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Evaluating the Impact of Wind Generation on the Reliability of the Electrical Unified Network of Egypt

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Abstract- This paper presents a novel algorithm for the integration of wind generation with conventional power system for reliability studies. The algorithm is based on dividing the wind turbine generator (WTG) output power into corresponding four states. The mean time to fail (MTTF) and the mean time to repair (MTTR) are calculated for each state based on the generated power. A four-state model for WTG is then estimated using the calculated MTTF and MTTR for each state. The proposed model in this general form matches with the simulation techniques of conventional generating units for reliability analysis. The conventional generating units of the power system under the current investigation are simulated as a two state model using state duration sampling approach. A Mont Carlo simulation technique is adopted throughout the investigation for results verification. Recorded output results with conventional generating units are compared with integrated system composed of both conventional generation and wind energy included under the same load. The satisfactory agreement of results with the measured ones justifies the excellence of the proposed mathematical model.

Index Terms **- Reliability, Wind Turbine, Monte Carlo Simulation.**

I-INTRODUCTION

The application of renewable energy in electric power system is growing rapidly due to enhanced public concern for adverse environmental impacts and escalation in energy costs, shortage of fossil fuels associated with the use of conventional energy sources. Throughout the world, wind energy resources are being increasingly recognized as cost effective generation sources in bulk power generation. In recent years, one would hope for failure free electric supply. This eventually leads to reliable supply, since most of the failures occur due to insufficient generation.

The generation system reliability evaluation has become the most important component of power system reliability Moreover, it is important to investigate the WTG in reliability analysis to work as a grid connected generator working in parallel with other types of conventional generators.

Several studies [1] have looked at the wind level penetration in power systems. A new simulation technique has been developed to assess wind power impacts on unit commitment and dispatch of thermal generation units in power systems for increasing the level of wind power penetration [2]. In this case the simulation of WTG output was based on the assumption that the wind speed follows a weibull distribution function. This is not a quite reasonable assumption for representing the wind speed since the wind speed has a random nature.

A multi-state WTG simulation model was then introduced to provide a reasonable assessment in practical studies. This model was used to incorporate WTG in a large scale power system studies without requiring significant increase in computer simulation time [3].

The capacity expansion of small isolated power systems using wind energy was also analyzed and a model was presented for reliability evaluation. This model was able to provide the penetration level in the formulation of capacity expansion scheme for isolated power system [4].

Most of the previous models were concerned with reliability studies of WTG. They did not consider the reliability analysis of large systems with both types of conventional generators and WTG presented at the same time. Therefore, the model presented during this investigation considers the reliability analysis of a large network dealing with both types of generation; conventional and WTG as a renewable source of energy. The developed model is examined by taking the Egyptian grid as a case study. The grid is generally composed of different types of conventional

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generating units and two wind farms in two different sites located at the red sea area in Egypt. The Egyptian demand is used for performing reliability analysis for the Egyptian grid. The network reliability analysis was presented through the calculation of the interruption frequency, interruption duration, the loss of load expectation, and the expected energy not supplied. The current study also shows the effect of wind energy penetration to the Egyptian power system reliability analysis. Throughout the proposed model a WTG is simulated as a four-state model to present the wind power generated. The proposed WTG model is formulated and analyzed in details in the next section. The conventional generating units in the Egyptian grid, however, are simulated using state duration approach for reliability studies. A Mont Carlo simulation technique is used for the convergence of the results.

II- PROPOSED ALGORITHM

The improvements in wind generation technologies will continue to encourage the use of wind energy in both grid connected and stand alone systems. Owing to the random nature of the wind, the wind generators behave quite differently from conventional generators. Therefore, it is important for the power system planners and engineers to take into consideration the reliability issues associated with the wind energy resources connected to the grid. During the present investigation the wind turbine generator model for reliability analysis is presented. The model is based on assuming that the ever changing WTG power is divided into four-states with MTTF and MTTR being calculated for each state. The model presented in this form will be similar to the model describing the conventional generating units for reliability studies. The simulation model is applied to the Egyptian network.

The Egyptian grid is composed of different types of conventional generators. These may include steam, gas, hydro and wind turbines. There are also, two sites for wind generation connected to the Egyptian grid.

