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Voltage Stability Investigation of Grid Connected Wind Farm

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***Abstract*—**At present, it is very common to find renewable energy resources, especially wind power, connected to distribution systems. The impact of this wind power on voltage distribution levels has been addressed in the literature. The majority of this works deals with the determination of the maximum active and reactive power that is possible to be connected on a system load bus, until the voltage at that bus reaches the voltage collapse point. It is done by the traditional methods of PV curves reported in many references. Theoretical expression of maximum power limited by voltage stability transfer through a grid is formulated using an exact representation of distribution line with ABCD parameters. The expression is used to plot PV curves at various power factors of a radial system. Limited values of reactive power can be obtained. This paper presents a method to study the relationship between the active power and voltage (PV) at the load bus to identify the voltage stability limit. It is a foundation to build a permitted working operation region in complying with the voltage stability limit at the point of common coupling (PCC) connected wind farm.

***Keywords*—**Wind generator, Voltage stability, grid connected

I. INTRODUCTION.

RECENTLY Wind Generator (WG) has been experiencing a rapid development in a global scale. The size of wind turbines and wind farms are increasing quickly; a large amount of wind power is integrated into the power system. As the wind power penetration into the grid increases quickly, the influence of wind turbines (WT) on the power quality and voltage stability is becoming more and more important.. Highlight a section that you want to designate with a certain style, then select the appropriate name on the style menu. The style will adjust your fonts and line spacing. It is well known that a huge penetration of wind energy in a power system may cause important problems due to the random nature of the wind and the characteristics of the wind generators.

In large wind farms connected to the transmission network the main technical constraint to take into account is the power system transient stability that could be lost when, for example, a voltage dip causes the switch off of a large number of WGs. In the case of smaller installations connected to weak electric grids, power quality problems may became a serious concern because of the proximity of the generators to the loads.

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The existence of voltage dips is one of the main disturbances related to power quality in distribution networks. In developed countries, it is known that from 75% up to 95% of the industrial sector claims to the electric distribution companies are related to problems originated by this disturbance type [4, 5]. These problems arise from the fact that many electrical loads are not designed to maintain their normal use behaviour during a voltage dip. The aim of this paper is to conduct a voltage stability analysis using exact representation of distribution line with ABCD parameters, to evaluate the impact of strategically placed wind generators on distribution systems with respect to the critical voltage variations and collapse margins. This paper concludes with the discussion of wind generators excellent options for voltage stability [1].

II. INDUCTION MACHINES

Induction machines are use extensively in the power system as induction motors but are not widely used as generators. Despite their simplicity in construction, they are not preferred as much as synchronous generators. This is mainly due to the defined relationship between the export of P and absorption of Q. However, induction generators have the benefits of providing large damping torque in the prime mover, which makes it suitable for the application in fixed speed WTs. The fixed speed WT uses a squirrel cage induction generator that is coupled to the power system through a connecting transformer as shown in Fig 1 [1]. Due to different operating speeds of the WT rotor and generator, a gearbox is used to match these speeds. The generator slip slightly varies with the amount of generated power and is therefore not entirely constant [4].

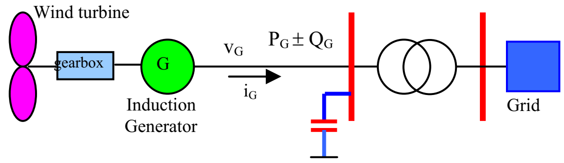

Fig. 1 Modelling wind turbine connected grid [1]

However, because these speed variations are in the order of 1 per cent this wind turbine is normally referred to as constant speed. Nowadays, this type of wind turbine is nearly always combined with stall control of the aerodynamic power, although pitch-controlled constant speed wind turbine types have been built in the past. Induction machines consume reactive power and consequently, it is present practice to provide power factor correction capacitors at each WT. These are typically rated at around 30 percent of the wind farmcapacity. As the stator voltage of most wind turbine electrical generators is 690V, the connecting transformer of the wind turbine is essential for connection to the distribution network and should be considered when modeling the electrical interaction with the power system [2].

