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Impact of Wind Farms on Power System Voltage Stability

أثر تشغيل مزارع الرياح علي اتزان جهد منظومة القوى الكهربية

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ملخص البحث:

ازداد اهتمام العالم بربط مزارع تربينات الرياح مع نظم القوى الكهربية ولما كان اتزان جهد الشبكة الكهربية ضرورة ملحة مع الانتشار المتزايد لمزارع الرياح . يقدم البحث برنامج لدراسة احتمالية اتزان الجهد عند ربط وحدات توليد تربينات الرياح ˝(WTGU) مع شبكة كهربية وذلك من خلال تحليل تدفق القوى الكهربية حيث يتم نمذجة هذه الوحدات وإدماجها في البرنامج لاكتشاف نقط الانهيار علي منحنيات ˝(Q-V) .

يقوم الخوارزم المقترح بحساب القدرة الكهربية الفعالة و الغير الفعالة لتربينة رياح – ثابتة السرعة –متغيرة الخطوة (Fixed Speed – Pitch Regulated) عند موقع معين وسرعة رياح معينة لجهد شبكة محدد. ونظراً لطبيعة الرياح المتغيرة يقدم البحث حد اتزان الجهد المتوقع (EVSM) كمعامل لربط جهد الاتزان وتوزيع الرياح معاً.

تم تنفيذ الخوارزم المقترح وتطبيقه علي نظام اختبار (IEEE 26 - BUS) لحساب حد جهد الاتزان الذي يمثل الفرق بين نقاط الانهيار ونقاط التحميل وحد جهد الاتزان المتوقع عند سرعة رياح محددة. الجمع التكراري لحد جهد الاتزان المتوقع (EVSM) يمثل قيمة يمكن مقارنتها مع مثيلاتها من نظم القوى الكهربية التقليدية.

Abstract

Steady state analysis of wind turbine generating units (WTGUs) interconnected with the grid is needed as the use of WTGU are getting more popular and many new systems are being planned. In this paper, probabilistic voltage stability algorithm of WTGUs interconnected with the utility grid is developed via power flow analysis where these units are modeled as P-Q bus(es) by detecting the collapse point on the Q-V curves. The developed algorithm also facilitates the computation of both the real and reactive power output of the fixed speed pitch regulated wind turbine at a specific site, wind turbine characteristics, wind speed and terminal voltage. The probabilistic nature of wind is considered by introducing the expected voltage stability margin as an index that combines both of the voltage stability and the wind distribution in one index. The proposed algorithm is implemented and applied on the IEEE 26-bus, voltage stability margin (VSM), and expected voltage stability margin (EVSM) are calculated at each wind speed. The accumulation of the EVSM over a specific period, can be considered as the system voltage stability margin which is a single value that can be compared with the voltage stability margin of the all-conventional power system.

Keywords:

wind turbines generating units, voltage stability, voltage stability margin, utility grid, fixed speed pitch regulated induction generator.

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1. Introduction

A tendency to increase the amount of electricity generated from wind turbines can be observed. Therefore, the penetration of wind turbines in electrical power systems will increase and they may begin to influence overall power system behavior, making it impossible to run a power system by only controlling large scale power plants. It is therefore important to study the behavior of wind turbines in an electrical power system and their interaction with other generation equipment and with loads [1]. Ref [2] was concerned with transient behavior of grid connected fixed speed while ref [3] presented the impact of connecting two different types of WTGU on the transient stability of a Spanish system. In [4] models for various type of WTGU compatible with commercially available power system dynamic simulation were established. The other class of investigation [5-7] attempts to address the grid - wind turbines interaction in steady state context. In [8], the equivalent circuit model of induction motor has been used to represent the WTGU, assuming the generator mechanical input is known. The studies carried out in attempt to model a wind farm consisting of only the fixed speed type of wind turbine.