A 225 MW wind farm located at Zaafarana at the coast of the Red Sea with average wind speed of 9.3 m/s. The cut in, rated, and, cut out wind speed at Zaafarana are 2, 9.2, 11.2 m/s respectively.

A 5.2MW wind farm is also located at Hurghada at the red sea coast with an average wind speed of 6.7 m/s. the farm includes 42 units of different types of WTG .All WTG units are simulated as a 4-state model for reliability analysis.

A-Modeling wind turbine generator

Wind power generation depends mainly on the location of the site due to variation of wind speed between sites. During this work the wind speed is simulated by super-imposing white Gaussian noise to the available measured site wind speed. Comparing the simulated wind speed and measured ones, the results show a good matching. . The output power of WTG is a function of several variables. The variables that has a significant effect on a WTG output power are the cut-in speed (V_{ci}),cut-out speed (V_{co}), rated wind speed (V_r) and rated generator power (P_r).The hourly output power from WTG (P_c) is calculated from simulated hourly wind speed using (1) [5]. The constants A, B, and C are presented in details in [6].

$$Pc = \begin{cases} 0 & 0 \le V < Vci \\ (A + B * V + C * V^2) * pr & Vci \le V < Vr \\ pr & Vr \le V < Vco \\ 0 & V \ge Vco \end{cases} \tag{1}$$

The WTG output power is fluctuating in nature due to the variable nature of wind speed. A WTG can operate at a reduced capacity state designated as a derated state. The proposed algorithm sectionalizes the calculated power into four derated power states. The WTG fluctuating output power is, therefore, presented by the use of the four steps derated power (P_d). The calculated wind power (P_c) obtained earlier from (1) is classified to four derated power stats as described in (2).

$$P_d = \begin{cases} 0 & Pc < 0.25Pr \\ 0.5Pr & 0.25Pr \le Pc < 0.5Pr \\ 0.75Pr & 0.5Pr \le Pc < 0.75Pr \\ Pr & Pc \ge 0.75Pr \end{cases} \tag{2}$$

For the derated power states obtained in (2), the MTTF for derated up stats are calculated. Similarly, the MTTR for the down state is estimated. The three derated powers are considered as up1, up2, up3 states and the zero or down state is the state which carries zero power. A Mont Carlo simulation technique is used for the convergence of MTTF's and MTTR estimated. The state duration approach [7] is employed to calculate the simulated WTG power using the estimated MTTF's and MTTR. At the beginning of the simulation time, it is assumed each the unit resides in the up state. There are three possible alternatives for the next unit state; the first, second and third derated states are 75%, 50%, and zero power of unit rated power. The up state intervals are calculated using (3).The sampling value of the down state duration is estimated using (4).

$$Tup_i = -MTTF_i \ln(u1) \quad (3)$$

$$Tdown_i = -MTTR_i \ln(u2) \quad (4)$$

Where

$MTTF_i$: the MTTF of the i^{th} state.

MTTR: the MTTR of the down state.

u1, u2: two uniformly distributed random numbers between zero and one.

$$Ts1 = \min(Tup1, Tup2) \quad (5)$$

$$Ts2 = \min(Tup2, Tup3) \quad (6)$$

The next state during simulation process can be determined using (5) and (6). If Ts1=Tup1, the next state is the first derated state (75% of Pr). However, if Ts2=Tup2, the next state will be the second derated state (50% of rated power). In case Ts2=Tup3, the next state will be the down state. Fig. 1 illustrates the transition process between the different states. The process of transition between different states is executed based on the described conditions using the MTTF and MTTR of each state. The transition from sate to another is performed using the failure rate (λ) which is the inverse of the parameter MTTF for each state. It can be noticed from the figure that the system can switch between the different states according to the procedure mentioned earlier.