III. VOLTAGE STABILTY

A system experiences a state of voltage instability when there is a progressive or uncontrollable drop in voltage magnitude after a disturbance, increase in load demand or change in operating condition. The main factor, which causes these unacceptable voltage profiles, is the inability of the distribution system to meet the demand for reactive power. Under normal operating conditions, the bus voltage magnitude (V) increases as Q injected at the same bus is increased. However, when V of any one of the system's buses decreases with the increase in Q for that same bus, the system is said to be unstable. Although the voltage instability is a localised problem, its impact on the system can be wide spread as it depends on the relationship between transmitted P, injected Q and receiving end V. These relationships play an important role in the stability analysis, can be displayed graphically [1].

III.1. PV Curves

When considering voltage stability, the relationship between transmitted P and receiving end V is of interest. The voltage stability analysis process involves the transfer of P from one region of a system to another, and monitoring the effects to the system voltages, V. This type of analysis is commonly referred to as a PV study.

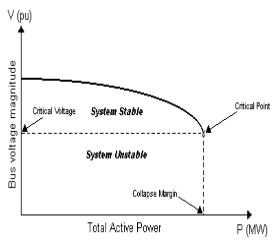

Fig. 2 Charactic P-V

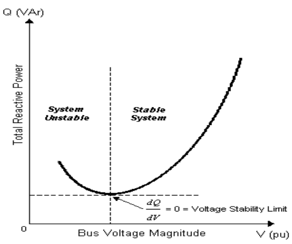

Fig. 3 Charatic Q-V

The Fig 2 shows a typical PV curve. It represents the variation in voltage at a particular bus as a function of the total active power supplied to loads or sinking areas. It can be seen that at the "knee" of the PV curve, the voltage drops rapidly when there is an increase in the load demand. Load flow solutions do not converge beyond this point, which indicates that the system has become unstable. This point is called the Critical point. Hence, the curve can be used to determine the system's critical operating voltage and collapse margin. Generally, operating points above the critical point signifies a stable system. If the operating points are below the critical point, the system is diagnosed to be in an unstable condition [5].

III.2. QV curves

Voltage stability depends on how the variations in Q and P affect the voltages at the load buses. The influence of reactive power characteristics of devices at the receiving end is more apparent in a QV relationship.It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions. Fig 3 shows a typical QV curve, which is usually generated by a series of load flow solutions. Figure 3 shows a voltage stability limit at the point where the derivative dQ/dV is zero. This point also defines the minimum reactive power requirement for a stable operation. An increase in Q will result an increase in voltage during normal operating conditions. Hence, if the operating point is on the right side of the curve, the system is said to be stable. Conversely, operating points in the left side of the graph are deemed to be unstable [4, 5].

IV. VOLTAGE STABILITY BOUNDARY

If the WG produces $P_{gen} + jQ_{gen}$; local load is $P_{load} + jQ_{load}$, the complex power delivered to the line shown in Fig 4 is:

$$S_{line} = (P_{WT} - P_L) + j(Q_{WT} - Q_L) \tag{1}$$

From the phasor diagram in figure 5 the per-unit voltage rise at the local busbar may be estimated as:

$$\Delta U = \frac{R.P_{grid} + X.Q_{grid}}{U_{grid}} + j\frac{X.P_{grid} - R.Q_{grid}}{U_{grid}} \tag{2}$$

