Introduction of Wind Power into a Weak Power System Considering System Fluctuation and Limitation

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Abstract: - This paper presents the methodology to estimate stable and dynamic operational characteristics of Wind Power Turbines (WPT) in a targeted weak power system under the defined wind condition. Operational characteristics of WPT under regular and irregular wind speeds are determined and verified against system operational particularities. The losses from reactive power and grid voltage drop are useful to determine the system safety range. Impact current resulting from when WPT connects with power systems and its use for analysing the stability of the grid. Electric parameters of WPT in weak power systems under the short circuit condition are simulated and used for checking the stability of the power system. The maximum capacity of wind power generation that can be safely introduced into the targeted power system is determined by considering the fluctuation range of grid voltage. This paper provides a synthetic way to judge the operational characteristics of WPT when installed into a weak power system; it shows value in a practical application.

Key-Words: - WPT, Weak Power System, Operational Process, Electric Fluctuation, Wind Power Limitation

1 Introduction

In the past ten years, wind energy has been one of fastest growing electricity generation technologies. According to the Press Release "New World Record in Wind Power Capacity" by World Wind Energy Association, the globally installed capacity of wind power energy grew from 7475MW in 1997 to 73904MW by the end of December 2006, and is expected to keep growing and reach 160000MW by the end of 2010 [8]. Since wind power energy has a more important role in electricity generation today, it is important to analyse the operational characteristics of WPT and the effect on the targeted power system before WPT installation.

In planning installation of wind power generation in any scaled power system; it is important to examine the operational characteristics of WPT. Furthermore, it is also crucial to examine the possible impact on the power system of the installation site. In order to achieve the above, the simulated results from the following tests are scrutinized closely:

- Testing the WPT under regular wind speed at the installation site
- Testing the WPT under sudden wind speed change at the installation site
- Determine the impact on WPT when connecting with the power system grid
- Determine the impact on WPT and the power system when short circuit occurs
- Calculate the maximum capacity of wind power generation at the installation site

When WPT is connected to the power system, it may result in voltage drops and loss of reactive power in the power system. However, the impact on weak power systems is stronger when compared to strong power systems; but in particular, it always found in weak power system areas where the wind conditions are best. Thus, weak power systems with WPT are discussed in depth in this paper.

2 Background of Installation Site

Wind power system composes of WPT and Power system. In this paper, 600kW fixed speed WPT and weak power system have been installed at the installation site. Followings are more detailed explanations on these two components:

2.1 Weak power system

The word "weak" of Weak power system is used when the substation grid is not stiff enough, such that the grid voltage could not be well-controlled. The substation system in the weak power system usually comprised of several buses. In order to reduce the impact on the existing power system, the optimal bus must be selected carefully.Without this step, this research presented in this paper may lose its meaning. However, the task for selecting the optimal bus for WPT has been achieved in our previous research, hence here author only make simple introduction to introduce these methods.For large power system, the selection of the optimal bus can be conducted through the Domain-Link Method (DLM)[2]. Whereas for the small power system, the Weakness Degree in Energy Supply Method (WDES)[3] and Endurace Index of Crisis Hours Method (EICH)[4] can be utilised.

For the purpose of this paper, it is assumed that the WPT has already been connected to the optimal bus, and the stability limit of connection system has all been satisfied.The circuit diagram (Fig.1) below describes the interconnection of wind power farm at the terminal of weak power system, and this model is applied in this research.

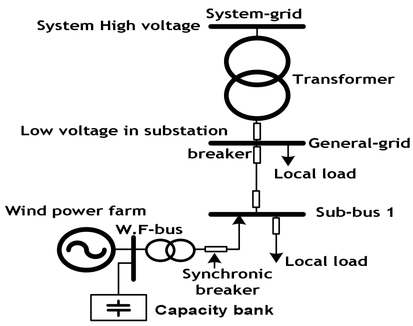

Fig.1. Inter-connection of wind power farm at terminal of a targeting weak power system

The parameters of the above model for this research are listed in Table 1:

Table 1: Parameters of targeting weak power system at the defined installation site

Transformer on wind power farm side	690V/22.8kV 12MVA
Transformer on system high voltage side	22.8kV/69.3kV 25MVA
Capacity bank	0.23MVAR
Load on general-grid	2MVA Power Factor 0.85
System-grid short circuit level	70MVA

2.2 Fixed speed WPT

In this research, 600 kW fixed speed WPT is employed. Fixed speed WPT is chosen because it is inexpensive and easy to construct. However, it does have a property of high starting current and it absorbs reactive power from the power system. As a result, the grid voltage fluctuates. The parameters of the 600kW Fixed speed WPT use in this research are given in Table 2.

