Electrical Power Quality & Utilization Magazine
Volume 3, Issue 2

Leonardo ENERGY

Grid Connection Requirements for Wind Turbine Systems in selected Countries - Comparison to Turkey

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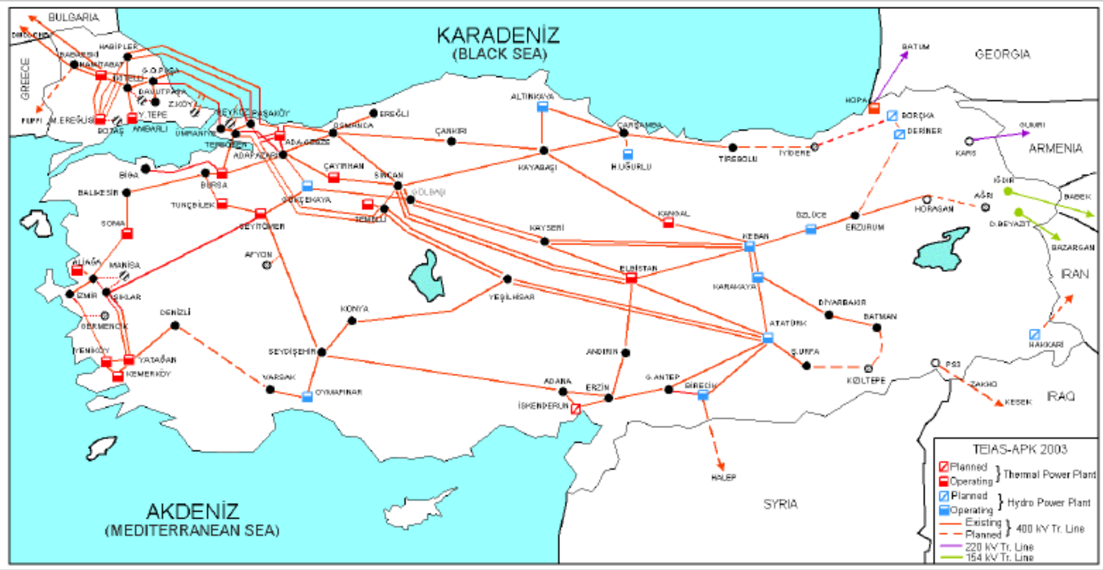
Available online June 2008



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Abstract

The aim of this paper is to review the connection requirements of wind farms to the grid and how grid codes must be adapted in order to integrate wind power generation capacity without affecting the quality and stability of the electricity system. This paper also summarizes the grid codes that have already been modified to incorporate high levels of wind power. Grid connection requirements in selected countries such as Denmark, Germany, Netherlands and Turkey are investigated in detail.

Introduction

During the last decade, wind energy has developed fast in the world but especially in Europe because of subsidies and tax allowances for private investors in wind farms. As the amount of wind power connected to the grid increases, the electricity system has started to change in countries such as Denmark, Germany, and other regions in the world. The number of medium and large wind farms (greater than 50MW) connected to the high voltage transmission system is likely to increase dramatically, especially with offshore wind farms. Wind power is expected to be an important contributor to power generation. Denmark has 20% of its generation capacity supplied by wind power and expects to reach a level of 50% penetration thanks to strong grid connections with Norway, Germany and Sweden. The situation is similar in other countries and regions such as Schlesswig-Holstein in Germany, Navarra and Galicia in Spain. The growth in medium and large size wind farms has reached the point in Denmark where they have a major impact on the characteristics of the transmission system and under conditions of low load and high wind speed, close to 100% of power may be generated by wind [1].

Wind Turbine Technology

Wind turbine generating systems (WTGS) can be divided into two main categories: fixed speed and variable speed. A fixed-speed WTGS generally uses a Squirrel Cage Induction Generator (SCIG) to convert the mechanical energy from the wind turbine into electrical energy. The fixed speed SCIG consumes reactive power and cannot contribute to voltage control. Therefore, wind farms with this type of generators use static capacitor banks to provide reactive power. Variable-speed WTGS can offer increased efficiency in capturing the energy from wind over a wider range of wind speeds, along with better power quality and the ability to regulate the power factor, by either consuming or producing reactive power.

