Grid Integration of Large Capacity Wind Power: A Review.

Joseph N. Mathenge [1], D.K Murage [2], J.N Nderu [3] and C.M Muriithi [4]

Abstract— Since the adoption of the Kyoto Protocol in 1997, the world has inclined towards the integration of renewable energy sources into the grid with the aim of reducing carbon emissions in the environment. Developed and developing countries have continued investing millions of dollars into research and deployment of renewables and this has sparked a huge interest in this field by researchers aiming to streamline and make this technology efficient. Initially, renewables were adopted in small quantities posing negligible threat to the security and running of power systems. However, over the last two decades, there has been a huge interest in large capacity integration of renewable energy sources. The disadvantage of this is that some of the renewables have a stochastic nature which makes their integration pose challenges to the wider grid. These stochastic renewables include solar and wind. Between the two, wind is the most intermittent yet the most widely adopted renewable. This paper reviews the integration of large scale wind power – the present, the future and challenges being faced.

Keywords—Large capacity, Renewable Energy, Wind Power.

I. INTRODUCTION

RENEWABLE energy sources are the interest of most if not all power systems across the world. The fact that they occur freely in nature gives them an edge over other sources since they do not have any running costs associated with them. The prices of fossil fuels are subject to forces of supply and demand as well as world politics. This makes the per-unit cost of power from fossil fuels volatile in nature [1]. Renewable energy sources incur a zero fuel cost and hence make them cheaper than fossil fuels. Other than the capital cost of installation of the technology, there are minimal running costs associated making them an attractive option.

Wind and solar have one disadvantage associated with them – they occur intermittently in nature. This natural variability makes it difficult to integrate the two sources with the grid and is referred to as non-dispatchability. Despite the fact that solar and wind have both seen considerable interest from researchers and power system operators, it is wind that has been mostly deployed in large capacity plants. Wind technology has matured to great extents in the last two decades and as the wind power plants continue to be deployed in present day grids, the issue of power system security becomes one of great concern that requires deep planning and evaluation [2].

This, however, has not discouraged the use of renewables in the grid. Despite the fact that China has substantial fossil fuel resources, it comes out as the country with the most ambitious wind and solar power targets in the world. China aims to have between 150GW -180GW of installed wind capacity by 2020. Developing countries have not been left behind either in this expansion and have been observed to be expanding their renewable energy demand at a rate of 3.5% per annum since 2009 [1]. For renewable energy to achieve better penetration and be adopted by many power systems, the government need to play a pivotal role in ensuring the adoption of this technology [3]. This happens in the form of legislation, encouraging feed in tariffs, tax credits and the development of smart grids. The result of adoption of renewable energy sources results in cheaper power tariffs, reduction of the global carbon footprint associated with power generation, and meeting the growing energy demand in the world among other benefits.

II. REVIEW

A. Wind Power Generation

Wing turbine generators harness wind power and convert it to electricity using an aerodynamic rotor. Wind acts as the prime-mover in this system of generation. Figure.1. below shows the structure of a wind turbine generator:

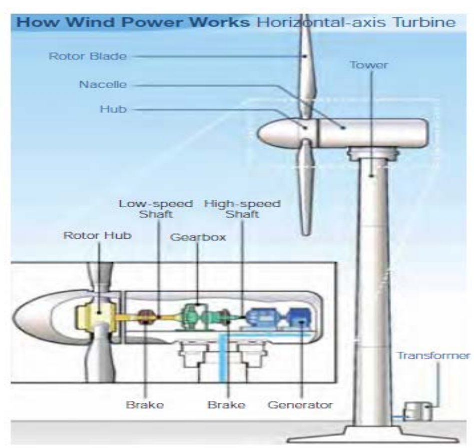

Fig. 1. A wind turbine generator [1].

Wind energy can be harnessed in two categories:

i. Onshore
ii. Offshore

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Wind turbine technologies have seen the development of turbines with a capacity of 1.5MW – 3 MW for the onshore harnessing and 2MW – 5 MW for offshore. Larger versions of wind turbines are in the range of 5MW to 6MW. Offshore winds are more uniform and stronger than the onshore winds and hence more power can be obtained from them. However, offshore wind power harnessing involves a more complex installation system and thus not much work has been done on it. Typically, a wind power curve has three speeds: The cut in speed, the rated speed and a cut out speed [4]. The turbine begins working at the cut in speed, achieves maximum power output at the rated speed and stops working at the cut out speed to prevent the turbine from getting damaged [5].