Table2. Parameter of 600kW fixed speed WPT

P/W	S/VA	f/Hz	R1/ohm	L1/H
0.6M	0.652M	60	0.0079	0.00017
R2/ohm	L2/H	Pole	Cut-in wind speed	Cut-out wind speed
0.0006	0.00017	6	3.2m/s	13.8m/s

3 Operational Characteristic of WPT in Different Conditions

This section presents the simulation result from the five different installation tests mentioned in the Introduction.

3.1 Under regular wind speed

In most of the operational time, the WPT works under regular wind speed. Hence, it is important to analyse the operational characteristic of WPT and the effect on the targeting power system under this wind speed condition.

3.1.1 Equations for WPT in stable process

Wind power generation highly depends on wind speed, and the amount of wind power generation is the key factor to determine the stability of power system. Power generation of define WPT under the regular wind speed condition is shown in Fig2.

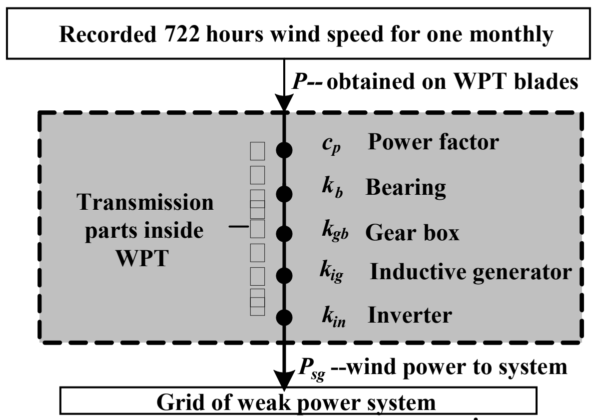

Fig.2. Transmission parts inside WPT connected to Weak power system under recorded wind speed

In WPT, the power absorbe by the blade is giveing in P, and this kinetic energy P then transforme to the electrical energy P_{sg} through the transmission part inside of WPT. The equation explain this energy conversion process expresses by the following equation (1).

$$\begin{cases} P = 0.5\rho\, A\, V^3 \\ P_{sg} = C_p\, k_b\, k_{gb}\, k_{ig}\, k_{in} \end{cases}$$

(1)

Where V is wind speed, A is cross-section area swept by blades, ρ is air density of installation site and C_p is power factor of defined WPT. The coefficient k from equation(1) is only apply with single WPT, therefore in case a group of WPT apply, the total generation can be obtained from the sum of each generation of each WPT. But for the losses reactive power and grid voltage drop has no longer linear relation with amount of each WPT. It is not possible to estimate these parameters directly from the calculation.

3.1.2 Regular wind speed at the installation site

In this paper, actual wind speed data recorded from the targeting installation site are entered into the simulation. In comparison with the average wind speed that is usually obtained by statistical method from *Wind and Generation Matrixes* [1], this real wind speed data allows the result of the simulation to become more realistic in relation to the real operation conditions at the targeting installation site. The month selected for wind speed data recording was the month with the strongest and most volatile wind speeds; this data can represent all possible wind conditions at the installation site. The regular wind speed as shown in Fig.3.

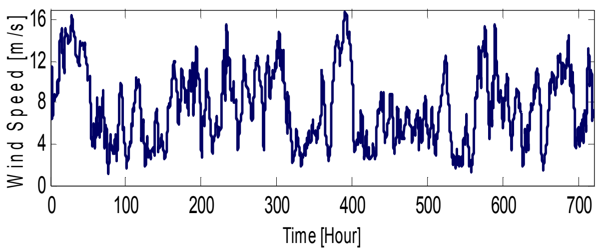

Fig.3. Regular wind speed data at the defined installation site

3.1.3 Simulation result

The simulation result indicates that a single 600kW fixed speed WPT operates in fine condition; and has good tracking ability under regular wind speed condition. According to the results, when wind speed increases, the rotor of WPT will rotate faster; real power generation will increase; and WPT will absorb more reactive power. Vice versa, when wind speed goes down, smaller amount of real power will be generated, and WPT will absorb less reactive power.