There are two main types of variable speed wind turbines: Doubly Fed Induction Generator (DFIG) and Synchronous Generator (SG).

The variable speed wind turbine with DFIG can be controlled to provide frequency and voltage control with a back-to-back converter in the rotor. Control software upgrade and hardware modifications are necessary. More precisely; the converter ratings may have to be increased for frequency response. This type of generator has some difficulties to ride-through voltage dips, because voltage dips generate high voltages and currents in the rotor circuit and the power converter could be damaged. This is the most extended variable speed wind turbine technology and manufacturers already offer this type of wind turbines with fault ride-through capabilities.

The variable speed wind turbine with SG is connected through a back to-back converter to the grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride-through capability during voltage dips. Again, only control software upgrade and minor hardware modifications are necessary to contribute to the system stability [1, 2].

Requirements Wind Farm Connections to the Grid

If wind farms would be installed solely to maximize energy output, they would have major limitations in terms of:

1. Power Control and Frequency Range.
2. Power Factor and Voltage Control
3. Transient Fault Behavior, Voltage Operating Range

These are the three main issues that new grid codes must address for wind farm connection. The most worrying problem that wind farms must face is a voltage dip in the grid. The effects of transient faults may propagate over very large geographical areas and the disconnection of wind farms under fault conditions could pose a serious threat to network security and security of supply because a great amount of wind power could be disconnected simultaneously.

Grid Connection Requirements in selected Countries

In this section, present grid connection requirements in selected countries such as Germany, Denmark, Netherlands and Turkey. Grid connection requirements in wind turbines are evaluated according to three categories for every country.

Germany

The interconnected German transmission system is operated by different companies. These transmission network operators, first of all E.ON, issued grid requirements on wind turbine connection and operation on the grid. VE-T published a grid code in a single document which addresses renewable energy systems together with conventional power plants. E.ON consolidated its grid requirements also in one grid code. At the same time, the association of German transmission grid operators, VDN, summarized special requirements concerning renewable energy sources operating on the high voltage network in a document as an appendix to the existing general grid codes [3,4]. The transient fault behavior is divided mainly two categories: one for generators with big contribution to the fault current at the grid connection requirement (GCR) i.e. fault current is at least two times nominal current for at least 150 ms, and one for generators where the fault current contribution is less than that[4].

Power Control and Frequency Range

It must be possible to limit the active power output from every operating point as a percentage of the nominal power. For power reduction a ramp rate of at least 10% of nominal power per minute must be possible. If power is ramped down, this must not imply disconnection of single turbines from the grid. In the wake of loss of grid voltage, power has to be ramped up with a gradient of not more than 10% of nominal power per minute. This ramp can be realized in steps (reconnection of single wind turbines), if the step size does not exceed 10% of nominal power per minute [4]. The frequency range wind turbines have to tolerate is about 47.5-51.5 Hz. According to the requirements of German transmission grid operators, large wind farms have to be treated in the future like conventional power plants [3].

Power Factor and Voltage Control

It has to be possible to operate wind farms with nominal power of less than 100 MW with power factor between 0.95 lagging and 0.95 leading. The required power factor values are always applied at the grid connection point. Wind farms rated 100 MW or more have to be able to operate at power factor between 0.925 lagging and 0.95 leading. The power factor range is however limited depending on the grid voltage to avoid leading power factor at grid voltages below nominal. Generators with small fault current contribution are required to support grid voltage in case of faults by supplying reactive power proportional to the voltage drop. Between 10% and 50% voltage drop the generators have to supply reactive current between 10% and 100% rated current, linearly proportional to the voltage. Generators with big fault current contribution, on the other hand, are not required to contribute to voltage support during transient faults [4].

