Effects Over Distribution Feeder of High Penetration Level of WECS Based on Induction Generators

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***Abstract*— In this paper, simulations on steady state over a typical radial distribution feeder with several penetration and dispersion levels of distributed generation using wind turbine based on inductions generator is developed. A MATLAB™ power flow program with a derailed model of single squirrel cage induction machine is used to quantitatively demonstrate inherent typical weak characteristic of the distribution system that make undesirable the use of large wind turbine based on induction generator. Results of these studies are shown here.**

***Index Terms*— Distribution feeder, reactive power flow, reactive power support, and wind energy conversion system based on induction generators**

I. Introduction

As result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources [1]. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted into electricity [1], [2]. One way of generating electricity from renewable sources is to use wind turbines that convert the energy contained in flowing air into electricity [3]. In recent years wind energy has become an important part of electrical generation in many countries and its importance is continuing to increase [4], [5].

Up to this moment, the amount of wind power integrated into large-scale electric power systems only covers a small part of the total power system load [6]. The rest of the power system load is for the largest part covered by conventional thermal, nuclear, and hydropower plants. But tendency to increase the amount of electricity generated from wind 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.

In particular, the new paradigm of distributed generation is giving rise to interconnection of small production units with the public utility MV or LV networks [5]. Due to economical and some technical reason squirrel cage induction machines result attractive to be used this wind turbine scheme. It consists of a conventional, directly grid coupled squirrel cage induction generator. The slip, and hence the rotor speed of a squirrel cage induction generator varies with the amount of power generated. These rotor speed variations are, however, very small, approximately 1 to 2 per cent. Therefore, this wind turbine type is normally referred to as a constant speed or fixed speed turbine [7].

The wind turbine system using traditional squirrel cage induction machine is attractive to be connected on distribution system, but a great number of generation units present some technical challenges to utilities. In this paper the steady state effect of high penetration level of wind turbine using squirrel single case induction generator.

II. Modeling

It is well known that distribution networks are typically radial and passive, were designed for one direction power flows. The interconnection of wind turbine generator injects power in different points of the network, where only consumptions have been previously planned. Therefore the presence of this generation units in MV distributions networks can cause several problems, namely:

- Voltage regulations difficulties at the HV/MV substations.
- Short-circuits level increase;
- The need for protective device coordination;
- Transient voltage dips resulting from induction generator interconnections.

These facts are presenting technical challenges to the utilities. In order to evaluate the impact of wind turbine on distribution network, simulation must be developed to overcome the technical operation problems and ensure a safe and reliable operation. This paper is focalized on determine the effects of high penetration levels of wind turbines with induction generator on voltage regulations and power losses; in order to evaluate the impact on these variables steady state simulation must be doing; load flow analysis.

When a wind turbine or wind farm with single cage induction machine generation is to be include in a load flow

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analysis the PQ, RX and PX buses are the most commonly used.

A. Single Squirrel Cage Induction Generator-Wind Turbine

A way to simulate a wind turbine is to assume a generated active power and a given power factor, with witch the consumed reactive power is calculated. Some improvement can be achieved if the steady state model of the induction machine is take in account (Steinmetz model, Fig. 1) [5], [8].

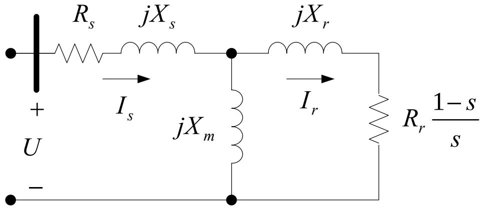

Fig. 1. Steady state equivalent circuit of induction machine. Positive phase sequence of balanced operation. R_s: stator resistance, X_s: Stator reactance, X_m: Magnetizing reactance, R_r: Rotor resistance (referred to stator), X_r: Rotor reactance (referred to stator), s: slip (negative for generator operation), U: Voltage applied, I_s: Stator current, I_r: rotor current.