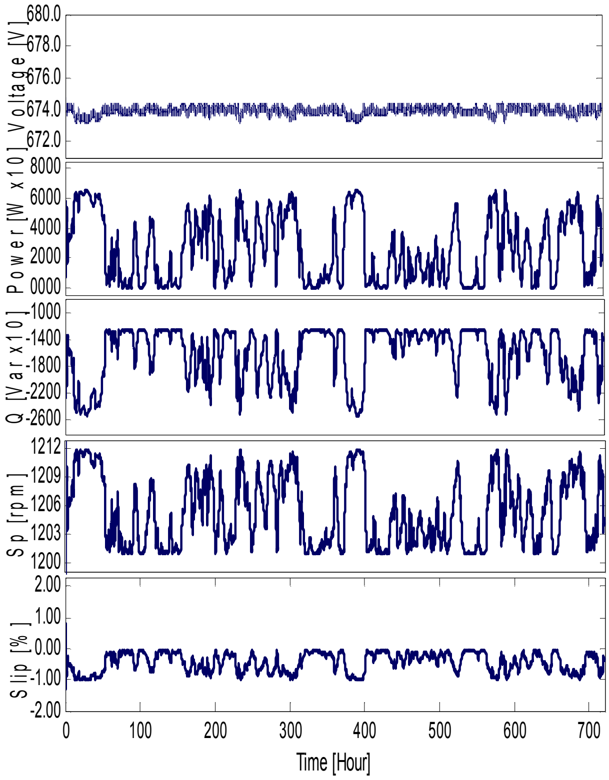

Fig.4. Simulation result of single 600kW fixed speed WPT under regular wind speed at the defined installation site

3.2 Under sudden changes in wind speed

WPT suffers from transient process under sudden changes in wind speed conditions. Actually, there are many reasons that lead to transient process of WPT therefore affecting the system's stability. From the view of wind speed, small variations in wind speed may be absorbed by WPT blades and inertia without causing transient process, but when large and sharp variations of wind speed occurs for relatively long periods of time, WPT must reach a new operation point through transient process by tracking the control way $dP/d\omega = 0$ .This simulation result can be used to judge the dynamic characteristic and stability of WPT under sudden wind change.

3.2.1 Equations for WPT in dynamic process

Transient equations included electrical equation and mechanic equation [5] that derived from basic theory of asynchronous inductive generator. All parameters are converted to DQO candidate system. Uppercase and lowercase letters indicated the parameters of rotor and stator according. ω and ω_1 are synchronous and asynchronous velocity of state magnetic field and generator rotor, the electrical equation of inductive generator can be expressed by equation (2)

$$\left.\begin{aligned} p\psi_d &= R_1 i_d + \omega\psi_q + V_d \\ P\psi_q &= R_1 i_q - \omega\psi_d + V_q \\ p\psi_D &= -R_2 i_D + (\omega - \omega_1)\psi_Q \\ p\psi_Q &= -R_2 i_Q - (\omega - \omega_1)\psi_D \end{aligned}\right\}$$

(2)

Where, $p = d/dt$, i, ψ and V are currents, magnetic linkages and voltages. R_1 and R_2 are resistances of stator and rotor. In the view of WPT, defined magnetic-electric torque as $T_E = \psi_d i_q - \psi_q i_d$, T_T and T_W are mechanic torque on WPT blade axes and generator input axes. The Mechanical equation can be expressed by equation (3)

$$\left.\begin{aligned} ds/dt &= (T_T - T_E)/T_J \\ dT_T/dt &= (T_w - T_T)/T_H \\ d\theta/dt &= \omega_1 \end{aligned}\right\}$$

(3)

Where s is slip of generator, T_H and T_J are inertia time constant of turbine and generator, and θ is angle between stator and rotor. Based on equation (2) and (3), the voltage, current and torque equation can be expressed by equation (4). Based on (2), three standard equations that can be used for transient simulation are expressed by matrix equation (3), where; $p = d/dt$, I, ψ , V and E are respectively current, magnetic linkages, voltages and electrical potential matrixes. A in each equation is variable matrix related to same electric parameters such as current, magnetic linkage, voltage and electric potential. B in each equation is additional matrixes with same degree as A.

$$\begin{cases} p\psi = A\psi + BV \\ pE = AE + BI \\ pI = AI + BV \end{cases}$$

(3)