Transient Fault Behavior and Voltage Operating Range

Wind farms require connection to the 400 kV high voltage network and must be treated like conventional power plants. For increased wind exploitation, the new wind farms will be equipped with 3-5 MW generators. New technical solutions are also required for connecting large wind farms at a distance of 100-200 km offshore to the mainland. Today, wind farm may already lead to overloads in the 110 kV network. Therefore, further increase of wind power utilization requires investment in network infrastructure. Also the high voltage 220/400 kV network is not designed for transmission of wind power from the north to the south. Therefore, German transmission grid operators are conducting comprehensive studies for identifying the necessary network measures and operational requirements to meet future challenges [4]. If the grid voltage at the connection point of the wind farm falls quasi-stationary (i.e. voltage does not change faster than 5% per minute) below 80% of the value before the voltage dip, disconnection must happen at the earliest after 3 seconds and has to happen within 5 seconds. A 3-phase short circuit in the transmission system close to the connection point, with a fault clearance time of 150 ms, must not lead to instability or disconnection of the generator, provided that the short circuit ratio of the grid is larger than 6 after the fault clearance. If the short circuit ratio is less, a shorter fault clearance time can be agreed on. This requirement applies irrespective of the operating point prior to the fault. Furthermore it is required that dynamic effects in the wake of transient faults, which might cause longer lasting voltage dips must not lead to a disconnection of the generator. Generators with small fault current contribution also have to fulfill requirements concerning power ramp rates after faults. Generally applies that after fault clearance power output has to be ramped up with at least 20% nominal power per second, unless the voltage recovers only slowly. If the conditions for slow voltage recovery (which will not be outlined in detail here) are fulfilled, power may be ramped up with 5% nominal power per second. It can be agreed on that the generator may shortly disconnect if the voltage behaves such that a power ramp of 5% nominal power per second would be justified. In this case the generator has to resynchronize no later than 2 seconds after the fault clearance and power output has to ramp up with at least 10% nominal power per second[4].

Denmark

The transmission network has historically been administered by two independent transmission system operators (TSOs): Eltra in the West, and Elkraft in the East. In 2005, these merged to form the new state-owned operator, Energinet Denmark which also oversees operation of the gas network. The two separate TSOs arose because their respective networks were geographically and electrically separate from each other as Fig. 1 shows [5].

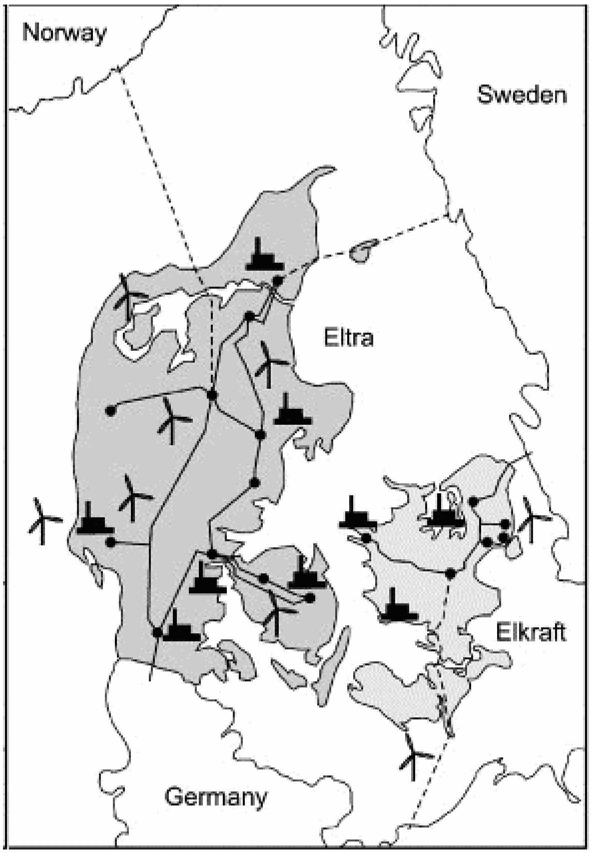

Fig1- Map of the Danish electrical networks, interconnections

While not directly connected, both are interconnected to neighboring countries. Western Denmark is synchronized by the UCTE system with Germany and has 1670 MW of DC links with Norway and Sweden. Eastern Denmark is part of the NordPool market and is connected synchronously to Sweden and asynchronously to Germany. While the physical transfer capability is significant, there are operational limits of 800 MW to the North and 1300 MW to the South because of congestion on their neighbor's grid [5].