The wind turbine types are classified according to its control strategy either fixed speed or variable speed. The most common control strategies are stall (based on the design of the blade), pitch (depends on pitch angle of the blade) and active stall (which is a combination of both). Each control strategy coupled to either squirrel cage induction machine, doubly fed induction generator or direct drive synchronous machine. Pitch Regulated Fixed Speed WTGU has a squirrel cage induction generator which is driven by a wind turbine either having a fixed turbine blade angle (stall regulated fixed speed WTGU) or having a pitch controller to regulate the blade angle (pitch regulated fixed speed wind turbine).

Voltage instability is a major power system weakness resulting in severe detriments with economical, technical and social dimensions. A number of recent contingencies and voltage collapses around the world has prompted a significant effort towards the study and prevention of voltage instabilities [9]. Different causes and scenarios of voltage collapse have been revealed [10]. It can be triggered by a sudden disturbance or alternatively by a gradual change of parameters followed by reaching steady state stability margin limits. In practice, this general approach is often reduced to power flow feasibility analysis, and feasibility is treated as voltage stability [11].

The main contributions of this paper are:

1. Calculating both real and reactive power output of the fixed speed pitch regulated wind turbine coupled with squirrel cage induction generator (FSPRIG) for a specific location, specific wind speed.
2. Modeling of FSPRIG into the power flow analysis as a P-Q bus.
3. Incorporating FSPRIG into the voltage stability module to calculate the voltage stability margin at a specific situation,
4. Introducing the expected voltage stability margin as an index to incorporate the probabilistic nature of wind and its output power effect on the system voltage stability. So, we can compare the behavior of the power system from the voltage stability point of view with and without FSPRIG.

The proposed algorithm is applied on the IEEE 26-bus after injection of WTGU at bus (2) that is treated as a P-Q bus after calculating both active and reactive injection power from WTGU using wind speed distribution curve. Then the power flow analysis, voltage stability margin

(VSM), and expected voltage stability margin (EVSM) are calculated at each wind speed. The accumulation of the EVSM over a specific period, say one year, can be considered as the system voltage stability margin which is a single value that can be compared with the voltage stability margin of an all-conventional power system.

The paper is organized as follows: section 2 represents wind farm modeling, section 3 introduces power flow analysis including FSPRIG, section 4 represents voltage stability calculations of the power system after the injection of WTGU and the effect of the probabilistic nature of the wind as a source, section 5 presents the developed algorithm section 6 shows the case study and the result analysis followed by the conclusions and the list of references.

2. Wind Farm Modeling

The wind farm is affected basically by many factors one of them is the wind speed distribution which is a characteristic of the site the other one is the control strategy of the wind turbine system either fixed speed or variable speed , also stall or pitch, finally the type of the generator coupled to the rotor of the turbine.

2.1 Wind Speed Distribution

The variation in wind speed are best described by the Weibull probability distribution function, (*p*) with two parameters, the shape parameter (*k*) and the scale parameter (*c*). The probability of wind speed being (*v*) during any time interval is given by [12]:

$$p(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} e^{-(\frac{v}{c})^k} \quad \text{for } 0 < v < \infty \qquad (1)$$

The developed program includes modeling for equation (1) to present probability distribution function as a function of both shape factor and scale factor.

2.2. Wind Turbine Modeling

The power output of a FSPRIG depends on wind speed, rotor speed, turbine characteristics, generator characteristics, and the terminal voltage. For a given situation, wind speed alone is the independent variable while the rotor speed and terminal voltage are dependent variables that vary with wind speed as well as the network conditions. In some of the existing models, either the turbine characteristics are neglected (constant mechanical power) or the WTGU power output is to be independent of the terminal voltage variation [8].