The active power is calculated from the wind speed for this first iteration of the power flow analysis, and from then its value is remain as a constant. The reactive power depends on the active power and the bus voltage. In this case, we are decided calculating the reactive power as a function of the voltage.

$$Q_T = \left(\frac{(U)^2}{(R_s + R_{th})^2 + (X_s + X_{th})^2} \right) \left[X_s + \frac{X_{th}^2 + R_{th}^2}{X_m} + \frac{X_{th}^2 + R_{th}^2}{\left(\frac{R_r}{s}\right)^2 + X_r^2} \right] \quad (1)$$

where R_{th} and X_{th}, are Thevenin resistance and reactance respectively, both view from magnetizing reactance. The value of reactive power specified is updated each iteration; and this value is estimated from the steady-state equivalent circuit of the induction machine. A second order polynomial, calculate slip from mechanical power and, considering terminal voltage reactive power is update.

$$\alpha_2 s^2 + \alpha_1 s + \alpha_0 = 0 \quad (2)$$

where:

$$\alpha_2 = P_{sh} R_{th}^2 + P_{sh} (X_{th} + X_r)^2 + R_r |V_{th}|^2$$

$$\alpha_1 = 2 R_{th} R_r P_{sh} - R_r |V_{th}|^2$$

$$\alpha_0 = R_r^2 P_{sh}$$

The wind speed (v_w) is datum and active power can be obtained as a function of it. This is done by means of the power curve for the turbine and next equation [9]:

$$P_{sh} = \frac{1}{2} \rho A C_p v_w^3 \quad (3)$$

where A is the rotor area, ρ is the density of air and C_p is the power coefficient of wind turbine.

The power coefficient is obtainable as a function of the tip speed ratio, $\lambda = (\omega R / v_w)$, where ω is the rotor speed and R is its radius.

III. SIMULATIONS

The relevant results of the steady state simulations of 6.6 kV Kumamoto distribution feeder (Figure 1) including wind turbines based on induction generators are presented in this section. The steady state behavior of the test system was simulated by a program on MATLAB™ developed by the author. This program resolves the load flow problem, with a Newton-Raphson iterative method, and fully configurable to develop load flow studies. The load nodes are modeled as PQ node. There are modeled as constant power load that is independent of voltage level.

A. Test Feeder

To exanimate the effect of penetration level of wind turbine based on induction generator on a typical radial network. A modified version of the distribution feeder in the Kumamoto area of Japan [10] is used in the studies. The network parameters can be found in Appendix A, where the base power is 10 MVA and the base line voltage is 6.6 kV. The loads are considered as constant power and the total load in this distribution system is P_{load} = 18.9 MW, Q_{load} = 1.3 MVAR. Fig. 2 shows the test system used throughout the simulations, and locations of loads, are also shown.

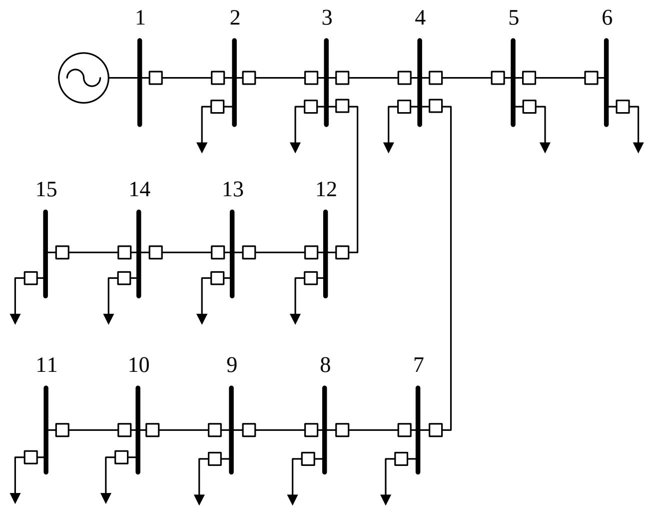

Fig. 2. Kumamoto 15-bus distribution system online diagram [10]

B. Wind Turbine

For simulations purpose, stall regulated wind turbine with induction generator is considered. The area swept by the blades of the wind turbine is 861 m^2, the hub height is 31m, and the rated power is 335 kVA.

