Studying of Wind farm performance at Zafarana Egypt

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Abstract— This paper proposes a study of Zafarana Egypt wind farm performance and verification of its equivalent by studying the load power flow and short circuit for both the detailed model and the equivalent model; also it discusses some possible layouts for offshore wind farms and comparison of method of connections. It was noticed that Zafarana wind farm consists of two types of induction machines, fixed speed and variable speed induction machine. Finally optimal capacitor placement is proposed using the simulation program (ETAP).

Index Term— component; Load flow; Short circuit; optimal capacitor placement; DFIG

I. INTRODUCTION

In Middle East and Africa wind energy development is very slow. Most projects require financial support from international and organizations, as there is only limited regional support. Projects are planned in Egypt, where government agency for new and renewable energy authority (NREA) would like to build about 7200 MW wind farms. The total capacity at Zafarana reaches 545 MW at 2010 [1]

Wind Atlas for Egypt indicates there are many promising areas to host wind energy projects, particularly on the Gulf of Suez, East and West of the Nile valley.

The power in wind can be calculated as follows:

\[ \text{Power in wind} = \frac{1}{2} \rho A V^3 \]

Where

- \( \rho \): air density \((kg \ m^{-3})\);
- \( V \): wind speed \((m \ s^{-1})\);
- \( A \): the area of the wind turbine rotor.

The air density is a function of air pressure and air temperature,

which both are functions of the height above sea level[2].

\[ \rho(Z) = \frac{P_o}{RT} \exp\left(-\frac{gZ}{RT}\right) \]

Where;

- \( \rho(Z) \): Air density as a function of altitude \((kg \ m^{-3})\);
- \( P_o \): Standard sea level atmospheric density \((1.22 \ kg \ m^{-3})\);
- \( R \): Specific gas constant for air \((287.05 \ JK^{-1} k^{-1})\);
- \( g \): gravity constant \((9.81 \ ms^{-2})\);
- \( T \): Temperature \((k)\);
- \( Z \): Altitude above sea level \((m)\).

The theoretical optimum for utilizing the power in the wind by reducing its velocity was first discovered by Betz in 1926, so the theoretical maximum power that can be extracted from wind is;

\[ P_{\text{BetZ}} = \frac{1}{2} \rho A V^3 C_{\text{BetZ}} \]
\[ C_{\text{BetZ}} = 0.59. \]

In steady state calculation of the mechanical power from wind turbine, the so called \( C_p(\lambda, \beta) \) curve can used. The mechanical power, \( P_{\text{mech}} \) can be determined by:

\[ P_{\text{mech}} = \frac{1}{2} A \rho C_p(\lambda, \beta) V^3 \]

\[ \lambda = \frac{\Omega_r r_r}{\omega} \]

Where \( C_p \) is the power coefficient, \( \beta \) is the pitch angle, \( \lambda \) is the tip speed ratio, \( V \) is the wind speed, \( \Omega_r \) is the rotor speed (on the low-speed side of the gearbox), \( r_r \) is the rotor-plane radius, \( A_r \) is the area swept by the rotor.

At high speeds it is necessary to limit the input power to the wind turbine, i.e. aerodynamic power control. There three major ways of performing this; i.e. by stall, pitch, or active stall control. Pitch control is the most common method of controlling the aerodynamic power generated by the wind turbine.

Wind turbines can operate with either fixed speed (actually within a speed range about 1%) or variable speed which has become the dominant type among the installed wind turbines. Variable speed operation is gained using doubly-fed induction generators (DFIG) controlled by power electronic frequency converters. The (DFIG) is a wound rotor induction generator where the rotor circuit is connected to the power grid through the power electronics frequency converter on the slip rings of the rotor. The stator of the (DFIG) is directly connected to the power grid.

Large wind farms can be represented using one of the following options [2]:

1. Detailed models with representation of all wind turbines in the wind farm and also all electrical components (transformers, cables...) grid connected.
2. Aggregated model which implies that the large wind farm is represented using a single machine equivalent.