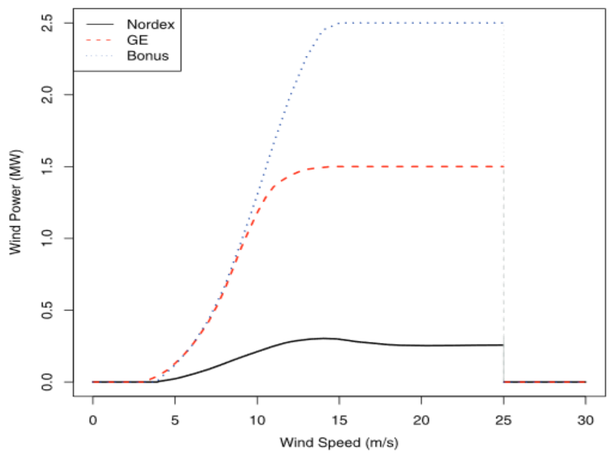

Fig. 2. Deterministic Power Curve Showing Cut-in Speed, Rated Speed and Cut-out Speed for Turbines with Capacities 0.3MW-Nordex, 1.5MW-GE and 2.5MW-Bonus.

Single wind turbine generators are limited in capacity and hence they are aggregated to form wind farms whose output now becomes considerable compared to the other sources in the grid. Their power is collated and injected into the grid as power from a single source [1].

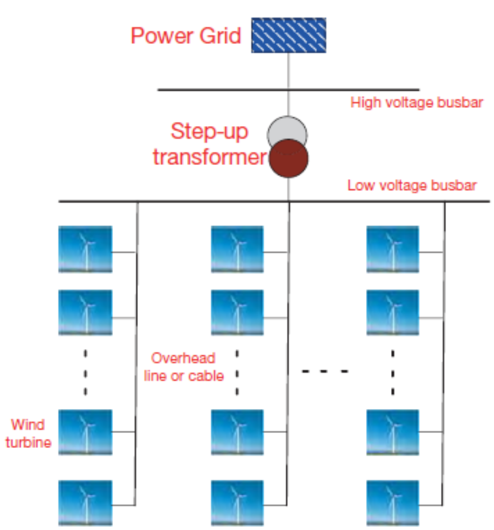

Fig. 3. Structure of a wind farm [1].

B. Wind Energy Conversion Systems (WECS)

There are four WECS: Type I, II, III and IV [5]

Type I: Fixed Speed Induction Generator:
It is based on the squirrel cage induction generator and as its name suggests its speed is fixed with little variations of around 1-2% [6] which means that its output power fluctuates as the speed of wind varies. Induction generators draw a lot of reactive power and hence the Type I wind energy generator is fitted with a reactive power compensation mechanism.

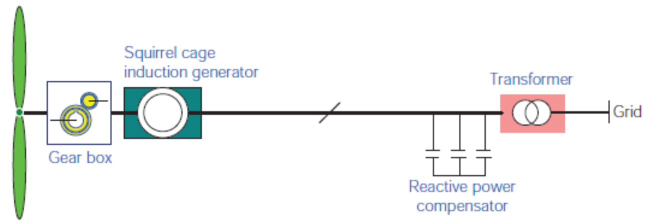

Fig. 4. Type I Wind Turbine Generator [1]

Type II: Variable Slip Induction Generator
It is based on the wound rotor induction generator (WRIG). Unlike the type I, power electronics are used to control the WRIG hence allowing a speed variation of up to 10%. As is the case with the Type I, Type II also has reactive power compensating components due to its inductive part [7].

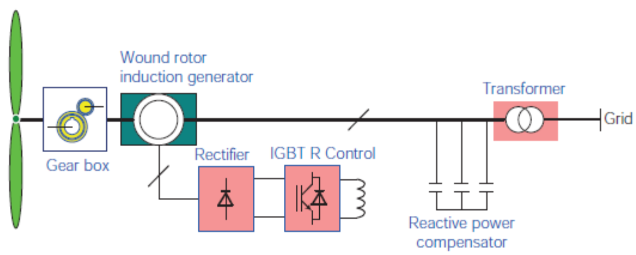

Fig. 5. Type II Wind Turbine Generator [1]

Type III: Doubly Fed Induction Generator
It is the most common technology used currently. It uses the WRIG that is fed to the grid through two paths. 40% of the power output passes through the converter to the grid while the remainder is directly fed to the grid. This gives the DFIG a flexibility of around 40% in speed variation [1]. Other than that, the power electronics technology used is more superior than in previous wind energy generators, it has decoupled active and reactive power control and hence better performance.