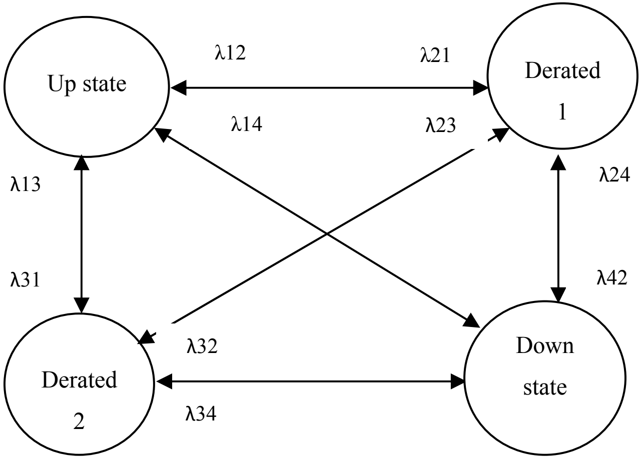

Fig. 1. Four-states Model of a WTG

B- Modeling conventional generating units

The Egyptian grid is composed of different types of conventional generating units. It has 60 steam units, 31 gas units, 29 hydro units and 40 units of combined cycle generators**.** All the above units are simulated using state duration sampling technique. A conventional unit is simulated as a two state model. The available data for each unit are the MTTF, the MTTR, the forced outage range (FOR), and the availability. The sate duration sampling approach is based on sampling the probability distribution of the component state duration [5].

Generally, it is assumed that all units are initially in the success or up state. The sampling value of the state duration is given by the use of (3) and (4). Chronological component state transition processes in the given time span for each unit in the Egyptian grid can be obtained. The chronological system state transition process can be obtained by combining the chronological component state transition processes for all units [7]. The chronological grid state transition process for all conventional units in the grid during the present investigation is presented in Fig. 2.

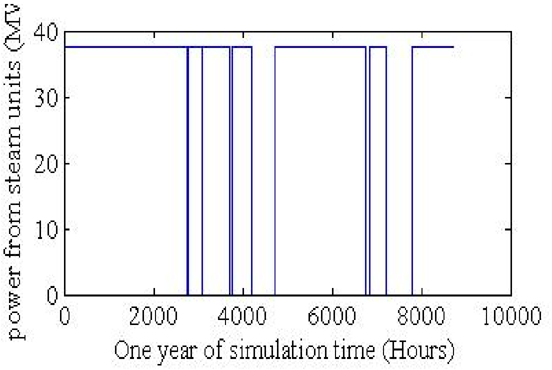

Fig .2. Generated power from one steam unit

The next step in the proposed simulation algorithm is combining the four-state wind power with the power generated from conventional units. The load of the Egyptian power system is used to determine the amount of unsupplied load, the frequency of occurrence of which the load exceed the generation, and the duration of which the load is unsupplied. A Mont Carlo simulation technique is used for the convergence of the results after a long time of simulation through the model.

III– MATHEMATICAL MODEL VALIDATION

The algorithm presented in the present investigation is applied to the Egyptian network. This network, as mentioned earlier, is composed of different types of conventional units such as thermal, combustion, and hydro. In addition, it has two wind farms connected to the grid at Hurghada and Zafarana. Fig. 3 illustrates the Egyptian map with some of the conventional units which are presented in black circles while the wind units are denoted as wind fans.

Wind energy in Egypt is produced mainly from large scale wind farm at zaafarana site and a small scale wind farm at the site of Hurghada. The Hurghada wind farm is composed of different types of WTG'S. Some of them are two blades the rest are three blades turbines. The Hurgada wind farm is a small scale farm which produces 5.2 MW connected to grid. The large scale wind farm at Zafarana has been implemented and operated in three stages with a total generated power of 225 MW. Zaafarana farm is also connected to the unified network of Egypt. All the WTG in the two farms are simulated as a four state model according to the procedure mentioned earlier in this paper. The simulation of WTG is estimated based on the MTTF's and MTTR of each state and for each of WTG.