The model details of wind farm depend on the target of investigations. Detailed models are applied when there is any risk of mutual interaction between wind turbines or internal faults. The use of an aggregated model is used because this simplification reduces the complexity and time of computations. Wind farm power capacity is the sum of the power capacities of all the wind turbines in the wind farm. The active power of the reduced equivalent, is the sum of the active power supplied by all the wind turbines to the power grid, $P_{IJ}$.

$$P_{\sum \sum} = \sum_{I=1}^{N} \sum_{J=1}^{M} P_{IJ} = NM \langle P_E \rangle$$

Here $\langle P_E \rangle$ is the average active power supplied by the wind turbines in the large wind farm. The reactive power of the reduced equivalent, is the sum of the reactive power exchanged by all the wind turbines with the power grid, $Q_{IJ}$.

$$Q_{\sum \sum} = \sum_{I=1}^{N} \sum_{J=1}^{M} Q_{IJ} = NM \langle Q_E \rangle$$

Here $\langle Q_E \rangle$ means the average reactive power.

II. TRANSMISSION SYSTEMS FOR OFFSHORE WIND FARM [3,4]

a) The interest in the utilization of offshore wind power is increasing significantly world-wide. The reason is that the wind speed offshore is potentially higher than onshore, which leads to a much higher power production. A 10% increase in wind speed results, theoretically, in 30% increase in power production.

However, investment costs for offshore wind power are much higher than those for onshore installations.

b) General Electrical Requirements:

The internal electric system of an offshore wind farm and its connection to the main power system pose new challenges. Onshore, the standard solutions are an AC network within the wind farm, which collects the power production of each wind turbine. The voltage level within a wind farm is usually the same as the medium voltage level of the distribution network point. As most wind turbine regenerators operate at a generator, the voltage level of 690 V, transformers that are installed directly in or close to the basement of each wind turbine are used to increase the generator voltage level to the voltage level in the wind farm network. The highest medium voltage level used within an onshore wind farm lies usually in the range of 33-36 kV, as the market offers competitive standardized equipment for this voltage range.

However, offshore wind farms tend to be bigger, and the distance between wind turbines is usually greater than that in onshore wind farms because of the large wake effect offshore. Often, the distance to the shore or to the next (offshore) transformer station is also significantly longer than for onshore wind farms. For large offshore wind farms with an AC network, higher voltage levels will certainly be useful in order to minimize power losses, but higher voltage levels may result in bigger transformers and higher costs for these transformers. The transformers will be placed in the nacelle, the tower or in a container next to the wind turbine; hence the size of the transformer might become an issue. In addition, the cost and size of switchgears will also increase with voltage levels. Today, a collection voltage of up to 36 kV is considered the standard solution.

Large offshore wind farms can certainly have different layout configurations. Looking at Figure 1, for instance, in Alternative B it might be possible to increase the voltage level within each wind farm block and to have only one offshore substation per block. This might reduce total investment costs yet increase the risk that the whole wind farm may be lost in the case where there are technical problems with the single network connection. Hence, designers of general wind farm layout have not consider only the main wind direction but also the technical transmission solution, the investment and operating costs and the overall reliability as well as issues to the location, such as water depth throughout the proposed area.

Fig. 1. Possible layouts for offshore wind farm. Note: OSS = offshore substation.

Usually, the cable from the offshore wind farm to the shore does not include any redundancy either (see also Figure 1, Alternative A). A fault on this cable, however, will result in a loss that is equivalent to the entire wind farm. The economic consequences from such a fault may be huge. The repair might take months, depending on the availability and current position of cable repair ships. It is, however, very difficult to protect the cable from damage, particularly if the cable crosses major shipping routes.

Redundancy could be achieved by using another, backup, cable following another route to shore (see Figure 1, Alternative B). Besides the significant costs of such a second
connection to shore, it might be also very difficult to carry this out in practice. At many locations, environmental restrictions would make it very difficult to find a second cabling route. A second connection point to the onshore network might not always be available either. Currently, no developers of offshore wind farms seriously consider any redundancy for the onshore cabling. Experience from the operation of the first large offshore wind farms will show whether redundancy for onshore connections will become necessary in future.

III. ZAFARANA WIND FARM [5]
Zafarana wind farm is as shown in fig.2 its models are as follows:
1. Fixed speed induction generator (N 43-stall), total power 30 MW, Germ 1
2. Variable rotor resistance (V47-Pitch), total power 47 MW, Germ2.
3. Fixed speed induction generator (N43-stall) total power 30 MW, DAN.
4. Doubly fed induction generator (DFIG), (G52-pitch) total power 85 MW, Spanish.
5. Doubly fed induction generator (DFIG), (G52-pitch) total power 95 MW, Japan.
6. Doubly fed induction generator (DFIG), 120 MW, Japan.
7. Doubly fed induction generator (DFIG), 120 MW, Denmark.