TABLE I
WIND TURBINE INDUCTION GENERATOR PARAMETER

Parameter	*Value*
Nominal Voltage	660 V
Nominal Power	335 kVA
Rotor reactance	0.0639 p.u
Stator reactance	0.1878 p.u
Rotor resistance	0.00612 p.u
Stator resistance	0.00571 p.u
Magnetizing reactance	2.78 p.u
Inertia constant	3.025 s

Table I show the parameters of the induction generator and Figure 3, show the output power and power coefficient of the wind turbine. Every wind turbine is connected to distribution feeder through step-up transformer.

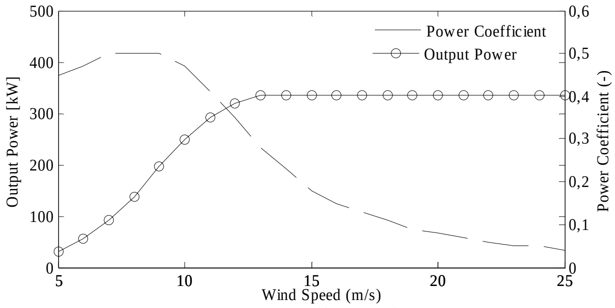

Fig. 3. Output power and power coefficient of wind turbine considered

C. Simulation Sceneries

To define and characterize the effects of wind turbines with induction generator main simulation scenarios would be defined. Some quantitative indicators would be defining the value and abdication of generator to be integrated on distribution feeder: Penetration level, Dispersion level.

Penetration Level (%*Penetration*) is fraction of total load (P_{load}) served by distributed generation (P_{DG}):

$$\%Penetration = \frac{P_{DG}}{P_{load}} \times 100\% \quad (4)$$

The key scenarios of penetration levels are (Table II):

- *Low Penetration Level:* consider a penetration level below 30%.
- *Semi-ideal Penetration Level:* Capacity of generation installed in this scenario is the half of all loads installed.
- *Ideal Penetration Level:* We consider generation installed with a capacity equal to all load installed.
- *Utopic Penetration Level:* In this scenario generation capacity is more than all loads installed, possibility of energy exportation to power utility is possible.

TABLE II
MAIN CHARACTERISTIC OF PENETRATION LEVELS SCENARIOS

Case Number	*Penetration Level*	P_{GD} *[MW]*	*Case Identification Name*
VI	150.0%	28.3545	Utopic
V	100.0%	18.9030	Ideal
IV	50.0%	9.4515	Semi-Ideal
III	30.0%	5.6709	III
II	20.0%	3.7806	II
I	10.0%	1.8903	I

Dispersion Level (%*Dispersion*), is ratio between number of nodes with generation (#*GDBus*) to number of nodes with loads (#*LoadBus*).

$$\%DispDG = \frac{\#DGBus}{\#LoadBus} \times 100\% \quad (5)$$

The main scenarios with penetration level are following (Table III):

- *Low Dispersion Level:* 21% and 28% level is considered.
- *Semi-ideal Level:* Generations are installed in half of all nodes.
- *Ideal Level:* In this case total dispersion is considered, generation is installed in each bus.

TABLE II
MAIN CHARACTERISTIC OF DISPERSION LEVELS SCENARIOS

Dispersion Level	*Number of Buses with GD*	*Case Identification Name*
100.000%	14	Ideal
92.857%	13	
85.714%	12	
78.571%	11	
71.429%	10	
64.286%	9	
57.143%	8	
50.000%	7	Semi-Ideal
42.857%	6	
35.714%	5	
28.571%	4	Low
21.429%	3	Low
14.286%	2	Low
7.143%	1	Very Low

IV. RESULTS

The steady state behavior of the test system was simulated by a program on MATLAB™ developed by the author. This program resolves the load flow problem, with a Newton-Raphson iterative method, and include wind turbine with induction generator by PQ bus model. A maximum power error of 10^{-3} p.u was considered. Preliminary simulation only with power utility generator, reveal an acceptable voltage profile (between 0.95 and 1.05 p.u.) (Figure 4).