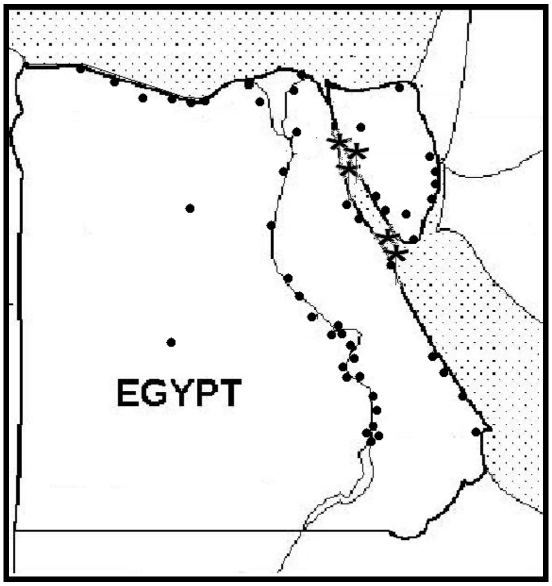

Fig. 3. Map of Egypt

For the two wind farms under the study the generated power of each WTG in the farm is calculated using (1). The calculated power fluctuates as the speed varies. The produced power is divided into 4 sections according to (2). The MTTF and MTTR of each state are calculated for a long time of simulation of 500 year for the Zaafarana and Hurghda sites. A Mont Carlo simulation approach is used for the convergence of the results. The simulated MTTF and MTTR at Zaafarana farm are illustrated in Fig. 4.

The state duration approach is used to simulate WTG using the calculated MTTF's and MTTR for each site. The hourly simulated power of WTG at the Zaafarana site is shown in Fig. 5. It can be noticed from the figure that the WTG output power is varying between the four different states. It can be also observed that the output power from Zaafarana wind farm varies with time between the zero power and rated power of the farm.

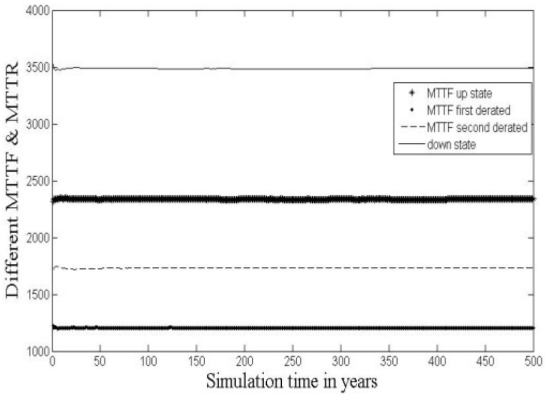

Fig. 4. MTTF's and MTTR of four-state

All conventional units in the Egyptian network are simulated using state duration method for reliability analysis. The state duration approach is mentioned earlier during the current investigation. The conventional units are simulated as a two-state model. Each of conventional unit varies between the up state and the down state.

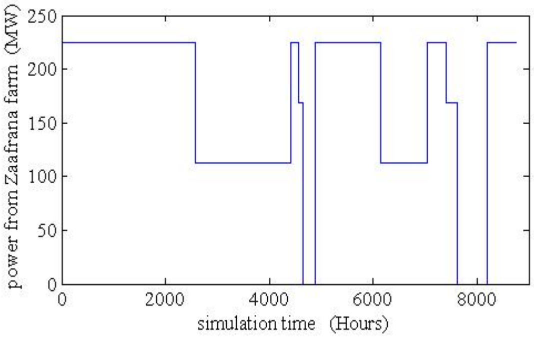

Fig. 5. Generated power from Zaafrana farm

Fig.6 presents the simulated power from all conventional generating units in the Egyptian grid during one year of simulation time. It can observed from Fig.6 that the power is at its maximum value at the beginning of simulation time. This is due to the assumption that all generators are in the up state at the beginning of simulation time.

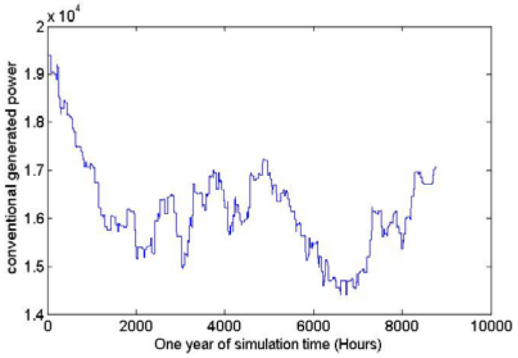

Fig. 6. Total generation from conventional units

The recorded Egyptian energy load in MWh with the power from the conventional generators is used for the reliability calculations. The Expected Energy not Supplied (EENS) of the Egyptian grid is calculated during simulation time. For verification of the EENS, a Mont Carlo technique is used for convergence of the results. Fig.7 depicts the EENS in Mega Watt Hour after the application of the Mont Carlo simulation. It can be observed from Fig.7 that the unsupplied load presented by the EENS of Egyptian grid is approximately 19.8 MWh per year. This result is obtained considering the random variation of conventional generators power each year during simulation time.