The method suggested here facilitates the computations of the power output of the WTGU without making these simplifying assumptions. For the FSPRIG, the pitch angle controller regulates the wind turbine blade angle (β) according to the wind speed variations. Hence, the power output depends on the characteristics of the pitch controller in addition to the turbine and the generator characteristics. The model is based on the steady state power characteristics of the turbine. The wind turbine mechanical power out is a function of rotor speed as well as wind speed and is expressed as [13]:

$$p_m(v_w, \omega_r) = \frac{1}{2} \rho A v_w^3 C_p(\lambda, \beta) \qquad \text{and}$$

$$\lambda = \frac{\omega_r R}{v_w} \qquad (2)$$

where,

P_m : Mechanical output power of the turbine (W)
C_p : Performance coefficient of the turbine
ρ : Air density (kg/m^3)
A : Turbine swept area (m^2)
v_w : wind Speed (m/s)
λ : Tip Speed Ratio, the ratio of the rotor(1) blade tip speed to wind speed
β : Blade pitch angle (deg)
ω_r : generator rotor angular speed (rpm)
R : Radius of the turbine blade (m)

A generic equation is used to model $C_p(\lambda, \beta)$ based on the wind turbine characteristics as [7]:

$$C_p(\lambda, \beta) = C_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4)e^{\frac{-c_5}{\lambda_i}} + C_6\lambda \qquad (3)$$

where, λ_i is given by

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (4)$$

and, C_1 , C_2,….., C_6 are constant parameters depend on wind turbine type.

2.3 Squirrel Cage Induction Machine Modeling

The induction generator output in terms of ω_r and the terminal voltage, V is obtained by using the equivalent circuit of the induction machine. The expressions for active and reactive power are obtained as [14]:

$$P_g = |I_2|^2 R_2 \frac{1-s}{s} \qquad (5)$$

$$Q_e = |I_2|^2 X_2 + |I_1|^2 X_1 + \frac{|V_A|^2}{X_m} \qquad (6)$$

Where;

V_m : Terminal Voltage
I_1 : Stator Current
I_2 : Rotor Current
R_1 : Stator Resistance
R_2 : Rotor Resistance
I_m : Magnetizing Current
X_m : Magnetizing Reactance
X_1 : Stator Reactance
X_2 : Rotor Reactance
ω_s : Synchronous Speed
ω_r : Rated Speed
S : Slip ($S=(\omega_s - \omega_r)/ \omega_s$)

3. Power Flow Analysis Including FSPRIG

Power flow analysis is the primary tool for assessing the operation of system in steady state and voltage stability as well. WTGU buses can't be treated as voltage specified buses (P-V buses) because none of the WTGU types have enough reactive power capability to hold their terminal voltage at a specified value. The WTGU buses can be treated as only P-Q buses (with P and Q varying across iterations in contrast to a conventional P-Q bus where they remain constant).

A developed algorithm is designed to calculate power output P_e as a function of the wind speed and consequently as a function of the slip as follows [7]:

$$P_e = \frac{[R_1(R_2^2 + S^2(X_m + X_{l2})^2 + SR_2X_m^2)]|V|^2}{[R_2R_1 + S(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_2(X_m + X_{l1}) + sR_1(X_m + X_{l2})]^2} \qquad (7)$$

P_e can be expressed as a function of slip (rotor speed) in a quadratic equation:

$$aS^2 + bS + c = 0 \qquad (8)$$

where,

$$a = P_eR_1^2(X_{l2} + X_m)^2 + P_e(X_mX_{l2} + X_{l1}(X_{l2} + X_m))^2 - |V|^2 R_1(X_{l2} + X_m)^2,$$

$$b = 2P_eR_1R_2X_m^2 - |V|^2 R_2X_m^2, \qquad (6)$$

and

$$c = P_eR_2^2(X_{l1} + X_m)^2 + P_e(R_1R_2)^2 - |V|^2 R_1R_2^2$$

Then the slip is given by:

$$S = \min\left|\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right|$$

Knowing P_e and the machine parameters, we can solve for the slip and therefore, the reactive power output Q_e can be calculated from the induction generator equivalent circuit equation, as follows [7] :

$$Q_e = \frac{[X_mX_{l2}S^2(X_m + X_{l2}) + X_{l1}S^2(X_m + X_{l2})^2 + R_2^2(X_m + X_{l1})]|V|^2}{[R_2R_1 + S(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_2(X_m + X_{l1}) + SR_1(X_m + X_{l2})]^2} \qquad (9)$$