Power Control and Frequency Range

Controlled limitation of active power is demanded to limit the reactive power demand of wind farms after a fault. In addition, power limitation is demanded to ensure supply and demand balance if a part of Denmark becomes an island due to a fault. It must be possible to reduce power to less than 20% of nominal power within less than 2 seconds. This corresponds to a ramp rate of 40% of rated power per second. In a transient fault situation the full power decrease and a subsequent power increase must be possible within approximately 30 seconds. Normal operation between 49 and 50.3 Hz is required. Beyond the outer limits of 47 and 53 Hz the turbines have to disconnect within 300 ms. Frequency control is not required [5].

Power Factor and Voltage Control

Wind farms are required to have sufficient reactive power compensation to be neutral in reactive power at any operating point. This requirement has to be fulfilled at the grid connection point. In the 150 kV system, steady state operation has to be possible under full load in the voltage range between 0.95 pu and 1.13 pu. In the 400 kV system the voltage range is narrower, hence less onerous for generators to cope with. If the voltage reaches 1.2pu at the grid connection point (irrespective of the voltage level) the wind farm has to start performing voltage reduction within 100ms of detection. Voltage reduction can be achieved by switching in reactors to increase the reactive power demand of the wind farm [4].

Transient Fault Behavior and Voltage Operating Range

No specific voltage operating ranges and respective trip times in transient fault situations are specified in these GCR. Simulations of specific grid topologies and wind farms have to be carried out in order to determine voltage values likely to occur at the wind turbines terminals. It is stated however that these requirements do not apply to radial connected wind farms, where a fault would isolate the wind farm, i.e. wind farms don’t need to ride through faults whose clearance would open-circuit the wind farms’ terminals. Under such circumstances the wind farms may disconnect. Wind farms have to stay connected and stable under permanent 3-phase faults on any arbitrary line or transformer and under transient 2-phase fault (unsuccessful auto-reclosure) on any arbitrary line. In the wake of a fault the voltage can be down to 70% of the initial voltage for duration of up to 10 seconds, which must not lead to instability of the wind farm. The controllability of the wind farm must be sustained for up to 3 faults within 2 minutes, or for up to 6 faults if the delay between the faults is 5 minutes; each fault happening during steady state operation. This requirement makes sure that the turbines are fitted with sufficient auxiliary power supplies. When the voltage directly after a fault falls below 60- 80% for longer than 2-10 seconds, it is likely that the turbines have accelerated so much, that the grid cannot get them back to normal speed. In such a case, a fast reduction of the active power and a fast increase of reactive power have to be conducted. If this does not successfully re-establish the grid voltage, the wind farm has to be disconnected [4].

Netherlands

It is possible to classify the Dutch transmission system as networks at 380, 220, 150 and 10 kV. Here the networks at 380kV and 220kV serve a transmission function, while the networks at 150kV and 10kV are regarded as having more a sub-transmission function. A ring at the 380 kV voltage level constitutes the main structure with several radial branches in Fig. 2[6].