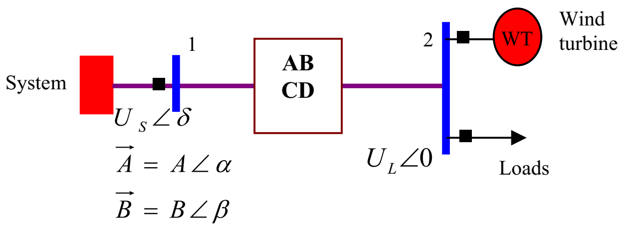

Fig. 4 Radial feeder with connected WG

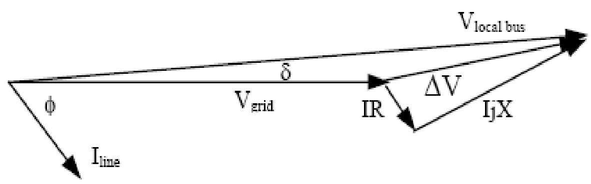

Fig. 5 Voltage Phasor Diagram

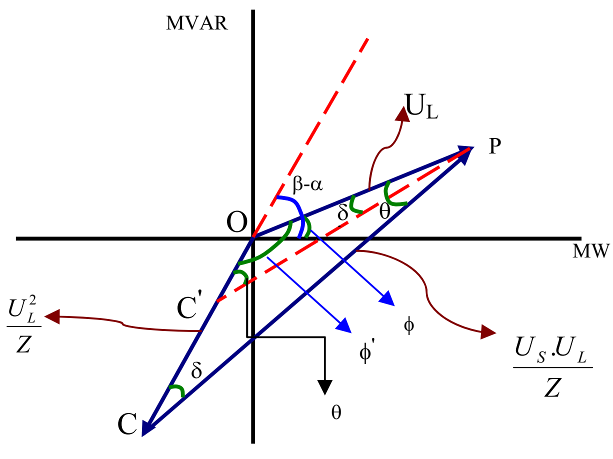

Fig. 6 UPCD for short distribution line

Equations 1 and 2 show that, where line power flow is dominated by WG production, operating asynchronous WGs at a constant power factor will result in voltage excursion as the plant tries to export reactive power in constant proportion to active power. Line impedance directly increases voltage rise. Line X/R ratio skews the effects of real and reactive power. A clearer appreciation of these may be obtained by considering the Universal Power Circle Diagram (UPCD) for a short distribution line shown in Fig 6 [1], [11].

A radial transmission line is shown in Fig. 4 in which a generator with a constant voltage $U_S\angle\delta$ supplying complex power S_L to a load with a terminal voltage $U_L\angle 0$ through a transmission line represented by its ABCD parameters. Complex power at the receiving end of a transmission line shown in Fig. 4 is given as [4,8]:

$$S_L = \frac{-AU_L^2}{B}\angle\beta-\alpha + \frac{U_S U_L}{B}\angle\beta-\delta \tag{3}$$

The above equation (3) represents a circle for varying value of δ with position of centre indicated by $\frac{-AU_L^2}{B}\angle\beta-\alpha$ and radius by $\frac{U_S U_L}{B}$ where A = A ∠α and B = B ∠β are the line constants and δ is power angle. From Fig. 6:

$$OC = \frac{AU_L^2}{B}; \quad OP = S_L; \quad CP = \frac{U_S U_L}{B} \tag{4}$$

$$\phi' = 180^0 - (\beta-\alpha)+\phi; \quad \delta' = \delta-\alpha \tag{5}$$

ϕ is the power factor angle and is positive for lagging power factor and negative for leading power factor. In ΔOCP:

$$\frac{OP}{\sin\delta'} = \frac{CP}{\sin\phi'} = \frac{OC}{\sin\theta} \tag{6}$$

From (3) to (6): $$S_L = \frac{U_S^2 \sin\theta \sin\delta'}{AB\sin^2\phi'} \tag{7}$$

Also from ΔOCP: $$\theta = 180^0 - (\phi' + \delta') \tag{8}$$

Therefore: $$S_L = \frac{U_S^2 \sin(\phi'+\delta')\sin\delta'}{AB\sin^2\phi'} \tag{9}$$

For S_L to be maximum: $$\frac{dS_L}{d\delta} = \frac{dS_L}{d\delta'} = 0 \tag{10}$$

Solution of (9) provides critical value of power angle δ, critical value of voltage and maximum value of complex power:

$$S_{L-\max} = \frac{U_S^2}{4A.B.\sin^2\phi'/2} \tag{11}$$

$$\delta'_{th} = 90^0 - \frac{\phi'}{2} \text{ and } \delta_{th} = 90^0 - \frac{\phi}{2}+\alpha;$$

Therefore : $$U_L^{th} = \frac{U_S}{2A.\sin\phi'/2} \tag{12}$$

Equation (9), (11) and (12) relate complex power with maximum complex power:

$$S_L = \frac{S_{L-\max}\left[\sin(\phi'+\delta')\sin\delta'\right]}{\cos^2\phi'/2} \tag{13}$$

The maximum value of active power and limiting value of reactive power:

$$P_{L-\max} = S_{L-\max}.\cos\phi$$
$$Q_{L-\lim} = S_{L-\max}.\sin\phi \tag{14}$$