Equation (3) can be feasibly used in according to the simulation target and it can be also expressed by (4):

$$\left.\begin{aligned} \Delta pX_i &= \frac{\partial f_i}{\partial X_1}\Delta x_1 + \ldots + \frac{\partial f_i}{\partial X_n}\Delta x_n + \frac{\partial f_i}{\partial U_1}\Delta u_1 + \ldots + \frac{\partial f_i}{\partial U_r}\Delta u_r \\ \Delta Y_j &= \frac{\partial F_j}{\partial X_1}\Delta x_1 + \ldots + \frac{\partial F_j}{\partial X_n}\Delta x_n + \frac{\partial F_j}{\partial U_1}\Delta u_1 + \ldots + \frac{\partial F_j}{\partial U_r}\Delta u_r \end{aligned}\right\}$$

(4)

here, n is the order of system and r is the number of input, above equation can be written as (5):

$$\left.\begin{aligned} \Delta pX &= A\Delta X + B\Delta U \\ \Delta Y &= C\Delta X + D\Delta U \end{aligned}\right\}$$

(5)

Here C is output constant matrix; D is constant matrix related to input. Equation (5) is linearization state of (3), and it enable in defined time range to represents the states denoted by (3), two states are therefore equivalent states. Equation (5) is able to be linked to SIMULINK program and calculated by numeral method. The linearization form of equation (5) can be realized by equation (6):

$$\left.\begin{aligned} \dot{X} &= AX + BU \\ Y &= CX + DU \end{aligned}\right\}$$

(6)

This simulation is based on the data given in the provided wind data that shown in Fig. 5

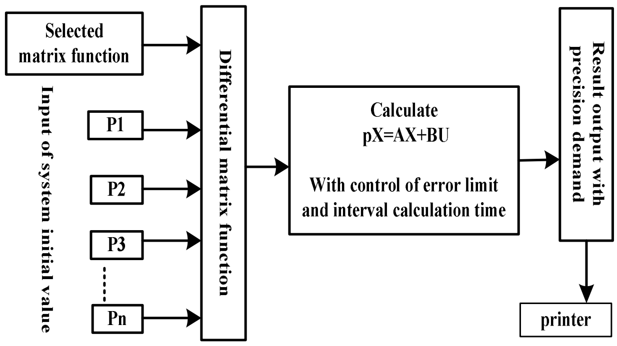

Fig.5. Diagram of simulation process

3.2.2 Simulation result

The result of the simulation indicates a single 600kW fixed speed WPT operates in good condition and has good tracking ability during sudden increase in wind speed at the targeting installation site. According to the simulation results, when wind speed increases spontaneously, WPT will generate more real power, and also absorbed reactive power is required at the same time to maintain operation. Since the fixed compensating capacitor used in this research is sufficient to supply one WPT's reactive power needs, therefore this is one of the reasons the grid voltage only fluctuated in small amounts during this simulation. But in the case where the compensating capacitor is not available, the reactive power required for the WPT will be absorbe from the power system, and this may result in a grid voltage drop.This type of voltage drop phenomenon will be exacerbated if the weak power system is in the application