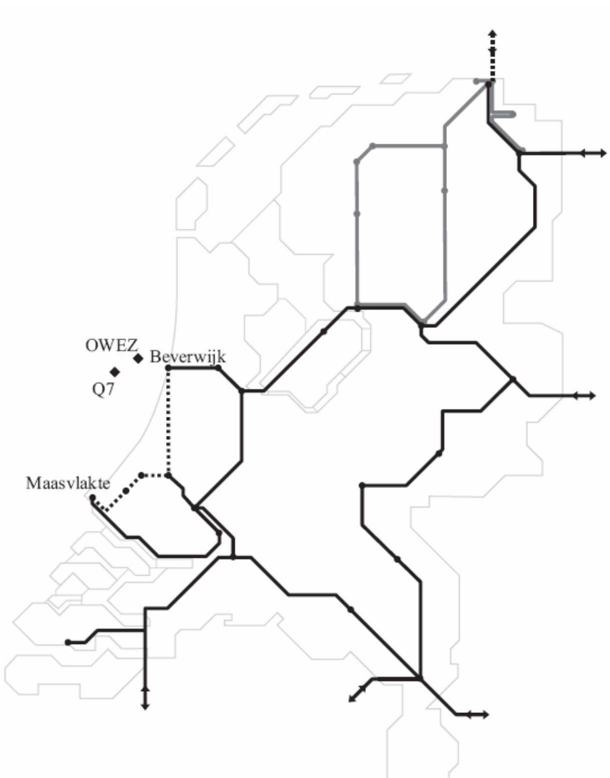

Fig. 2 A ring at the 380 kV voltage level with several radial branches

In the Northern part of the country, there is a similar ring structure exists at 20 kV level. On the other hand, in the Randstad, a second and third 380 kV ring structure are envisaged to fulfill demands to ensure the security of supply [4]. The 380 and 20 kV grids are operated by the transmission system operator (TSO) TenneT which is fully owned by the State of the Netherlands. The regional sub-transmission and distribution grids are operated by regional distribution system operators (DSOs).

The neighboring countries Germany and Belgium are connected to the transmission grid through five interconnections at 380 kV. At the Dutch- German border in Meeden, phase shifting transformers have been established in order to regulate through cross-border flows. In addition the Norway power systems will connect with high-voltage direct current (HVDC) in near future. Therefore, this will contribute the generation technology market. Furthermore, a similar HVDC connection study is in progress. A HVDC interconnected with a rating of 70MW (NorNed) is to be commissioned late 2007 that will connect the Dutch power system to Norway. This will make the advantageous differences mix available to the market. Another HVDC link to England is in the study phase. For the grid connection alternatives investigated it was concluded that individual connections at a voltage level of about 150 kV are the most cost-effective (Fig. 3), but it might be attractive to combine some wind farms on one 380 kV cable to the shore (Fig. 4). Interestingly, these options also offer the most flexibility with regard to a phased development of offshore wind power and corresponding investments, as is highly desired by the government [6].

