Technical note

Instantaneous wind energy penetration in isolated electricity grids: concepts and review

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Abstract

Diesel-based electricity production is relatively expensive in small autonomous power systems which rely on fuel imports. In such systems, the introduction of renewable energy technologies can effectively reduce overall production costs, through fuel savings. However, the penetration of intermittent renewable energy sources, such as wind, into diesel-based grids is limited because of their disruptive effect on power quality and reliability. In the case of wind turbines, a high penetration requires changes in system design and management, such as grid reinforcements. The additional costs can reduce overall system performance and ultimately limit the exploitation of wind energy resources. This manuscript briefly outlines the reasons that restrict wind penetration in diesel-based electricity systems and reviews estimates and examples of autonomous and interconnected power systems.

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1. Introduction

The connection of wind turbines to an electricity grid can potentially affect supply reliability and power quality, due to the unpredictable fluctuations in wind power output. Reliability of supply can in principle be maintained through additional ramping...
duty. To estimate the increment in regulation capacity, one simply treats wind-output as a negative load in the network. However, for questions of grid stability, one must study in detail the mechanical and electro-magnetic interactions between the wind turbines and the grid.

This is why when designing wind–diesel hybrid systems it is crucial to address the balance between load and, non-dispatchable, wind generated power. In the short run (seconds time scale), the system load needs to match wind power output in order to ensure stability, whereas in the long-run (minutes time scale) the running level of the diesel plant must be adjusted for consistent power provision at lowest possible fuel use.

This manuscript briefly reviews key concepts concerning supply reliability and power quality at high wind penetration, principally focussing on medium-sized diesel-based electricity grids. The wind power penetration in a grid is the ratio of wind power–output/load at an instant in time, also known as instantaneous penetration. In contrast, energy penetration is the fraction of total load generated from wind over an extended period of time, typically a year. Clearly for a given system and observation period, the maximum instantaneous penetration will always be greater than the energy penetration.

2. Power reliability

Even in power systems based entirely on dispatchable plants, operation is continuously adjusted to secure power provision at lowest cost. The aim is to generate exactly as much power as is needed to meet a stochastic demand. For this purpose demand is decomposed into typical and variable parts, with a corresponding division of generating units into base load, load following and regulating units.

Load following units typically change their output every one or two minutes. A standard approach to determine the load following operation level and the regulating capacity is to construct a demand moving average [1,2]. Roughly, the load following plants run at moving average level (minus base load), and ramping duty is enough to cover the fluctuations around the moving average. More specifically, consider load following at 1 min time intervals. With a time window of 30 min, the moving average is:

\[ \hat{P}(t) = \sum_{j=-14}^{14} P(t + j) \]

The regulation sequence is then defined by

\[ R(t) = P(t) - \hat{P}(t) \]

Load following output is set to \( \hat{P}(t) \) — base load, which changes relatively slowly, since the fast fluctuations in \( P(t) \) are mostly in \( R(t) \). The regulating capacity is estimated by considering the statistics of \( R(t) \). This is approximately Gaussian, so most values can lie within three standard deviations of the mean. A rough division of generating capacity into load following \( C_L \) and ramping duty \( C_R \), ignoring availability
corrections, is then

\[ C_L = \max_t(\dot{P}(t)) - 3\sigma_R - \text{base load} \]

\[ C_R = 6\sigma_R \]

where \(\sigma_R\) is the standard deviation of the regulation sequence. In [1,2] the moving average method is used to analyse the joint fluctuation of wind and demand. In both cases, the ramping duty required to follow net demand oscillations is seen to be only slightly higher than without wind. For example, Persaud et al. [2] consider system variability in Northern Ireland, with a peak demand of 1543 MW and present installed capacity of 2063 MW, in the hypothetical situation in which 250 MW of wind capacity are connected to the grid. They conclude that with the extra wind plants, load following capacity could be reduced by 50 MW and ramping duty would need only increase from about 110 to about 115 MW. At higher wind penetrations, a substantial increase in regulation capacity is expected. By and large, the degree to which load following and regulating capacity need adjustment—as wind capacity on the system increases—depends on several principal aspects [3]. First, the size and type of the capacity reserve is already on the system. Second, the magnitude of aggregated wind-output and demand fluctuation. Third, the legal criteria that specify the reliability of the power system. Otherwise, energy storage and/or demand side management measures may also be a viable alternative or addition to adjusting the size of load following capacity and ramping duty (ibid).

3. Power quality

The Danish Wind Industry Association defines power quality as voltage and frequency stability, together with absence of various forms of electrical noise, such as flicker or harmonic distortion [4]. In a power supply system, voltage and frequency must be maintained near nominal values since electrical appliances are manufactured to work under the given alternate current (AC) specification. Conventional power plants fulfil two main tasks in large-scale electrical power systems: power generation and voltage control. In other words, as well as generating power for electricity consumption, they maintain power quality.

