for variable speed wind turbine generators (WTGs), which naturally provide inertia to the power system. All IEC-Type 1 and IEC-Type 2 WTGs, which use induction generators that are directly coupled to the grid, actually provide inertia to the system. IEC-Type 1 WTGs are fixed speed only. However, IEC-Type 2 WTGs allow for variable speed operation and Low-Voltage-Ride-Through-capability (LVRT) using variable rotor resistance. Because IEC-Type 2 WTGs don't have any reactive power control capability, dynamic reactive power compensation devices (STATCOMs) must be installed for fast reactive power/voltage control capability. Besides IEC-Type 1 and IEC-Type 2 WTGs, there are variable speed WTGs available, which use normal, directly coupled synchronous generators and a hydrodynamic variable speed gearbox for achieving variable speed operation[4]. This technology would even provide synchronizing torque to the system (see next section).

b. Reduced synchronizing torque

All synchronous machines in an AC power system must be in synchronism during all times. Synchronous machines automatically synchronize each other by exchanging “synchronizing torque”, which is torque (or power) in proportion to the rotor angle of a synchronous machine.

Synchronizing torque depends on several factors. One of them is the equivalent reactance between two generators (sometimes also named “electrical distance”): The larger the distance between any two synchronous machines, the lower is their synchronizing torque.

Non-synchronous generators (e.g. inverters) must also be synchronized with the rest of the power system. This is done via special devices, which measure the voltage angle at any moment in time and ensure that currents are injected in synchronism with the rest of the system. However, non-synchronous generators only follow the voltage angle but they don’t actively provide synchronizing torque to all other generators.

In the case of power systems with very large share of wind and PV, reduced synchronizing torque can become an issue, especially in the case that there are very long lines between the remaining synchronous generators. This can lead to increased transient or oscillatory stability problems and, in extreme situations, even to stability problems with VRE.

How to resolve the problem of reduced synchronizing torque?

The issue of reduced synchronizing torque can best be resolved by *synchronous condensers* (see above). Only with a synchronous generator (and no turbine), synchronizing torque is provided to all other generators in the system.

Besides synchronous condensers, it would also be possible to use wind turbine generators (WTGs) using normal, *directly coupled synchronous generators and a hydrodynamic variable speed gearbox* for obtaining variable speed operation (e.g. footnote [4] on previous page). This technology has already been used successfully in different wind turbine generators in Germany, USA and China, but so far, the issue of inertia and synchronizing torque hasn’t been important enough for most wind turbine manufacturers to justify a change of generator technology.

In theory, it would also be possible to provide synchronizing torque with *short-term battery storage systems* or even with every *wind or PV converter* system[5]. However, providing synchronizing torque with power electronics converters requires modifying their control algorithms substantially. Additionally, in a large power system, it is required that converters providing synchronizing torque are equipped with considerable short-term overload capacity allowing them to absorb substantial power excursions during short periods of time (time frame of seconds). With some technologies (air-cooled

[4] *see, e.g.: H. Müller, M. Pöller, A. Basteck, M. Tilscher and J. Pfister: „Grid Compatiblity of Variable Speed Wind Turbines with Directly Coupled Synchronous Generator and Hydro Dynamically Coupled Gearbox”, Workshop on Large Scale Integration of Wind Power and Transmission Networks for Offshore Windfarms, Delft, The Netherlands, 2006*

[5] *In the case of offshore wind farms with HVDC connection, it is actually the offshore HVDC-converter, which provides the required synchronizing torque to the offshore system.*

inverters) this can be achieved at moderate cost overhead, in the case of other technologies (water-cooled inverters), there is almost no short-term overload capacity and it is required to increase the converter's nominal rating leading to increased costs.

c. Reduced voltage control capability (reactive power/voltage control)

According to the South African Grid Code for REPP, every wind farm or PV farm must be able to provide a similar voltage control capability as any conventional power plant.

However, reactive power must always be provided locally and cannot be transferred over long distances. Because wind and PV farms will be installed at different locations (e.g. Northern Cape) and at different voltage levels than conventional power plants (predominantly at 132kV), it will be required to add additional reactive power compensation equipment in areas where there will only be few conventional power plants left.

How to resolve the problem of reduced voltage control capability?

There are different types of reactive power compensation equipment available:

Mechanically switched capacitors (MSCs): An MSC is a passive component that provides a constant level of reactive power. The level of reactive power support can be controlled by switching MSCs in and out. Because capacitors introduce additional resonance frequencies, MSCs at transmission levels are usually installed in the form of MSCDNs (Mechanically Switched Capacitors with Damping Network), which avoid such negative impact.