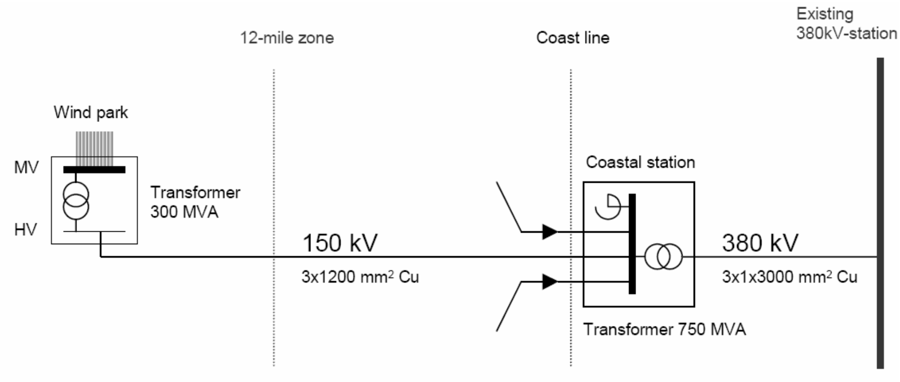

Fig-3 Individual wind farm connections in Netherlands

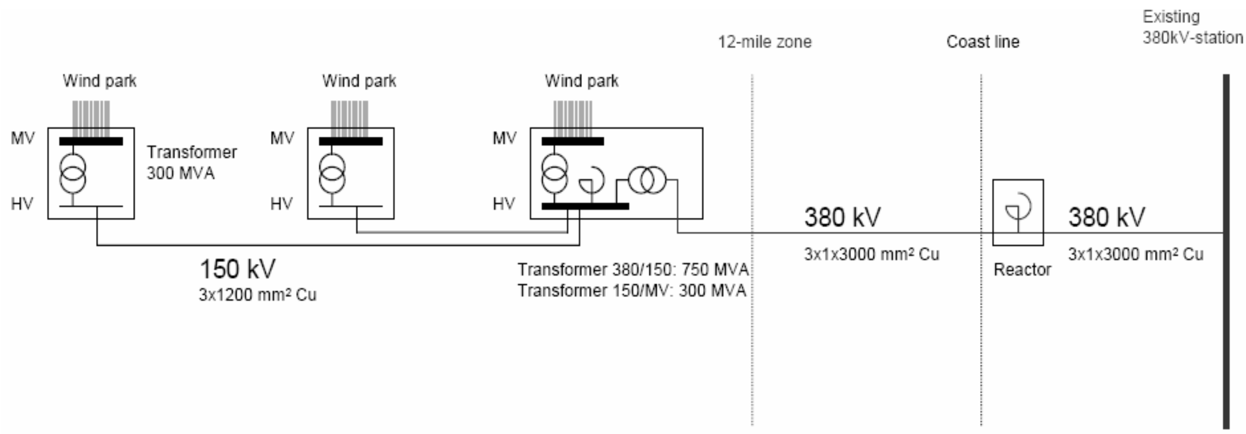

Fig-4 Combined wind farm connections in Netherlands

The respective TSO for each control zone (most control zones coincide with country borders) is responsible for power system balancing in the UCTE interconnected system. Energy transactions between control zones are not used for balancing. Therefore, the physical size of the balancing market is constrained to the control zone. For wind power, organization of the interconnected system in larger zones would be beneficial, since the amount of regulating capacity available for balancing would increase [6].

Power Control and Frequency Range

In the Netherlands, generation based on intermittent sources of energy (i.e. wind and solar power) are exempted from the obligation to supply primary reserves. Neither do they neither have to offer any capacity as reserve power or regulating power to the Dutch TSO nor provide reactive power compensation (Dutch Grid Code 2.5.1.4 and Dutch System Code 2.4.1.7). Important issues include the desired behavior in case of a voltage dip (the so-called fault ride-through behavior), the contribution to the primary response and the supply of reactive power [6].

Power Factor and Voltage Control

Local impacts of wind turbines connected to the distribution system mainly depend on local grid conditions and connected wind turbine type, and the effects become less noticeable when the (electrical) distance from the origin increases. The observed phenomena include changed branch flows, altered voltage levels, increased fault current, and the risk of electrical islanding, which all complicate system protection, and cause power quality problems, such as voltage levels, harmonics and flicker. Wind farms are required to have sufficient reactive power compensation to be neutral in reactive power at any operating point. In the early days of wind power in the Netherlands (1970–1990) mainly small projects of one or several wind turbines have been constructed, connected to the local distribution grid, usually at 10 kV. The turbines in those days chiefly comprised fixed-speed designs with synchronous generators or squirrel cage induction generators, with a rigid grid connection. In the case of asynchronous generators, capacitor banks have often been applied to achieve a power factor close to unity. Nowadays, wind turbines are equipped with versatile power electronics that, if controlled correctly, can mitigate most power quality problems [6].

Transient Fault Behavior and Voltage Operating Range

There are no specific regulations for the fault ride through behavior of wind turbine generators. Formally, all production units, including renewable, are required to remain connected to the grid for the first 30 ms independent of the dip depth or shorter if the calculated critical clearing time dictates otherwise. For voltage dips with a post-fault voltage> 0.8pu, production units should remain connected at all times (Dutch System Code 2.1.16). In practice, the grid operator and the wind power developer agree on this in the design stage according to the technical possibilities and local circumstances [6].