The interruption duration index is one of the important issues when considering reliability studies. The hours during which the load is not supplied is defined as interruption duration or the Loss of Load Duration (LOLD). It is calculated during the current algorithm per year during simulation time.

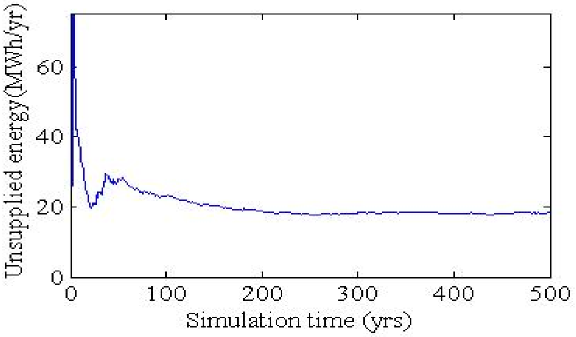

Fig. 7. The unsupplied load per year

It is calculated during the current algorithm per year during simulation time. The proposed investigation is tested for a long simulation time of 500 years. A Mont Carlo simulation technique is used for the convergence of the interruption duration index which converges at 60.4 hours per year. Fig. 8 shows the interruption duration per year in the Egyptian grid for conventional generation.

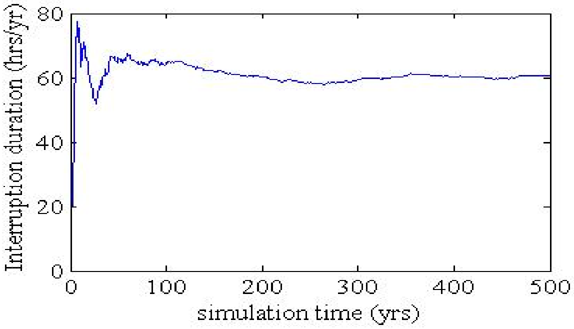

Fig. 8. Interruption duration per year

During the presented work the interruption frequency per year is also calculated during simulation time. The interruption frequency index or the Loss of Load Frequency (LOLF) is one of the most important indices for reliability studies and is defined as how many times the load is not supplied. The interruption frequency varies in its importance from customer to another. A Mont Carlo simulation is applied for the simulated interruption frequency index and it converges at 279.43 interruptions per year. Fig. 9 illustrates the convergence of Mont Carlo simulation for interruption frequency per year.

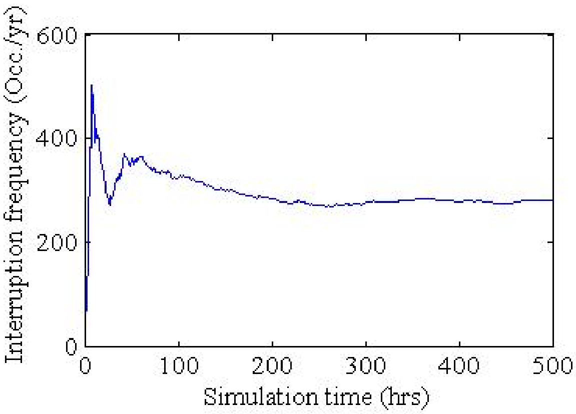

Fig. 9. Interruption frequency with conventional generation

IV. WIND LEVEL PENETRATION

This section presents the effect of wind generation in Egypt to the unified grid. The effect of wind level penetration to the Egyptian grid is discussed through the variation in three major indices; the unsupplied load, the interruption frequency index and the interruption duration index. All WTG's in the Egyptian network are simulated as four-state generators using the algorithm described in section II. The total generation is obtained by combining the two- state models of conventional generators with the four-state models of WTG generators. The total generated power in the Egyptian grid during one year of simulation time is presented in Fig. 10.

The total generation is used together with the total Egyptian load for reliability calculations. The unsupplied load is calculated with the total generation. A comparison between the unsupplied loads in both conditions of generation using the same demand is conducted. Fig. 11 presents the EENS per year for two generation schemes of conventional generation and the conventional generating units in addition to wind energy. It can be shown from the figure that the integration of wind generation to the Egyptian grid improves the amount of unsuppliedloadby17.27%.