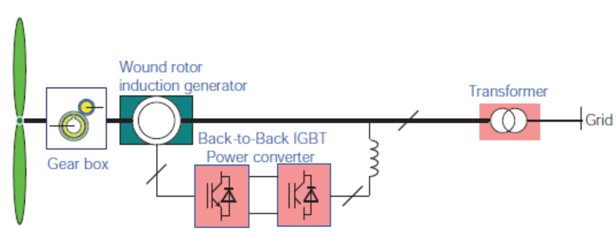

Fig. 6. Type III Wind Turbine Generator [1]

Type IV: Full Power Conversion Wind Turbine Generator
It is based on the SCIG and all its power is fed to the grid through the converter. It is this decoupling that allows it to have better control capability and little impact to the grid in the event of short circuit currents. It has similar properties to the Type 3 but achieves better speed and voltage control.

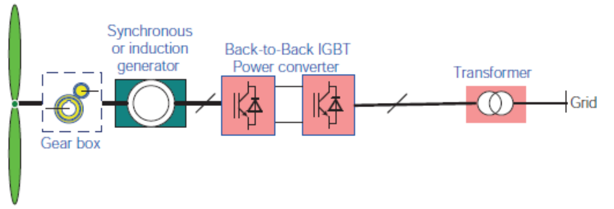

Fig.7. A Type IV Wind Turbine Generator [1]

C. Escalating Energy Access and Demand

There is a growing global demand for energy as people seek to get connected especially in developing countries. From 2009 to 2035, developing countries have shown and are projected to have a steady growth in demand of about 3.5% [1]. This demand for connectivity and hence load growth calls for injection of more power into the grid. The world is also looking at diversification of power generation portfolio with the aim of reducing reliance on fossil based power sources whose prices are not reliable and are prone to depletion. The world is going *green* with the aim of reducing its carbon footprint. Coal, oil and natural gas contribute the biggest share of CO_2 emissions amongst all generation technologies [8].

In 2009, the global energy consumption stood at 3900TWh. By 2035, it is projected that the figure shall be around 11100TWh which signifies a growth of around 300%. Fig. 7 below shows the growth of renewables from 2015 to 2035 for all renewable energy technologies [9]:

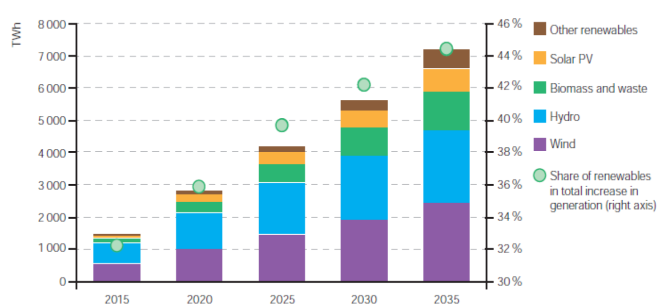

Fig. 8. Incremental Renewable Energy Based Generation Relative to 2009 [9].

The growing contribution of wind energy to the renewable energy mix from 2015 to 2035 can be noted in Fig.8 above. In 2015, wind was projected to contribute to 26% of the power generated through renewables. By 2035, it shall be contributing 35% of the renewable energy mix in the world [1]. This shows a very steady solid growth and adoption of wind energy technologies in a span of two decades hence showing the importance of this field to researchers. Power system stability and security is about to change as we know it and this transformation can be attributed to integration of renewables with stochastic behavior. Bulk wind power integration has taken the lead in having the highest capacity of installed renewables with intermittent behavior and hence forms the backbone of the review work in this paper.

Many countries have been very ambitious in the adoption of large capacity wind plants as shown in Fig. 8 below:

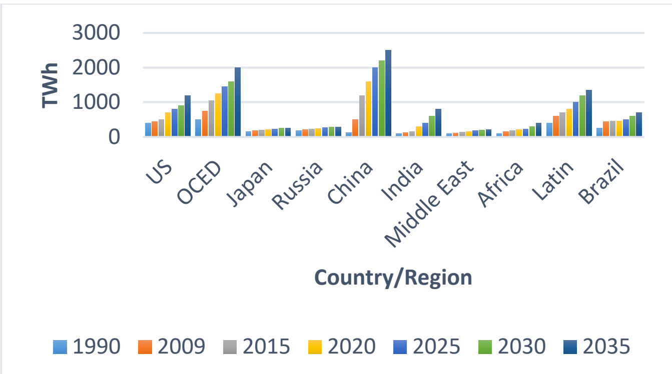

Fig. 9. Global Renewable Energy per Country/Region.