For example, at a diesel plant a voltage drop can be countered by simultaneously raising inductance and the steam input to the synchronous generator. The resulting surge in reactive power restores voltage to the desired level. In fact all voltage control devices are effectively controllable reactive power sources [5]. The flexible operation levels of thermal plants allows for a continuous control of reactive power.

Feeding intermittent power into electricity grids can affect power quality. The impact depends primarily on the degree to which the intermittent source contributes to instantaneous load (i.e. on power penetration). At low penetrations, wind farms can be connected to the grid as active power generators, with control tasks concentrated at conventional plants. Many studies agree that penetrations of up to 10–20% can be absorbed in electricity networks without adversely affecting power quality and
needing extra reserve capacity [3,6]. Key problems identified at higher penetrations are [4,7,8]:

- At wind speeds below cut-in or above furl-out, wind turbines are disconnected from the grid and left idle. When the wind speed returns to operating range, the turbines are reconnected. The sudden connection of a large turbine can result in a brownout (voltage drop incurred when instantaneous load exceeds generated power) due to the current required to magnetise the generator, often followed by a power peak when active power from the generator is fed to the network.
- There may be times when wind power output exceeds consumer load, making voltage raise above the grid threshold. Cutting off turbines to avoid the excess is not ideal in view of the reconnection problems, but also because ultimately it implies unnecessary shedding of wind energy.
- The short-term wind power variations cause voltage fluctuations in the grid, known as flicker because of their effect on light bulbs. Rapid voltage fluctuations can damage sensitive electrical equipment. In a very weak grid, even a single turbine may produce flicker.
- Harmonics produced by consumers’ electronic equipment can be magnified by wind turbine operation.

And more generally, the response of wind farms to an electrical fault may cause transient instabilities which cannot be countered by the control units in the grid. These problems have been reported mainly with reference to small-scale autonomous systems when significant wind power (> 100 kW) is connected to a low voltage grid\textsuperscript{1} [6]. Stronger grids, with a larger cross-section, have low impedance and so power variations result in smaller voltage variations. However, a sufficiently large wind farm is likely to disrupt power quality even if connected to a high-voltage transmission line.

4. Effect on diesel plant operation

In previous sections, the effect of wind power on regulation requirements was concerned with supply reliability only. For this purpose, it sufficed to consider the active power generated by a wind plant. However, to understand frequency stability in wind–diesel systems, one must also consider the reactive power of wind turbines. In such systems, the synchronous generators in dedicated diesel plants provide the main frequency control mechanism.

The AC frequency in a grid depends mainly on the inertia of the grid, the load fluctuations and the responsiveness and control system of the prime mover (diesel generators in most island/autonomous grids). The more rapidly the prime mover can respond to changing power flows, due to fluctuations in demand or in wind power output, the better the regulation of the frequency in the power system [9]. In systems with very

\textsuperscript{1} Classification of electricity grids, according to EMBRYO, Technical University of Eindhoven: high voltage (transmission network), > 50 kV; medium voltage (distribution network), > 1, < 50 kV; low voltage, < 1 kV.
high levels of wind power penetration, the prime mover may be unable to respond to the large power fluctuations and additional buffers, such as energy storage, are required to balance the system.

Therefore, it is important to consider the response time of the prime mover technology when designing hybrid power systems. Diesel engines, for instance, cannot be switched on and deliver nominal capacity output from 1 min to another but require some start up time. However, they generally respond fast to power demand surges when already running particularly at high load levels. The fuel used per kW h decreases as load level increases [10,11], except for a final increase near rated output. In addition, ensuring a minimum loading of diesel generators enables the system to rapidly respond to power changes and cuts down fuel consumption.

For example, industry data from Man B&W—a leading diesel engine manufacturer—indicates that medium-speed diesel engines in stationary power plants (sized at 4.5–10 MW) require at least 6 min to rise output to 30% of nominal capacity for a cold start, but only about 4 min to increase output from 50 to 100% if the engine was already running [12]. When the diesel engine is running at 80% of rated capacity, generating efficiency is 10% higher than at 50% of rated capacity.

In Cape Verde, for instance, the electricity company adopted a conservative operating strategy, keeping a technical minimum load on the diesel engines of no less than 30%. In this way, it ensures both sufficient spinning reserve and acceptable operation conditions for the diesel engines, albeit high wind energy penetration levels [13].

In medium-scale diesel-based power systems with intermittent RETs rapid response power plants (i.e. being able to adjust power output within seconds to significant power increases or decreases) can improve the ability for load following and regulating power. Therefore, higher levels of instantaneous wind penetration can be supported if more flexible and rapid response power plants, such as open-cycle gas fire plants or hydropower reserve, are part of a system’s plant portfolio.