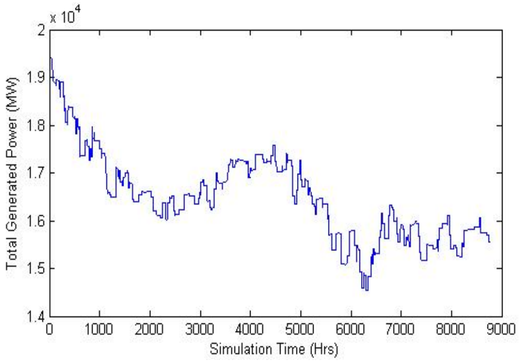

Fig. 10. Total Power from the Grid of Egyptian

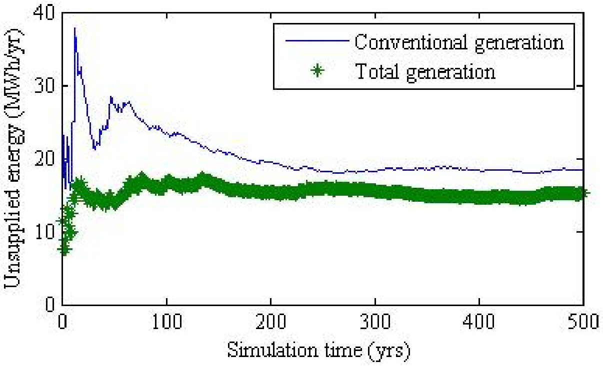

Fig. 11. Unsupplied load for the two generation scheme

Moreover, the interruption frequency is an important index to be taken into consideration in analyzing the effect of wind level penetration. The interruption frequency index shows how many times the load exceeds the generation per year. The interruption frequency is calculated for each year of simulation time in both generation schemes. Fig. 12 shows the interruption frequency under the two cases of generation. It can be seen that the use of wind generation changes the interruption frequency per year from 279.43 to 236.548 interruptions per year. It is improved by 15.3%. This improvement is due to the integration of wind generation to the Egyptian power system.

The effect of including wind generation to the conventional generators in Egypt is considered with respect to the interruption duration index. The interruption duration index indicates how many hours the load is not supplied. During the present investigation the interruption duration index is calculated first with conventional generation and second, with the total generation. The results are verified using Mont Carlo simulation technique with long time of simulation. It can be shown from the results that the interruption duration per year was changed from 60.4 to 51.3 hours per year which improved by 15.18%.

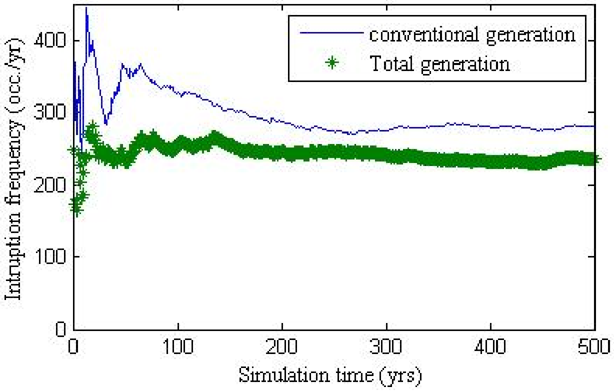

Fig. 12. Interruption frequency for the two generation schemes

V-CONCLUSION

The presented investigation shows how WTG can be simulated as a four-state model for reliability analysis. This model matches the two-state model for simulating conventional generating units. In addition, the presented model of WTG takes into consideration the random nature of wind speed. The proposed model for WTG can be easily combined with the two states model of conventional generating units for studying power system containing wind generation running in parallel with conventional units. The effect of wind generation to the Egyptian network is presented in three major aspects of EENS, LOLF, and LOLD. The results showed that the integration of wind energy to the unified grid of Egypt has an excellent improvement to the reliability issues. The study shows that including wind generation to the grid improve the unsupplied load, the interruption frequency, and the interruption duration by17.27 %, 15.3%, and 15.18% respectively.

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VII. BIOGRAPHIES

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