Receiving end voltage is obtained as:

$$U_L = \frac{U_S.\sin(\phi'+\delta')}{A.\sin\phi'} \tag{15}$$

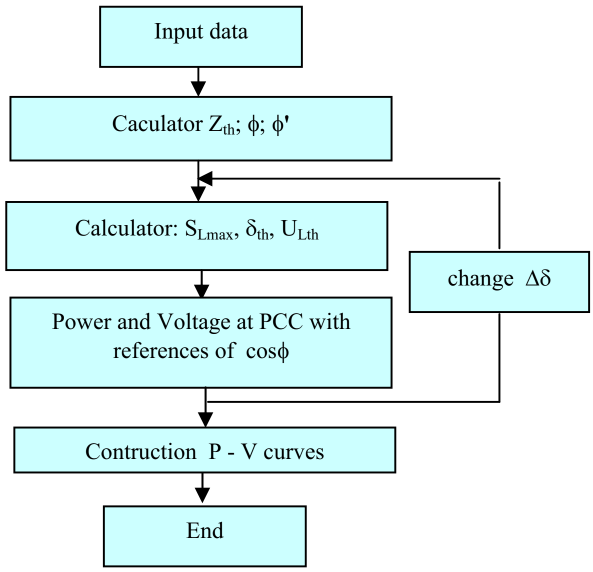

Fig. 7 Flow chart

This limits dispatch of complex power. While these diagrams are based on complex power flow in the line, they are useful to visualise the effects of network changes on the limits of operation and dispatch of asynchronous WGs connected to the local busbar, particularly where the capacity of the WG is dominant. They also enable computation and examination of loci of busbar voltage as the WG is loaded or as local demand varies, while the plant is in constant power factor or constant voltage control, the flow chart is shown in Fig. 7.

V. TEST SYSTEM

The studied model represents an equivalent of the Phuoc Ninh, Ninh Thuan, Viet Nam (Fig. 8) system in the area where large scale wind power production is located [6, 10]. The model represents a 50 MW wind power station consisting 50 turbines with fixed speed asynchronous generators directly connected to the grid. The turbines are stall regulated type, with a rating of 1.0 MW each. Fig 9 shows the equivalent model of the system. Z_{th} = (0,00125 +j0.005) [11]. Sending end voltage is constant.

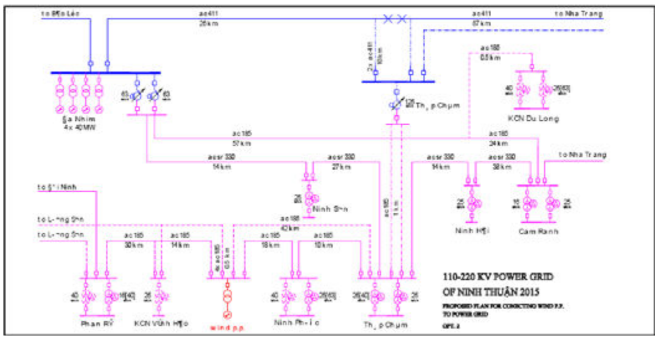

Fig. 8 The grid connection of the proposed Phuoc Ninh wind farm – Viet Nam (2015)

In order to investigate the impact of the injection of active power by the wind farm the system is approximated to a series of impedances as indicated below.

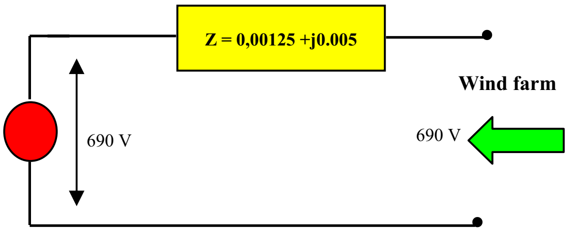

Fig. 9 Equivalent grid and connection system impedance as seen from the low voltage (690V)