Any change in voltage due to these output changes are computed and the above process is repeated till convergence

4. Voltage Stability Assessment

Voltage stability of the system is the ability of power system to maintain adequate voltage magnitude so that when the system nominal load is increased, the actual power transferred to that load will increase. The main purpose of the voltage instability is the lack of reactive power supply in the system. Voltage stability can be broadly classified based on time of simulation into two categories: static voltage stability and dynamic voltage stability. In dynamic consideration, studies include dynamic effects such as transformer tap, induction motor, load etc. Whereas, static studies consider load variation as a slow process over long period of time [15]. Most problems of power system realize voltage collapse as a static phenomenon.

Voltage security is closely related to reactive power, and a Q-V curve gives reactive power margin at the test bus. The reactive power margin is the MVAr distance from the operating point to the point at which the system breaks down. Voltage Stability Margin index (VSM)is the difference between loading reactive power and collapse point reactive power at a load bus. The sensitivity analysis reflects the most sensitive bus at which the system may collapse under increasing reactive power.

4.1 Impact of Wind Farm on Voltage Stability

The developed wind farm model has been used to study the impact of wind farm on voltage stability for sensitive buses of the system to determine voltage stability margin and collapse point for each load bus of the entire system.

At each wind speed, the injected active and reactive power to the system are determined and the power flow analysis is done. So, the voltage stability margin is determined. To consider the probabilistic nature of the wind, the Expected Voltage Stability Margin (EVSM) is introduced here as the summation of each voltage stability margin multiplied by the probability of its wind speed as follows [16]:

$$\mathrm{EVSM} = \sum_{i=1}^{n} \mathrm{VSM}\,(V_i) * p(\nu_i) \qquad (10)$$

where, n is the number of wind speed pattern

The expected voltage stability margin (EVSM) is taken as an index to evaluate the influence of wind farm on the system voltage stability analysis

5. The Developed Algorithm

A new algorithm has been developed to incorporate the model of the wind turbine pitch regulated fixed speed generating units into power system to study power flow analysis and detect voltage stability margin and collapse points required for voltage stability analysis at each wind speed and accumulate for the expected voltage stability margin over the entire period. The main steps of the developed algorithm are:

1. Input system data (bus data, line data, load data, and generation data for the test system.
2. Input site data, Weibull distribution parameters, wind pattern and wind turbine characteristics (cut-in speed, rated speed, cut-off speed, and rated power).
3. Specify applied terminal voltage.
4. Plot tip speed ratio (λ) versus performance coefficient, C_p.
5. Construct power curve (wind speed versus active power)
6. Specify applied wind speed.
7. Determine active power P_e corresponding to the specified wind speed.
8. Derive Slip S from active power P_e.
9. Knowing slip S, compute reactive power Q_e
10. Construct reactive power curve (wind speed versus Q_e)
11. Perform power flow analysis for the test system and sensitivity analysis to determine the most sensitive buses,
12. Inject wind power at a specified bus (P & Q calculated) of the test system.
13. Perform power flow analysis for the test system including wind farm at specified bus for certain wind speed.
14. Determine voltage stability margin and collapse point at the specified wind speed.
15. Calculate the expected voltage stability as a function of wind speed by multiplying the voltage stability margin at that speed by its probability.
16. Check if this is the last wind speed in the wind speed pattern; if not go back to step 6 otherwise go to next step.
17. Accumulate for the expected voltage stability margin over the entire wind speed pattern
18. End

6. Case Study

The developed algorithm was implemented on Matlab environment and applied on the IEEE-26 bus test system with wind farm injection of 320 MW injected at bus 2.

6.1 Original IEEE-26 Bus Test System

The IEEE- 26 bus system data is shown in figure 5. The system consists of 6 generating buses and 20 load buses, total active power generation excluding the slack bus of the system is 2140 MW. The total load of the entire system equals 2526 MW and 1276 MVAr, the base power of the test system is taken as 100 MVA and the total compensation reactive power is 22 MVAr. The system has 7 transformers and 46 transmission lines. Bus 1 is considered as the slack bus [17].