Turkey

Wind energy generating capacity was installed in Turkey in 2005, 2006, and in the first half of 2007, reaching 20, 51 and 131.35MW, respectively. Theoretically, Turkey has 160TWh a year of wind potential, which is about twice as much as the current electricity consumption of Turkey. The installed capacity of Turkey's wind energy has increased from 9MW in 1998 to 19MW in 2001. First half of 2007, it has reached 131,35MW. But the installed wind energy capacity is still very small. Actually, Turkey wind energy potential is high, although commercial wind energy is new [7,8]. Turkey has connected its electricity grid to neighboring countries from which it buys and sells electricity, even though the Turkish system is not set up for synchronous operations with the other countries. The connections are as follows:

- Azerbaijan (34.5kV and 154 kV)
- Armenia (220 kV)
- Bulgaria (400 kV)
- Georgia (220 kV)
- Iran (154 kV)
- Iraq (400 kV)
- Syria (66 kV)

Turkey also has plans for 400 kV connections with Greece, Iran, Iraq, and Syria. Map of the Electric Power Network of Turkey is shown fig-5[9].

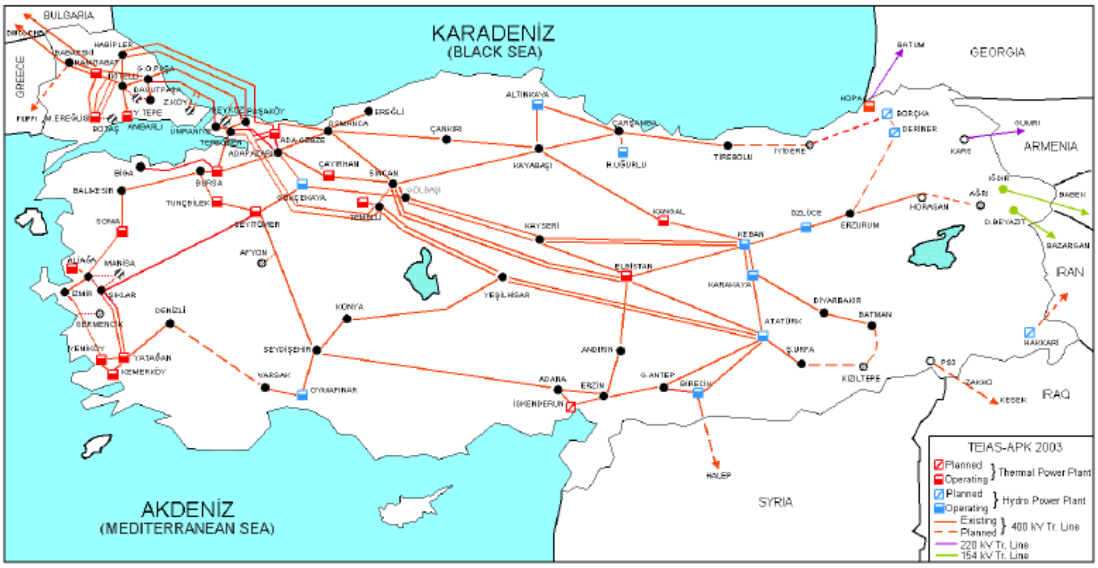

Fig-5 Map of the Electric Power Network of Turkey

There are no specific regulations for wind energy conversion systems connecting to the national grid in Turkey.

Power Control and Frequency Range

At a connection point, the installed power of the wind turbine generating system, which is at most 5% of the short circuit power of the national grid is allowed to connect. By considering the feature that wind turbine generating systems are automatically disabled when wind speed exceeds a given limit, wind turbine generating system is allowed to connect to national grid at the installed power which does not exceed alternative auxiliary power capacity in order to avoid instantaneous voltage variations and frequency fluctuations. System Nominal frequency is controlled by TEIAS at about 50 Hertz (Hz), in the range of 49.8 – 50.2 Hz [9].

Power Factor and Voltage Control

For the purpose of limiting the disturbances conveyed to the system by production plants based on wind energy, power factor of the production plant having asynchronous wind turbine based on wind energy, can not be below 0,99. The power factor can be increased by the suitable compensation foundations [9].