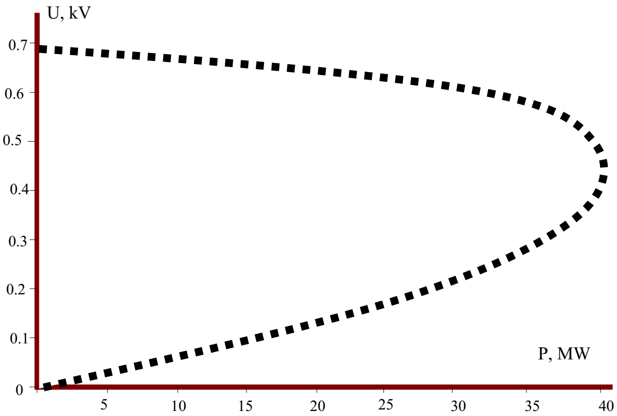

Fig. 10 PV Curve at different power factors: $\phi = 0^0$

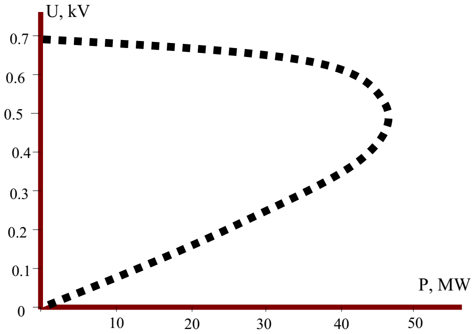

Fig. 11PV Curve at different power factors: $\phi = 10^0$ lead

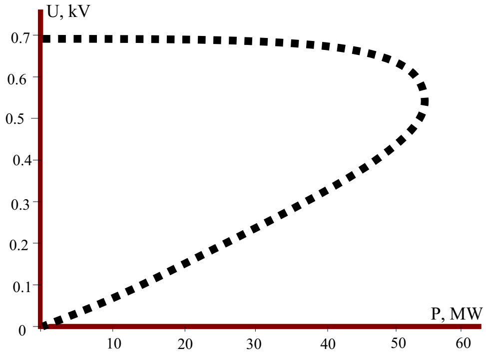

Fig. 12 PV Curve at different power factors: $\phi = 20^0$ lead

For this option the voltage profile at the generator terminals is required and therefore all the impedances need to be reflected to the voltage level at the generator, i.e. 690V. Fundamentally, it simulates the injection of current from the wind farm in steps and calculates the voltage dropped across the Thévenin impedance at each step. This builds up number of points for the voltage at the generator terminals as the power injected increases. The resulting plotted curve is known the voltage "nose" curve due to its shape.

The PV curves for the above problem has been drawn for 0°,10° leading and 20° leading power factor angle. From the curve we obtain that value of P_L increases from lagging to leading power factor. We also obtain that there are two values of U_L for a given P_L except at P_{Lmax}. The curves is shown in figure 10 to 12.

This graph shows that, following the pf =1 (i.e. power factor compensation so that it is corrected to unity power factor) from left to right, the voltage rises as the current injected increases and the power increases to about 39,03 MW. Then after 39,03 MW the voltage starts to drop until the "nose" point where the rate of decrease in voltage is faster than the rate of increase in the current injected and the power actually drops. This (the nose point) is the onset of voltage instability.

From this it can be seen that i) approximately a maximum of 39,03 MW power can be injected without instability, and ii) reactive power control is necessary so that the wind farm can be operated at, or very close to, unity power factor. If the power factor drops, it can be seen that operation is much too close to the point of voltage instability. Furthermore, the basic compensation known as "no-load" compensation (i.e. compensation for the reactive power drawn by the induction machines when they are connected but not operating) is insufficient. What all this means, in practice, is that if the power factor compensation units fail then wind farm production must be stopped.

VI. CONCLUSION

There is a need for WGs to be able to operate within a voltage envelope to maximise dispatch of active power. Additionally, at times when network voltage is depressed the same system could export controlled reactive power for system voltage support. Some Distribution Network Operator are now prepared to consider and integrate WGs that can operate to provide voltage support. Network reinforcement costs may be deferred and loss of generation due to over-voltage shutdown may be reduced. Busbar, generator and excitation system protection settings and timings will require to be applied carefully, within statutory and manufacturers' limits to ensure that WG plant operates within accepted network voltages and machine ratings.

Simple analytical expression for real power critical voltage has been formulated and had been used to draw PV curve of a radial transmission line. It is observed that real power increases from lagging to leading power factor. We also obtain that there are two values of receiving end voltage U_L for a given P_L except at P_{Lmax}. QV curves for fixed P_L and different U_L can also be plotted using the derived relationship and devised algorithm by varying reactive power.

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