6.1.1 Sensitivity Analysis of the Original IEEE-26 Bus System

At each load bus of the test system, the reactive power is increased till reaching the collapse point of the system. The difference of the reactive power between collapse point and first loading point is defined as Stability margin which is taken as an index of voltage stability. Table 1 shows the result of the voltage stability sensitivity analysis for the IEEE 26-bus system.

As shown from Table 1, the most sensitive bus in the system is bus 25. Increasing the load at that bus leads the system to collapse faster than any other bus in the system.

6.2 Injection of Wind Farm into the Test System

A 320 MW fixed speed pitch regulated wind turbine coupled with squirrel cage induction generator (FSPRIG) is interconnected with the IEEE 26-bus system.

Load Bus no	Load Mvar	Collapse Point		Stability Margin (MVAr)
		Voltage	MVAr	
6	58	0.469	377	319
7	0	0.526	735	735
8	0	0.589	2975	2975
9	100	0.536	400	300
11	30	0.453	255	225
12	96	0.498	528	432
13	30	0.543	3645	3615
14	24	0.696	816	792
15	62	0.526	465	403
16	54	0.497	405	351
17	76	0.608	418	342
18	134	0.428	1139	1005
19	30	0.546	210	180
20	56	0.561	336	280
21	46	0.587	230	184
22	44	0.489	286	242
23	24	0.526	156	132
24	54	0.617	189	135
25	26	0.509	117	91

Table 1. Sensitivity Analysis of 26 –IEEE bus System

6.2.1 Wind Turbine Generating Units Data

The study carried out fixed speed–pitch regulated Vestas 500 KW type [18] wind turbine generating units coupled to squirrel induction generator data. Wind turbine data shown in Table 2. are substituted in equations (2) and (3) to plot tip speed ratio (λ) versus performance coefficient (C_p) at different pitch angles and is shown by Fig. 1. The power curve of the wind turbine generating unit Vestas 500 KW is then constructed and illustrated in Fig. 2.

The characteristic of the sit shape factor and scale factor are 2 and 8 m/s respectively[8]. Knowing the characteristics of the site scale and shape parameters, the wind distribution function is plotted in Fig. 3. Using power curve to determine active power P_e corresponding to specified wind speed derive which is a function of Slip S as given in equation (8). Knowing the slip, reactive power corresponding for each value of active power P_e, can be calculated using equation

(9). Fig. 4. shows the reactive power curve (reactive power versus wind speed).

Table 2 Wind Turbine Data

Wind Turbine Data		**Induction Generator Data**	
C_1	0.5	Rating (MW)	0.5
C_2	67.56	Rated (KV)	0.69
C_3	0.0	R_1 (pu)	0.005986
C_4	0.0	X_1 (pu)	0.08212
C_5	1.517	R_2 (pu)	0.01690
C_6	16.286	X_2 (pu)	0.107225
β	5^0	X_m (pu)	2.5561
η	67.5	X_c (pu)	2.5561
R	29 m		
ρ	$1.225\ kg / m^3$		
c	8 m/s		
k	2		