China intends to be the world leader in wind energy integration into the grid by 2035 as seen from their ambitious targets. In 2010 alone, China installed 16GW of wind energy while Europe (as a region) installed only 10GW. The bulk of the wind capacity in Europe was installed by Germany and Spain [10].

In 2009, 159GW of the global installed Wind capacity generated 273TWh of energy. It is projected that by 2020, the world shall generate 1282TWh from wind alone – 8 times what was generated in 2009. By 2035, the power generated from wind hits 2703 – double the 2020 projection. Capacity grows from 159GW in 2009, to 582GW in 2020, to 1102GW in 2035. A keen look at the statistics from 2009 to 2035 shows that compared to 2009, more power shall be generated for every kW of installed capacity. This is an indicator of wind technology and harnessing maturing through time into a more efficient form [1]. Fig. 10, Fig. 11 and Table I below summarize these observations:

Fig. 10. Projected Global Installed Capacity for Wind Energy [9]

Fig. 11. Projected Global Wind Generation from Fig. 9 Installed Capacities

	2009	2015	2020	2025	2030	2035
Installed Capacity (GW)	159	397	582	752	921	1102
Generated Energy (TWh)	273	835	1282	1724	2182	2703
Generated Energy per GW of Installed Capacity (TWh/GW)	1.717	2.103	2.203	2.293	2.369	2.453

Table I: Generated Energy per GW of Installed Capacity

III. LARGE SCALE WIND INTEGRATION CHALLENGES

Wind is a naturally occurring resource that is intermittent in nature. Below are some of the challenges that system operators face when it comes to integration of wind power into the grid [11]:

Non-controllability – the fact that wind occurs naturally in nature means that it cannot be controlled by generation operators. Wind can only be consumed when available and when it is not available then operators have to look for other sources to satisfy the existing demand. The output of coal plants can be controlled by varying the quantity of coal used, hydros can be controlled by closing/opening of the valves which in turn controls the amount of water acting as the prime mover. This non-controllability nature of wind has in previous years not been much of a concern due to the limited injection of wind power into the grid. However, with the projected increase in the injection of bulk wind power into the grid this becomes a critical concern for power system operators. The balance of demand and supply becomes more sensitive since one of the large source in the grid does not inject constant power.

Partial predictability – Nature cannot be predicted with 100% precision and there is always a variation between the projected and the actual values. The output of wind cannot be determined to exact quantities. Despite all this, researchers have continued to invent and re-invent better systems aimed at prediction of the output of wind plants hence allowing the plants some form or partial dispatchability. This partial predictability if not well checked lead to voltage and frequency issues in the grid which affect the normal operations.

IV. THE FUTURE

It is now a global fact that power generation needs to move from being fossil-based to the renewable sources. Renewable energy is free in nature and despite its unpredictable nature can still be harnessed for the benefit of all. With fossil resources globally projected to get depleted within the decade, it is important to plan for the growing need for electrical energy by diversification of power sources for our grids. Wind energy is one of the sources that has the greatest potential for injection into the grid. The future is big; the future entails bulk wind injection into the grids and without proper planning, the world shall not be in a position to optimize harnessing of this free resource. Below is the future of the grid factoring in bulk wind injection:

Focus on generation flexibility: Conventional sources of energy have some form of generation flexibility in that the generation operator can vary the output of the generator when need be. The interaction of conventional generators with the grid falls under the control of utility operators hence output can be adjusted based on prevailing demand [12]. Wind, on the other hand, can only be consumed when available. The future lies in developing of control systems for wind farms and grids to ensure seamless integration of sources of power with various portfolios. Development of more efficient wind power prediction tools would also serve to give power system operators more specific information to allow for better planning and scheduling of the available resources [9].

Clustering of wind power plants: A good working example of such a setup is the Jiuquan Wind Power Base in China shown in Fig. 12 below [13]:

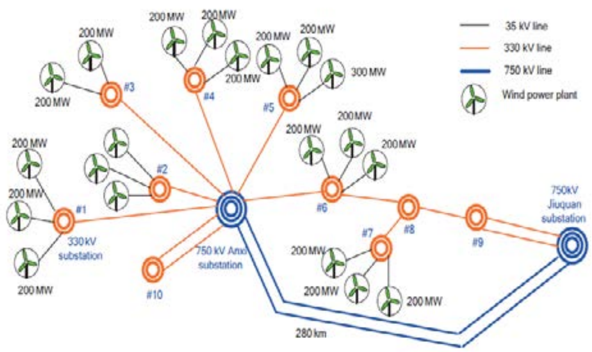

Fig. 12. Schematic of the Jiuquan Wind Power Base in China [11].