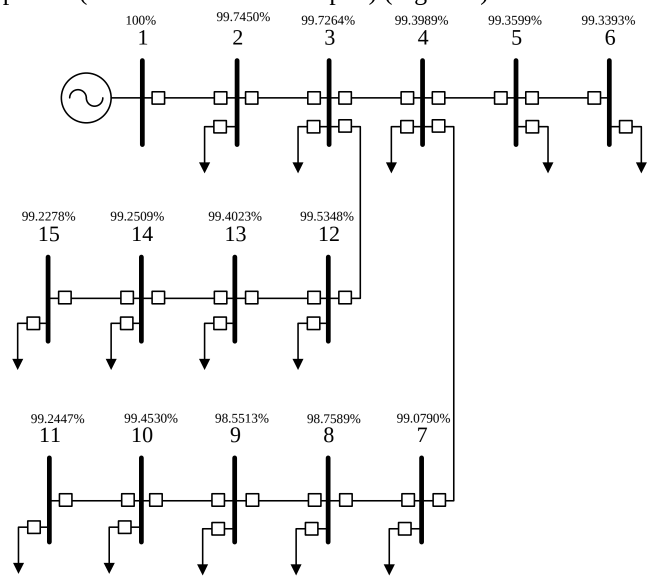

Fig. 4. Kumamoto 15-bus distribution system load flow results

Active power losses are near of 0.06 p.u, but when the penetration levels of wind turbines become high active losses come high, at generation about 120% of total load active power losses are 0.7 p.u, at low level of dispersion. Figure 5 show behavior of active power losses for all penetration and dispersion levels.

High losses of active power were found on high penetration levels and lowest dispersion level. At constant penetration level, low active power loses was found with high penetration levels.

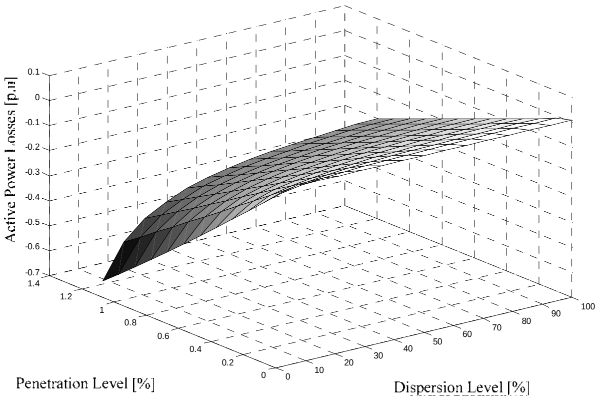

Fig. 5. Active power losses versus penetration and dispersion levels

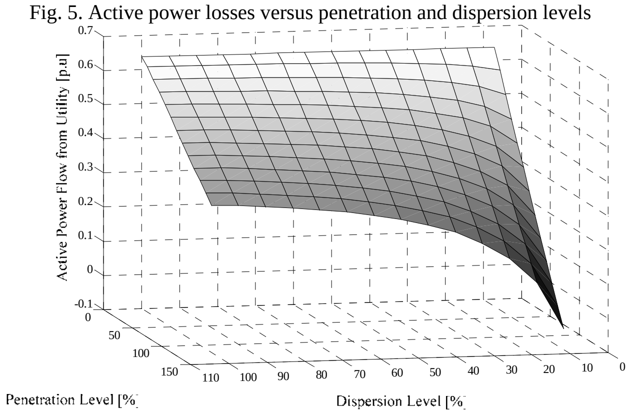

Fig. 6. Active power flow from utility. Minus sign mean power flow to utility system

Penetration level bigger than 100% in this radial feeder cause a change on active power flow direction. Bellow 100% penetration level active power flow come from utility system, but over 100% generator connecter on distribution feeder generate more power than all load connected, then active power is exported from distributed generators (see Fig. 6). Induction Reactive power flow with induction generation wind turbine grow with mechanical power increases, then when more favorable wind speed are available more high penetration levels would be reach, but consumption of reactive power is expected in all case. To improve the power factor it is common to fit local power factor correction capacitors on the terminals of the generator. In this case, high penetration levels implies a considerable number of small generator connected to the distribution feeder, with low short circuit level, including the effect of generators transformers, then additional reactive power is drawn from the utility.