5. Wind penetration standards

In view of the above it can be inferred that the amount of wind power that can be absorbed by the grid depends very much on the characteristics of the power system itself. Gonzalez et al. [14] put it as follows:

“The boundary between low and high penetration may be set at the wind energy capacity that can be assimilated without major problems. As the wind capacity rises, changes in operation [and design] of the electric system are necessary.”

Research institutes and regulating bodies base their recommendations on the track record of wind turbine installations till present. In modern European grids, for instance, numerous assessments have shown that no technical problems are likely to occur by allowing wind capacities up to an instantaneous penetration of 10–20% [3,15].

With respect to autonomous grids based on diesel engines, a report by Risø National Laboratory estimates the maximum instantaneous power penetration from wind turbines (single or in clusters) to be in the area of 25–50% [16]. However, the report notes that
the feasibility of high wind energy penetration decreases dramatically as the size of the power system increases to 100–10 MW—principally because storage is urgently needed at high penetration levels and because managers of large systems face higher power quality requirements. For even larger autonomous systems, Risø suggests a penetration limit in the range of 25–35%.

Similarly, the National Renewable Energy Laboratory (NREL) concludes that a low penetration of wind turbines (\(<20\%\) energy penetration and \(<50\%\) power penetration) is likely to have only a minimal impact on diesel plant operation. The control components required to maintain power quality are minimal [17]. In contrast, high penetration systems (\(>50\%\) energy penetration and \(>100\%\) power penetration) usually require energy storage to use wind energy effectively. In addition, substantial control components, such as a synchronous condenser and power converters, may be needed to regulate system voltage and frequency. However, measures to increase the penetration of instantaneous wind power come at a cost. Therefore, the degree to which penetration can be raised depends on the cost-effectiveness of these measures.

In western Denmark, for instance, a wind power penetration of about 50% has been achieved through a combination of grid reinforcement and the use of energy buffers [15]. The technical cost penalties in Denmark to allow for such high instantaneous penetrations without adversely affecting quality and reliability of supply is estimated at approximately £1.75/MW h [3]. Energy buffers in Denmark are provided by interconnections to neighbouring electricity grids, such as Norway, Germany and Sweden, which serve as back up in case of rapidly declining wind energy output. However, interconnectivity—a key strategy in Denmark’s energy policy—is clearly unavailable in isolated power systems.

In the absence of interconnection—as is the case for autonomous systems—some utilities have set an upper limit on wind power penetration as a practical response to power quality issues. In autonomous island grids of Greece, which are predominantly based on diesel engines, the Public Power Corporation limits wind farms to contribute not more than approximately 30% of instantaneous load [8].

Similarly, Ireland’s Electricity Supply Board (ESB) suggested that wind power levels should be limited to 30% of instantaneous load during daytime, with possibly a higher contribution at nights [14]. At the end of 2003, the Commission for Energy Regulation (CER) of Ireland reacted to a request from the ESB. It spelled out a moratorium on additional grid connected wind turbines in order to prevent possible problems regarding the reliability of power quality and supply until the effect of further intermittent power technologies on the system was better understood [18,19].

6. Examples

A few examples of medium-sized autonomous wind–diesel power systems show that, at present, instantaneous penetration of wind power has yet not exceeded 40% over longer time periods. Although in some cases this limit is self-imposed rather than equating to the possible technical limit, it is far higher than in larger grids of industrialised countries.
Small and medium-sized autonomous grids have characteristics that may make the limitation of instantaneous wind penetration more immediate. Geographical dispersion of wind turbines tends to flatten the combined wind power output due to different wind speeds at different locations. This results in a more steady wind power output and hence reduces the need for control measures otherwise needed under more erratic wind power output regimes. Due to the limited terrestrial size of autonomous power systems, the effect of geographic dispersion is, of course, somewhat limited and may result in higher penetration levels sooner than in comparison to hybrid power systems with dispersed wind farms.

6.1. Cap Verde

Situated in the Atlantic Ocean, Cap Verde has very good wind energy resources and wind turbines have been gradually phased in since the 1980s. A stepwise development approach has been favoured over a sudden introduction of high penetration levels to allow for necessary institution building and, mainly, to ensure reliable power system operation. Hansen [20] analysed the operation of three wind farms on the islands of Praia, Mindelo and Sal with installed capacities of 900, 900 and 600 kW, respectively. Penetration levels of up to 35% were recorded in some months, although a steady state increase of electricity demand has somewhat reduced wind penetration. Wind farm control was manually exercised by the diesel plant operators and no special wind farm control systems were used, apart from those inherent to the turbines. While some wind capacity need to be shut down at times of high wind speed, no serious technical problems were encountered upon disconnection or reconnection. Hansen concluded that from an economic point of view, more wind capacity should be installed but, given the limited international experience at high instantaneous penetration levels, the project risk may seem too high for investors.