This scheme borrows from the concept of cascaded hydros on a river. The active and reactive power balances of the wind cluster scheme can be intelligently coordinated such that the output injected into the grid does not cause any problems to the wider grid. For example, in the event that one cluster is injecting reactive power and another is absorbing reactive power, the cluster arrangement ensures that the reactive power balances out within the scheme and the net reactive power injected into/absorbed from the grid is zero. This would in turn ensure better voltage control in the grid. Using a wide geographical location helps in smoothening out oscillations in the system compared to concentrating wind farms in one location. It is reported that wind farms located in different geographical locations are 33 – 47% more reliable compared to those clustered in one geographical location [12].

Pricing incentives for bulk consumers: Bulk consumers can be encouraged to consume in instances when wind power injected into the grid is at its highest. This would ensure that this free power is mopped from the grid and does not go to waste since the supply exceeds the demand. Active and reactive power balances would become easier with the concept of load shifting using price based incentives. Electric vehicles which are the future of automobiles can also be used as storage facilities which can mop up the excess wind energy say at night when the load curve experiences a dip and the wind energy is at its highest.

Interconnection of grids and transmission expansion: Transmission expasion and grid interconnection go hand in hand. Interconnection of two grids from two different countries would have a large wind power plant constructed and this resource shared. This would reduce the costs incurred to have units commited as spinnign reserve since this can be catered for by the generators in the two or more grids tied together.

V. Conclusion

Bulk wind power injection into the grid is considered one of the most favorable options in grids globally as the world seeks to shift to cleaner sources of energy and at the same time meet the growing energy needs. However, high penetration levels of wind energy into the grid shall introduce challenges in the operations of power systems. The stochastic nature of wind introduces another factor of uncertainty in power systems operation thus putting the integrity of the grid at stake. However, researchers and power system operators are continually developing strategies to mitigate these effects of variability of wind power to ensure that grid security is ascertained. With improved wind plants control technology, better forecasting techniques, grid interconnectivity and pricing incentives for consumption of wind power, the future can only be bright as the world taps into this free resource by nature.

VI. References

[1] IEC, "Grid Integration of Large Capacity Renewable Energy Sources and use of Large Capacity Electrical Energy Storage," International Electrotechnical Commission, Geneva, 2012.

[2] Z. Chen, "Issues of Connecting Wind Farms into Power Systems," in *IEEE/PES Transmission and Distribution Conference & Exhibition*, China, 2005.

[3] Y K. Wu, L. T. Chang, S. M. Chang, T. Y Hsieh and T. C. Lee, "Integration of Large Scale Renewable Power into the Taiwan Power System," in *IET Conference*, 2015.

[4] Shahab Shokrzadeh, Mohammad Jafari Jozani, and Eric Bibeau, "Wind Turbine Power Curve Modeling Using Advanced Parametric and Nonparametric Methods," in *IEEE Transactions on Sustainable Energy*, 2014.

[5] Anissia Beainy and Chantal Maatouk, "Comparison of Different Types of Generator for Wind Energy Conversion Systems Topologies," in *International Conference on Renewable Energies for Developing Countries (REDEC)*, 2016.

[6] Jason M. Kennedy, Brendan Fox, Tim Littler and Damian Flynn, "Validation of Fixed Speed Induction Generator Models for Inertial Response Using Wind Farm Measurements," *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 1454 - 1461, 2011.

[7] Eduard Muljadi, Mohit Singh, and Vahan Gevorgian, "Fixed-Speed and Variable-Slip Wind Turbines Providing Spinning Reserves to the Grid," 2013.

[8] World Nuclear Association, "Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources," London.

[9] International Energy Agency, "World Energy Outlook 2011," 2011.

[10] IRENA-GWEC, "30 Years of Policies for Wind Energy: Lessons from China," pp. 48 - 52, 2012.

[11] L.Bouzidi, N. Bellaaj and M. El Euch, "Large Scale Wind Power Integration : extended power system operations," 2015.

[12] T.R. Ayodele, A.A. Jimoh, and J.T Agee, "Challenges of Grid Integration of Wind Power on Power System Grid Integrity: A Review," *International Journal of Renewable Energy Research*, vol. 2, no. 4, pp. 618 - 626, 2012.

[13] Hong Shen, "Transmission of large scale wind power in China," *IEC Workshop on Grid Integration of Large-capacity Renewable Energy and Large-capacity Energy Storage*, 2012.