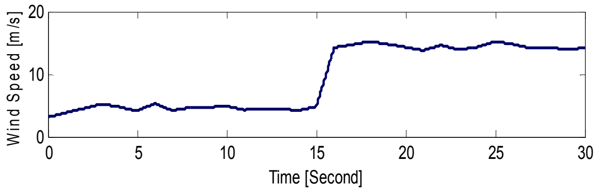

Fig.6. increase in wind speed at the defined installation site

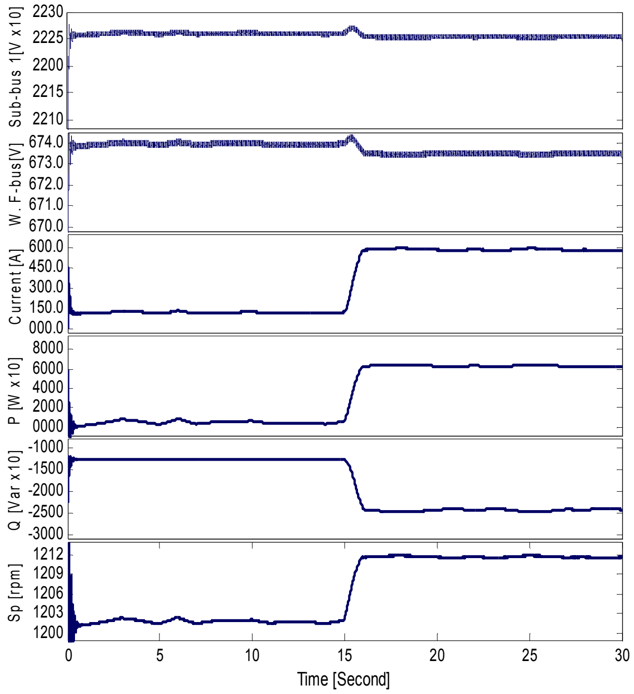

Fig.7. Simulation result of 600kW fixed speed WPT under increase in wind speed at defined installation site.

3.3 Connecting process with system grid

Differing from synchronous generator, WPTs connects to system grid when it satisfies the cut-in wind speed; and off the grid when it reaches to cut-off wind speed level. Because of these connects and disconnects characteristic, the WPT creates a transient response. Usually the transient response of the WPT takes into account the fluctuation on grid voltage, reactive power and active power. There are two key factors which influence the transient response on most WPT, the capacity of power system it connects to and amount of generation of the WPT. For example, when WPT connects with a strong power system with a stiff grid, the fluctuation level of the transient response may not have much influence on the system. But on the other hand, if the WPT connects to a weak power system, then the fluctuation of transient response will be more obvious. When a WPT with capacity less than 100kW connects with the power system grid, the transient processes can be approximately solved by the power flow calculations [6], and fluctuation of each parameter can be estimated directly from the equivalent circuit (shown in (b) Fig.8). But in the case of larger WPT, the fluctuation parameters are much more complex and involve non-linear properties. Hence simulation by using Simulink will be much more efficient than by using the power flow calculations.

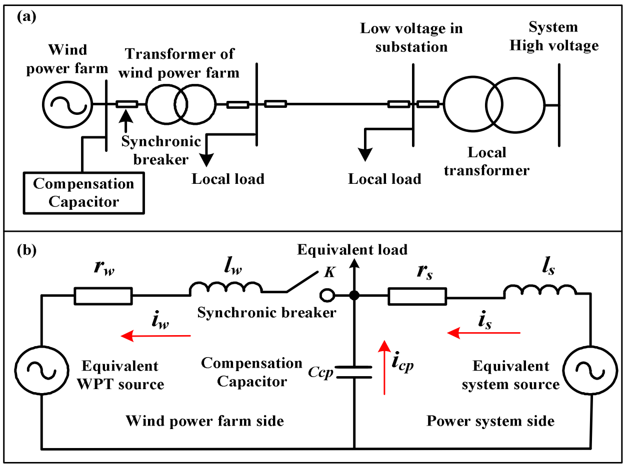

Fig.8. (a) Interconnection of power system and wind farm (b) Equivalent transient circuit of connection process

3.3.1 Simulation result

When WPT connects with a power system, it results in a momentary in-rush of current as the magnetic field is energized. This high impact in-rush current can be limited, but not eliminated. One of the methods to minimize this impact current is by controlling the rotor speed of the WPT when it connects with the power system. For this part of the simulation, 2 different rotor speeds of WPT are selected (rotor speed equal to zero, and rotor speed equal to 95 percentage of the synchronous speed). As the result of simulation indicates; the peak value of in-rush current will be smaller and the duration time of this current will also be much shorter if WPT connects with the power system with the rotor speed at 95% of synchronous speed.

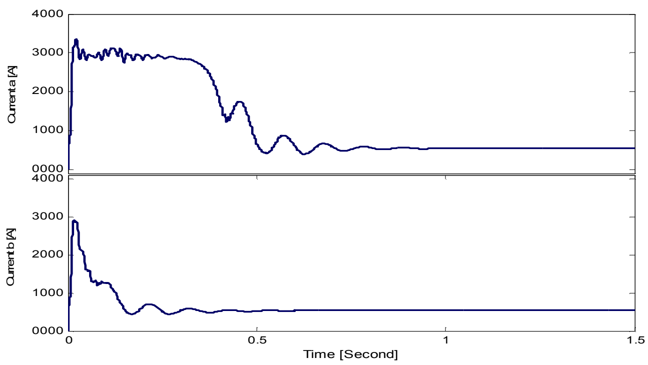

Fig.9.Imapct current on 600kW fixed speed WPT; when connected with power system grid with the rotor speed at (a)at zero (b)at 95% of synchronous speed