Transient Fault Behavior and Voltage Operating Range

Nominal voltages of the system are 380 kV, 154 kV and 66 kV. Planned voltage limits before failure are between 370kV and 420kV for 380kV transmission system, between 146 kV and 162 kV for 154 kV and between 62 kV and 70 kV for 66 kV. In the locations not having a 380kV system, the limit is assumed to be between 140kV and 170kV for 154kV.

Table-1 Reducing power transformers in interconnected grid and their properties

Operating Voltage (kV)	Transformer Power		Parallel operating of two same power transformer	Number of short circuits in secondary side (kA)	Impedance		No load turn ration and voltage regulation
	ONAN	ONAF			(%uk)	Base power (MVA)	
34.5 31.5	80	100	No	<16	12	100	154kV±12x1.25% /33.6kV
	50	62.5	Yes	<16	12	62.5	154kV±12x1.25% /33.6kV
	25	31.25	Yes	<16	12	31.25	154kV±12x1.25% /33.6kV
15.8	50	62.5	No	<16	16	50	154kV±12x1.25% /16.5kV
	25	31.25	No	<16	12	26	154kV±12x1.25% /16.5kV
	16	20	Yes	<16	12	16	154kV±12x1.25% /16.5kV
10.5	50	62.5	No	<16	17	50	154kV±12x1.25% /11.1kV
	25	31.25	No	<16	12	25	154kV±12x1.25% /11.1kV
6.3	25	31.25	No	<16	15	25	154kV±12x1.25% /6.6kV
	16	20	No	<16	12	16	154kV±12x1.25% /6.6kV

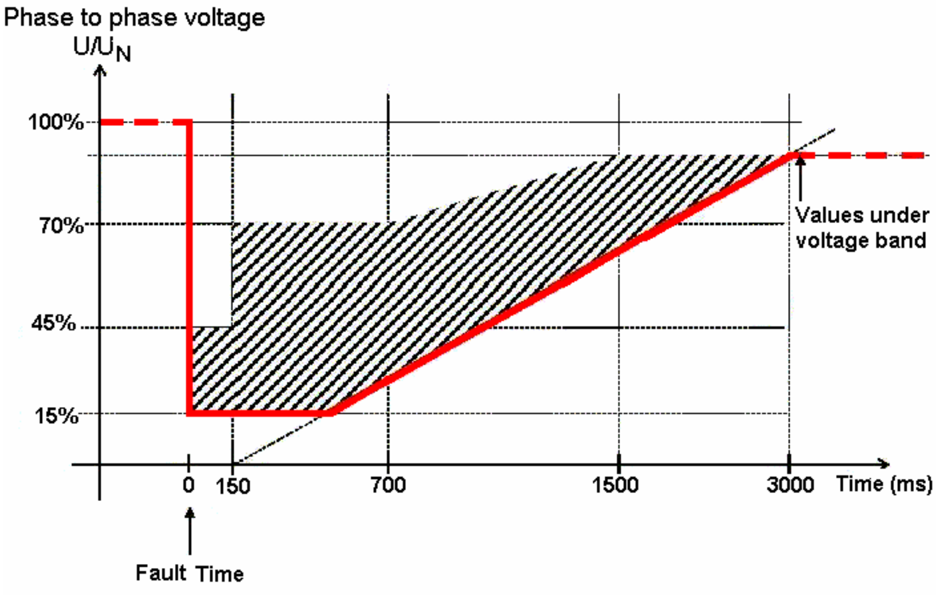

Fig-6 Failure and after failure performance of the production plants based on wind energy

The voltage level is increased from 380kV to 420kV since the beginning date of synchronous parallel operation with UCTE system. Reducing power transformers in interconnected grid and their properties can be seen in Table-1[9].Failure and after failure performance of the production foundations based on wind energy, should be within the limits shown in the graph in Fig-6.

CONCLUSION

In this study, the connection requirements of wind farms to the grid are reviewed. The grid connection requirements in some countries such as Denmark, Germany Netherlands and Turkey are investigated in detail concerning power control, frequency range, transient fault behavior, voltage operating range, power factor and voltage control.

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