6.2. Ten Mile Lagoon, Australia

Western Power operates several isolated regional power stations and networks in Western Australia. Their Ten Mile Lagoon wind farm consists of nine 225 kW variable speed wind turbines feeding into the regional 33 kV Esperance grid network. They contribute to about 10% of annual energy demand [21]. This wind farm is one of the few examples of middle-sized wind systems, which reach high penetration without use of energy storage. The wind park has a simple control system, which monitors instantaneous wind penetration and keeps it below 40%. It does so by either turning off individual turbines or ‘feathering’ the blades via remote radio control from the local diesel power station [11]. Under test conditions, power penetration has reached 60% without adverse effects on system stability. However, stability at such penetration levels is not guaranteed, as fluctuations in the wind plant power output and turbine reactive power are large relative to the inertia in the grid.

6.3. Crete, Greece

Since 1994 the region of Crete has adopted an energy policy with an emphasis on utilisation of renewable energy sources. By 2000, installed wind capacity was
approximately 67 MW and another 50 MW had been approved for construction. In 2000, wind energy contributed roughly 10% of electricity demand, which means a significant reduction in fuel costs and greenhouse gas emissions. Peak power penetration from wind farms was recorded at nearly 40% [22].

7. Towards dispatchable wind power

As discussed above, power quality requirements can constrain the use of wind turbines. To overcome this constraint, many researchers are now working to develop wind plants with control capabilities. Using dynamic models of wind plant/grid interaction, a base penetration limit could be calculated for a given grid and different solutions with higher penetration tested [7, 23]. For example, models confirm that, while passive stall turbines cannot restore voltage and frequency after a fault, variable speed turbines (e.g. blade angle control) allow for a swift recovery to nominal values [5, 24].

The different options to increase wind penetration can be grouped into [7, 14]:

- **Grid reinforcement.** Usually done by building a new line parallel to the existing line or by upgrading to higher voltage specifications. Although this can be costly, it may be a good option in areas where industrial development requires a higher capacity grid.
- **Grid voltage-controlled wind power production.** For example, the reactive/active power spike during reconnection can be avoided by using thyristors that connect the turbines gradually to the grid [4]. In [25] a wind–diesel system with voltage-controlled switches achieves periods of 100% wind penetration, while maintaining voltage stability. Using variable speed turbines with intelligent control equipment allows continuous control over the plant output.
- **Inclusion of storage as a wind-output buffer.** Wind power output beyond the technical instantaneous penetration limit can only increase the energy penetration from wind by harvesting the output at times of excess and redistribution at times of scarcity. Storage technologies may therefore have a role to play in increasing the contribution from intermittent RETs.
- **Wind velocity forecasting.** Forecasting wind speeds can provide important advantages in term of increasing the penetration of wind energy, as well as obtaining the best market price in liberalised markets [26]. Reliable estimation of wind speed probabilities—for hours or even days in advance—allows improved dispatch and operating rules for load following plants and ramping duty. This in turn eases load following and voltage control at higher penetrations of wind power.

8. Conclusion

High wind penetrations in autonomous wind–diesel power systems pose a threat to power quality. Different grids can absorb different levels of wind, depending on factors such as turbine type, grid strength and prime mover (e.g. diesel generator) responsiveness. For medium-scale systems, power penetrations of up to 30–40% are successfully in
operation without the need for special control measures. Long-term experience with penetration levels above 40% in autonomous and medium-scale grids have not been reported in the available literature.

However, as power control concepts mature the limit on penetration may become less stringent. For certain wind turbine installations, it is already the case that the cost of power control is paid back as added wind energy capacity value [7].

In parallel to control technologies, forecasting and strategic planning are crucial to increase overall wind penetration. Reliable short-term wind forecasting permits a more efficient unit commitment and dispatch. In particular, it improves the operational management of the prime mover technology. A lot can be gained from considering entire power systems, for then geographical dispersion and interconnectivity serve as energy buffers. In Denmark’s case, this has been crucial for its successful use of wind resources. The European project MORE CARE works on producing energy management software specifically dedicated to increase the use of renewables in isolated and weakly interconnected power systems.

Case studies in [16] indicate that storage is a key component in small autonomous systems with very high wind energy penetrations, i.e. with minimal use of diesel. More generally, energy storage is believed to be an essential component in renewable dominated electricity systems, irrespective of size—although such systems may not be cost-effective given the presently high cost of utility-scale energy storage and release technologies. However, as conventional plants are phased out, power-quality will have to be controlled by other units in the network. Ideally energy storage technologies with good ‘control skills’ are needed.

References