The voltage regulation in distribution feeder wind turbines with induction generator became a serious problem. In Figure 7, voltage profile is shown for several penetration levels at maximum dispersion level. A large number of nodes are below acceptable voltage level (0.95 p.u) at all penetration level.

Voltage regulations difficulties are present with high penetration and high dispersion level; mainly due the reactive consumptions of induction generators, low short circuit level of the feeder.

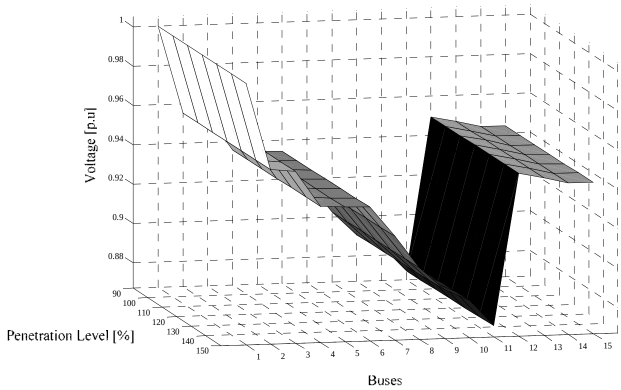

Fig. 7. Voltage profile for several penetration level considering a 100% dispersion level

V. Conclusions

The integration of wind turbine using induction generation is investigated in this paper. A typical distribution feeder was simulated in steady state a power flow program including staimetz induction machine model in PQ buses. Several penetration and dispersion levels were simulated. Simulation demonstrated the inherent typical weak characteristic of the distribution system that make undesirable the use of large wind turbine based on induction generator, because the high reactive consumptions of reactive power. Finally considerations of reactive support and compensation level was demonstrated due a poor voltage profile at high penetration and dispersion levels.

VI. Appendix

TABLE A.1
LINE AND LOAD DATA OF KUMAMOTO DISTRIBUTION SYSTEM [10]

Sending Node	*Ending Node*	*R (p.u)*	*X (p.u)*	*B (p.u)*	*Pload (p.u)*	*Qload (p.u)*
1	2	0.00315	0.075207	0.00000	0.02080	0.0021
2	3	0.00033	0.001849	0.00150	0.04950	0.0051
3	4	0.00667	0.030808	0.03525	0.09580	0.0098
4	5	0.00579	0.014949	0.00250	0.04420	0.0045
5	6	0.01414	0.036547	0.00000	0.01130	0.0012
4	7	0.00800	0.036961	0.03120	0.06380	0.0066
7	8	0.00900	0.041575	0.00000	0.03230	0.0033
8	9	0.00700	0.032346	0.00150	0.02130	0.0022
9	10	0.00367	0.016940	0.00350	0.02800	0.0029
10	11	0.00900	0.041575	0.00200	0.21700	0.0022
3	12	0.02750	0.127043	0.00000	0.01320	0.0014
12	13	0.03150	0.081405	0.00000	0.00290	0.0003
13	14	0.03965	0.102984	0.00000	0.01610	0.0016
14	15	0.01061	0.004153	0.00000	0.01390	0.0014

Bus voltage = 6.6kV, Base MVA = 10 MVA

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VIII. Biographies

Francisco M. González-Longatt (S’ 1998, M’2005). He received the electrical engineer degree from Instituto Universitario Politécnico de la Fuerzas Armadas Nacionales, Venezuela, in 1994, and Master of Business Administration from Universidad Bicentenaria de Aragua, Venezuela, in 1998. He is currently working for PhD degree of Universidad Central de Venezuela, researching on the impact of the distributed generation on dynamic stability of electrical power system. He is asistant Professor of Universidad Nacional Politécnica de la Fuerza Armada (UNEFA), Venezuela since 1994. He is member of IEEE Power Engineering, Industry Application and Power Electronics societies. He was director of the UNEFA Electrical Engineering Department and founder of the power system research center on UNEFA. He has written books on transient stability of power system, and has been lecturer on regional and international meetings. His main area of interest is the dynamic behavior of distributed energy resources and the impact on the power system stability. He has authored more than 30 technical papers and report in this area.

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