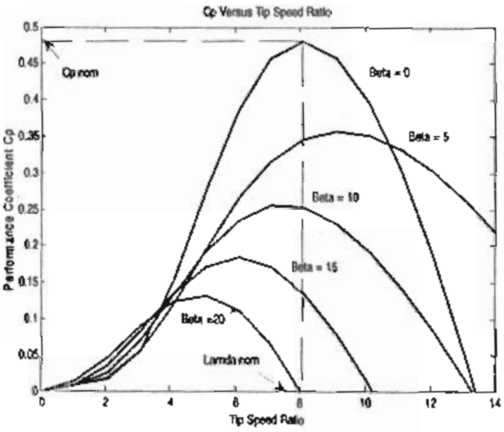

Fig. 1 Tip Speed Ratio Versus Performance Coefficient

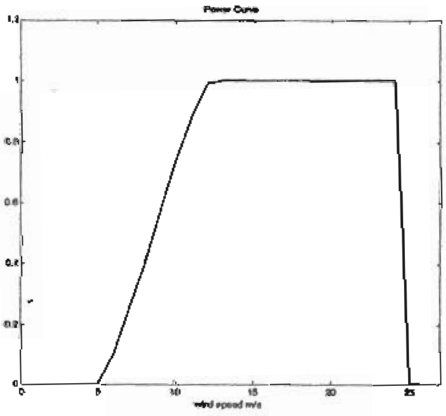

Fig 2 Active Power Curve

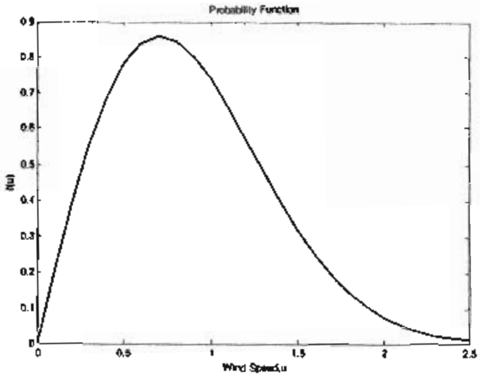

Fig. 3 Probability Distribution Function

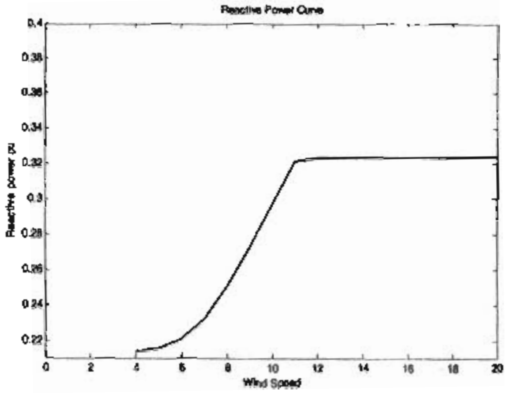

Fig.4 Reactive Power curve

6.2.2 Effect of WTGUs on Voltage Stability of the Test System

The wind farm consists of (640 unit each Vestas V29-500 fixed speed pitch regulated coupled with double squirrel cage induction machine) The WTGUs output is injected at a specified generating bus (bus 2 with 320 MW as a rated power) of the IEEE- 26 bus system.

For the most sensitive load bus (bus 25), the voltage stability margin at each individual wind speed is calculated by detecting the collapse point. Then the expected voltage stability margin of the system is calculated as a function of wind speed. The expected voltage stability margin of the system is then calculated. The impact of wind farm on voltage stability is explained by Table 3. The voltage stability, of the IEEE 26-bus Table 3

Table3. Voltage Stability Assessment for IEEE 26-Bus system after wind Farm Interconnection

Wind Speed	No of Hours	Probability P(v)	Collapse Point		Voltage Stability Margin (VSM)	EVSM
			Voltage	MVAr		
0-5	128	0.0146	----	0	0	0
6	302	0.03447	0.421	57	31	1.06
7	891	0.1017	0.430	61	35	3.56
8	1351	0.1542	0.447	64	38	5.86
9	1522	0.17374	0.450	68	42	7.297
10	1050	0.11986	0.455	72	46	5.51
11	877	0.10011	0.458	79	53	5.3
12	786	0.08972	0.466	82	56	5.024
13	514	0.05868	0.470	87	61	3.579
14	493	0.05628	0.473	92	66	3.714
15	425	0.04852	0.474	99	73	3.542
16	219	0.02454	0.474	102	76	1.865
17	94	0.01073	0.473	107	81	0.8691
18	68	0.00776	0.474	111	85	0.6596
19	27	0.00308	0.477	113	87	0.2679
20	9	0.00103	0.475	115	89	0.09
21	2	0.00023	0.473	115	89	0.011
22	1	0.00011	0.476	117	91	0.01
24	1	0.00011	0.477	117	91	0.01
25	0	0	----	0	0	0
Total	8760	1				48.22
Ratio of Wind Energy to Conventional System						53 %