Static Var Compensator (SVC): A SVC typically contains one or several MSCs (or MSCNDs) and a *Thyristor Controlled Reactor (TCR)*. With the help of a TCR, an SVC can provide continuous voltage control, like a conventional power plant. An SVC is still a passive component, which means that there is no active energy storage component involved. Therefore, an SVC can only provide voltage support under normal voltage conditions. In situations of low voltage, the level of reactive power that a SVC can provide decreases quadratically with voltage.

STATCOM: A *STATCOM (Static Compensator)* can provide continuous voltage control, similar to a SVC. In contrast to an SVC, a STATCOM contains a short-term storage device (capacitor, flywheel or even a small battery) and is based on a modern self-commutated power electronics converter. Because a STATCOM integrates energy storage, it represents an active component, which can deliver reactive current almost independently from voltage and can therefore be used for supporting the voltage during fault situations as well (contribution to short circuit currents).

Synchronous condenser: Voltage support can also be provided by synchronous condensers (see above). Any synchronous generator allows controlling the voltage, independent of the turbine.

The actual type of reactive power compensation device will depend on the specific application. At main transmission levels, most additional reactive compensation systems will be MSCDNs and some SVCs or STATCOMs. In Germany for example, all TSOs have invested considerably into MSCDNs in recent years. Amprion and 50 Hertz Transmission are about to install the first STATCOMs at main transmission levels (380kV and 220kV). TenneT has recently installed a (new) synchronous condenser with a capacity of +250Mvar/-170Mvar. In the U.K., National Grid plans to install a new synchronous condenser as well.

d. Reduced contribution to short circuit currents:

Synchronous machines deliver very high currents during grid faults. However, the level of current support decreases quadratically with the distance of the generator from the fault location. The delivery of short circuit currents is required for supporting the voltage during grid faults (and limiting the voltage dip to a narrow region around the fault location) and for exciting the starting characteristic of some protection relays.

Wind farms and PV farms, which are connected to the grid in-line with up-to-date Connection Conditions (like in South Africa) must contribute to short circuit currents in a similar way as synchronous generators. Sometimes, it is reported that the level of short circuit support of wind and PV farms is substantially below the level of short circuit support of synchronous generators. This is only true for close-up faults. However, when comparing the contribution to short circuit currents at remote fault locations, the level of current support from VRE and synchronous generators is very similar.

How to resolve the issue of reduced short circuit currents?

As in case of reactive power/voltage control, the problem is more related to the location of VRE than to the generator technology. In areas, in which there are only very few wind farms and PV farms, short circuit currents can indeed get quite low. However, when assuming very high penetration levels of VRE and a reasonable distribution of them, short circuit current support during grid faults shouldn’t be an issue at all (but should still be checked by stability studies).

In the case that relating problems are identified, they can be mitigated by either STATCOMs or synchronous condensers.

Summary and Conclusions

This paper discusses potential issues arising from the integration of very high shares of variable renewables (VRE) into the South African interconnected power system which could either justify annual build limits for VRE or justify the limiting of the overall penetration rates of VRE.

Grid constraints can only justify annual build limits in the very short-term. In the longer term, grid reinforcements will be required for all new generation technologies (nuclear or variable renewables). According to the TDP2014, the Cape Corridor will be substantially reinforced with two additional 765kV lines running into the Western and the Eastern Cape. Even though these lines where originally designed to accommodate nuclear power they can very well be used for exporting wind and PV generation from the Cape to the northern parts of South Africa.

In the case of very high penetration levels of wind and PV there are several potential stability issues associated with the generator technology and their distribution across the country. This paper shows, that all stability related problems in operating a power system with very high shares of VRE can be resolved with technology that is already available today. Because technical solutions do exist and because it cannot be expected that costs of these solutions will exceed the benefit of a scenario with very high share of VRE (which is in the range of several billions ZAR per year compared to other scenarios), stability issues cannot justify any limitation of the maximum penetration level of VRE.

Table 1: Stability issues and technical solutions for power systems with high penetration of VRE

Stability issue	Technical solution
Reduced inertia (frequency stability)	a) Artificial inertia b) Fast primary control c) Short-term storage (batteries, distributed pump-storage) d) Synchronous condensers (synchronous machine without turbine) e) Wind turbine technology (IEC-Type-2, synchronous generator with variable speed gearbox)
Reduced synchronizing torque (transient stability, oscillatory stability)	a) Synchronous condensers b) Wind turbines with directly coupled synchronous generator and variable speed gearbox c) PV inverters and WTGs with special control concepts
Reduced voltage control capability	a) MSCs: Mechanically switched capacitors b) SVCs: Static Var Systems (thyristor based) c) STATCOMs: Static Compensation Systems (transistor based) d) Synchronous condensers (synchronous machine without turbine)
Reduced contribution to short circuit currents	a) STATCOMs: Static Compensation Systems (transistor based) b) Synchronous condensers (synchronous machine without turbine)

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