In the simulation, in order to see the performance on the other parameters (such as voltage, real power, etc..) of WPT, we let the WPT operate independently into the rate condition at the start, and connect this WPT to target power system at t=6seconds. The simulation results indicate the voltage at W.F-bus will drop instantaneous and recover back in about 0.4 second. The percentage of instantaneous voltage vibration on this bus is about -4.5%. The main cause of this instantaneous voltage vibration is the transformer (690V/6.9kV) on the WPT side. This transformer is required to absorb the reactive power from power system when connecting with power system. In addition, because the compensating capacitor used in this simulation; the steady state voltage on any bus of the defined power system are not fluctuated. But in the case when a compensating capacitor is not available, the steady state grid voltage is expected to drop since the WPT is required to absorb reactive power from the defined power system.

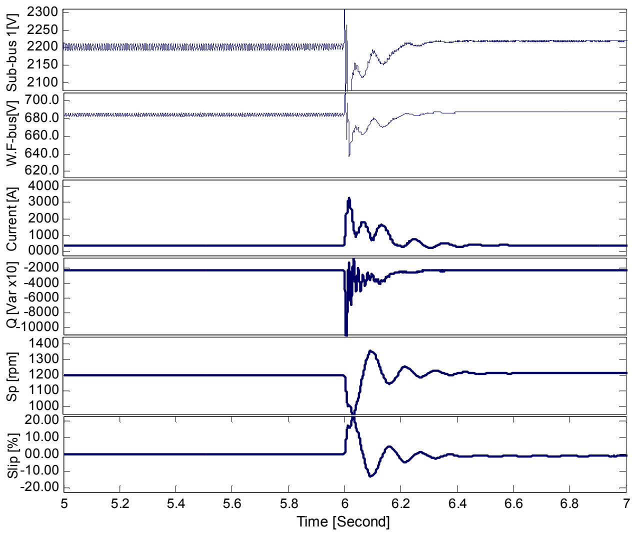

Fig.10. Simulation result on 600kW fixed speed WPT when connected with defined power system at t=6second

3.4 Short circuit condition

Before installing WPTs into the new site, it is necessary to test the dynamic stability of the wind power system under the short circuit condition. When a short circuit occurs in the wind power system, a large amount of impact current will be expected to flow from the WPT and power system into the short circuit dot, and the system grid voltage will be expected to drop immediately. The system grid voltage drop situation will be more obvious if operated in a weak power system. Therefore choosing the right fault protection to ensure all parts of the electric grid are able to bear this impact current is externally important when placing WPTs into the new site.

Generally there are two types of short circuit situations that might happen in the wind power system. The first one is a short circuit inside the WPT related to the stator coil. This problem can be easily solved by using equation (13). The second type of short circuit happens at the connection part where the WPT terminal connects with the system grid (see (a) and (b) in Fig.11).This type of short circuit is usually caused by animals or human error, and occurs often in wind power system. When a short circuit occurs, the system grid usually feeds a much bigger impact current to short circuit dot than the WPT. Simultaneously, grid voltage will drop sharply due to a loss of reactive power. It is also known that when a short circuit occurs on any part of the connected system, the range of impact current depended mainly on the remaining reactance from the generator to the short circuit point.Regarding to high frequency of current, impedance of compensating capacitor can be ignored; then the general short circuit power and impact current may be expressed by equation (17):

$$\begin{cases} S_{gsc} = k_1 \dfrac{U_s^2}{Z_s} + k_2 \dfrac{U_{wpt}^2}{Z_{wpt}} \\ I_{gsc} = S_{gsc} \big/ \sqrt{3} U_{ar} \end{cases}$$

(17)

Where, S_{gsc} is short circuit power; I_{gsc} is short circuit current; Z_s is remained reactance; U_s is voltage on system grid, Z_{wpt} and U_{wpt} are remained reactance and rated voltage of WPT. From Fig.11 it can derivate $Z_s = r_s + j x_s$ and $Z_{wpt} = r_s + r_{cn} + j(x_s + x_{cn})$, if short circuit happened at the output terminal, then $Z_{wpt} = X_d'' = x_d'' . U_{wpt}^2 \big/ S_{wpt.s}$ .Here, U_{ar} is average rated voltage on power line. k_1 and k_2 are constant, k =1.1 or 1.05 according to high or low grid voltage.