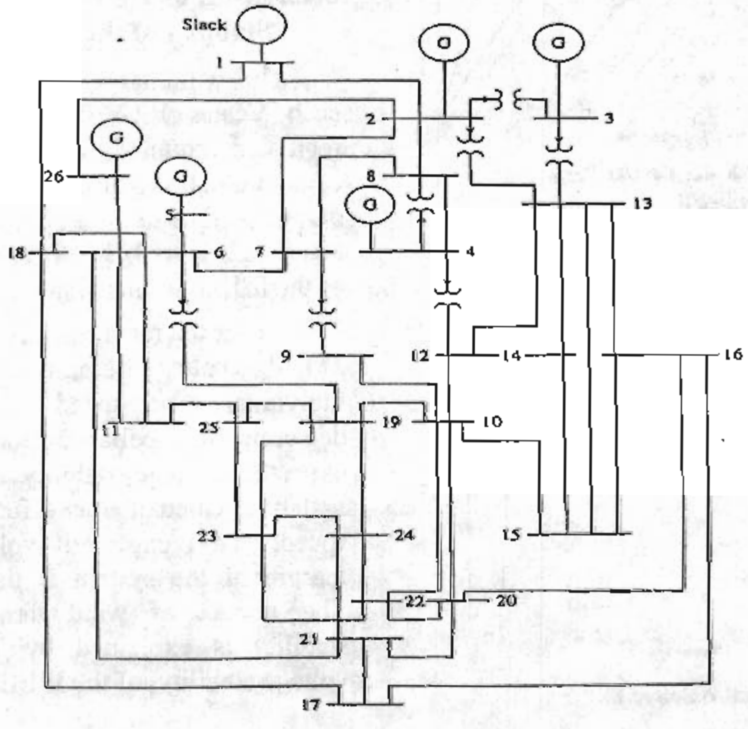

Fig. 5 IEEE -26 Test Bus System

system interconnected with the wind farm regulated wind turbine coupled with squirrel cage induction generator (FSPRIG) at the specified site, equals to 53 % compared with the conventional generation sources. This very important result can be used to determine the amount of the wind farm capacity that could be used to exactly replace the conventional sources from the voltage stability point of view.

7. Conclusion

The need for studying the steady state effect of wind energy interconnected with the grid is judged by the fact that the wind energy penetration in the grid is increasing every day under the pressure of the fossil fuel high prices and the rapidly increase of energy demand. Most of the studies on wind energy so far were interested on either a stand alone operation or transient analysis effect. The study carried out in this paper is innovative in dealing with the wind energy in steady state operation and its effect on one of the most important performance index which is the voltage stability.

In this paper, probabilistic voltage stability algorithm of WTGUs interconnected with the utility grid is developed via power flow analysis where these units are modeled as P-Q bus(es) by detecting the collapse point on the Q-V curves. The developed algorithm also facilitates the computation of both the real and reactive power output of the fixed speed pitch regulated wind turbine at a specific site, wind turbine characteristics, wind speed and terminal voltage. The probabilistic nature of wind is considered by introducing the expected voltage stability margin as an index that combines both of the voltage stability and the wind distribution in one index.

The proposed algorithm is applied on the IEEE 26-bus before and after injection of WTGU at bus 2. Voltage stability margin (VSM), and expected voltage stability margin (EVSM) are calculated at each wind speed. The accumulation of the of 320 MW fixed speed pitch EVSM over a specific period, say one year, can be considered as the system voltage stability margin which is a single value that can be compared with the voltage stability margin of an all-conventional power system. It is shown from the result that the developed algorithm detected the voltage stability, of the tested system with wind farm injection successfully. Also, we can use this very important result to determine the amount of the wind farm capacity that could be used to exactly replace the conventional sources from the voltage stability point of view. The proposed algorithm can be easily generalized for any type of wind turbine or generator driven by wind sources.

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