IV. VERIFICATION OF EQUIVALENT MODEL OF WIND FARM
The equivalent model is as shown in fig.3
A) A load flow analysis has been done using ETAP for both the detailed model and equivalent model as shown in fig 4 and fig 5, the same results which verify the accuracy of the equivalent model.
B) A 3 phase short circuit for period (100 ms) is simulated at 22 KV bus of Zafarana for both models as shown in fig 6,7. The two models behave in a similar way, also voltage spikes have matching magnitudes.

V. WIND ENERGY CONVERSION SYSTEM WITH PARALLEL COMPENSATION [6]
Parallel compensation is normally used to improve power factor of a wind turbine or a wind farm in wind power generation. It is believed that an improved power factor reduces the total line current, which, in turn, reduces the transmission loss and improves power transmission and voltage regulation of a wind power plant. Parallel capacitor is usually installed for each turbine generator. However, in wind power generation, both wind speed and the number of turbines added to a wind farm may change widely, making simulation an important approach for better understanding of the induction generator characteristics under compensation.

a) Fixed-Speed WECS with Parallel Compensation

For a fixed-speed IG, a parallel capacitor compensates for the magnetizing and leakage reactive power of the generator. The magnetizing reactive power depends on the voltage applied to the magnetizing reactance, and the leakage reactive power depends on current passing through the leakage reactance. When the value of the parallel capacitor is high, it can result in more capacitive line current especially for a low slip at which major reactive power of the generator is the magnetizing reactive power. As more turbines are added to a wind farm, the generator terminal voltage is boosted, the maximum torque is improved, and the generator stability is improved too. However, the improvement of the torque characteristics is at the price of a high over-voltage applied to the generator especially when more turbines are connected to a wind farm at a low slip. If a high over voltage is not allowed, a thyristor controlled parallel compensation or a parallel capacitor with a smaller fixed value should be adopted. However, for a small fixed-value parallel capacitor, it is found that the torque characteristics of a fixed-speed IG still shrink considerably as more turbines are added to a wind farm.

b) Variable-Speed WECS with Parallel Compensation[7,8]

The parallel compensation increases reactive power generation of a DFIG system particularly when the operating slip of a DFIG is low. The reactive power produced by the parallel capacitor together with the reactive power generated by a DFIG around the synchronous speed raises the generator terminal voltage even more if d-q control condition is unchanged, which increases the maximum torque. But, for a typical operating slip of a variable-speed DFIG system below the synchronous slip, for example, the boost of the torque characteristics by the parallel compensation is trivial.

VI. OPTIMAL CAPACITOR PLACEMENT

To compensate the reactive power drawn by the parts of the network (Trans, cables, fixed speed induction generators…), it is found that the optimal place is at the POC (point of connection) of the main loads at Bus 32 by a value of about 100 MVAR. The objective function is 0.9 P.F and the limits of voltage is 90 % and 110 %, after a large number of iterations and by choosing all the buses as candidate buses. It delivers reactive power to the fixed speed induction machines by about 27 MVAR and 33 MVAR at Bus 1 and 2, making power factor at these buses unity as shown in fig.8. The parallel capacitor compensation for DFIG may generate too much reactive power and raise the generator terminal voltage especially when more turbines are connected online, and it does not show the advantage of parallel compensation to DFIG.
Fig. 2. Zafarana wind farm network
Fig. 3. Equivalent network of Zafarana wind farm
Fig. 4. Load flow of the detailed model
Fig. 5. Load flow of the equivalent model
Fig. 6. Bus voltage of Zafarana 22 KV of detailed model

Fig. 7. Bus voltage of Zafarana 22 KV of equivalent model
VII. CONCLUSIONS

For short term voltage stability studies and investigations, it is assumed that wind speed is constant during the simulation time and also the speed control response of (DFIG) is relatively slow so that the current does not reach the saturation region. Zafarana Egypt wind farm has been studied in both cases detailed and equivalent model. The verification of the equivalent model has been done. A single unit aggregated model is sufficiently accurate to resemble wind farm behavior consisting of DFIG wind turbines, despite considerably different power levels and the operating points of the turbines. Also the reactive power compensation of the network and the optimal place of capacitor bank connection have been studied. There is no need for external reactive power compensation for DFIG since it is working at VAR mode, the compensation is needed only for fixed speed induction generators and also transformers, cables, etc. Another way for delivering the reactive power needed for the reactive power compensation is using a synchronous generator within the farm and it will be investigated in the future work.

REFERENCES