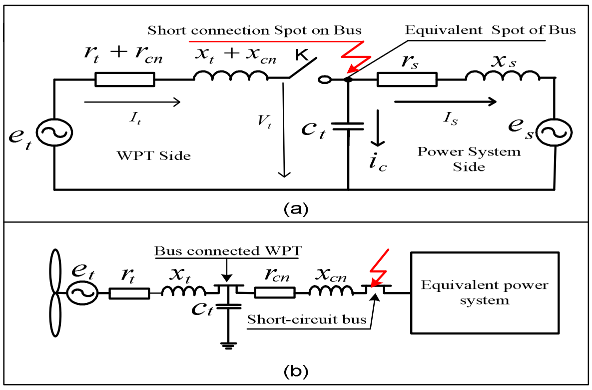

Fig.11. (a) Equivalent circuit of connection system, (b) typical connection system of WPT systme.

3.4.1 Simulation result

From the result of the simulation, the 3-phase fault occurred in the sub-bus1 at t=1 second. The voltage, current, real power, and reactive power of W.F-bus all dropped sharply and reached zero in approximately 0.2 seconds. The speed of the WPT rotor also increased sharply, in order to prevent damage to the WPT from this over-run condition, it is necessary for WPT to be disconnect from the power system immediately fault occurred.

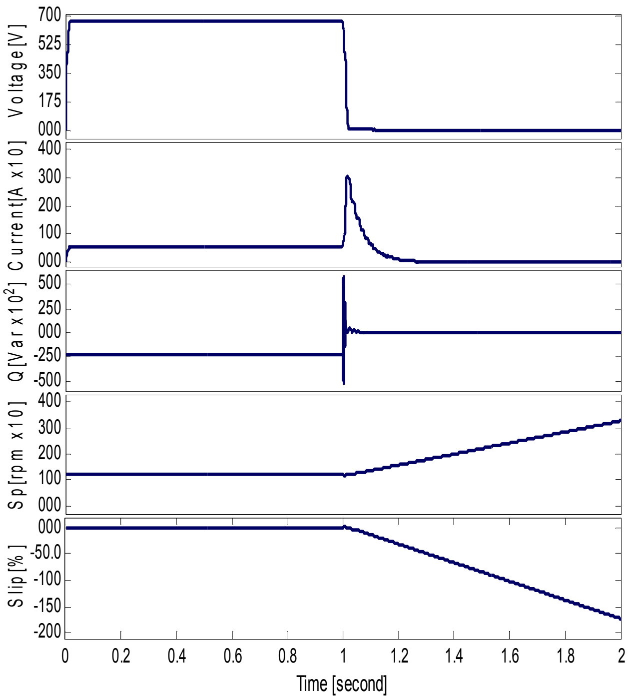

Fig.12. Simulation result of 600kW WPT under short circuit condition happened at t=1 second

3.5 Limitation of wind power capacity in targeting weak power system

WPT is based on the principal of induction machine. During its operation, WPT would absorb reactive power from either the connected power system or from the the compensating capacitor. Even though compensating capacitor is able to stabilise the grid voltage power without consuming too much reactive power from the main power system, the device itself is costly.

As mentioned previously, WPT would consume reactive power when it is connected to the power system. When large number of WPT is connected to the power system, the grid voltage would drop, and this may become problematic. In order to minimise the impact, the maximum capacity of wind power generation allowed at the targeting installation site is determined.

In this research, the voltage in every bus of power system is closely monitored. Furthermore, the simulation is terminated once the voltage fluctuations falls outside the ±5% range.

3.5.1 Simulation result

In this part of the simulation, we analyse the affect on the power system when we gradually increase the number of WPTs in the installation site. According to the simulation result, when increasing the generation capacity of WPTs (increasing number of WPTs), it requires the WPTs to absorb more reactive power (One 600kW fixed speed WPT require 228kVAR reactive power, and five this WPT require 1140kVAR). But since the compensating capacitor used in this wind power system is only provides 219kVAR, which only sufficient to compensate for one WPT, hence when there is more than one WPT in application, the insufficient reactive power will be absorbed from the power system. For example, when 5 WPTs are installed, the total reactive power required is 1140kVAR. An amount of this, 216kVAR, will be absorbed by the compensating capacitor, and the rest will be received by the power system.

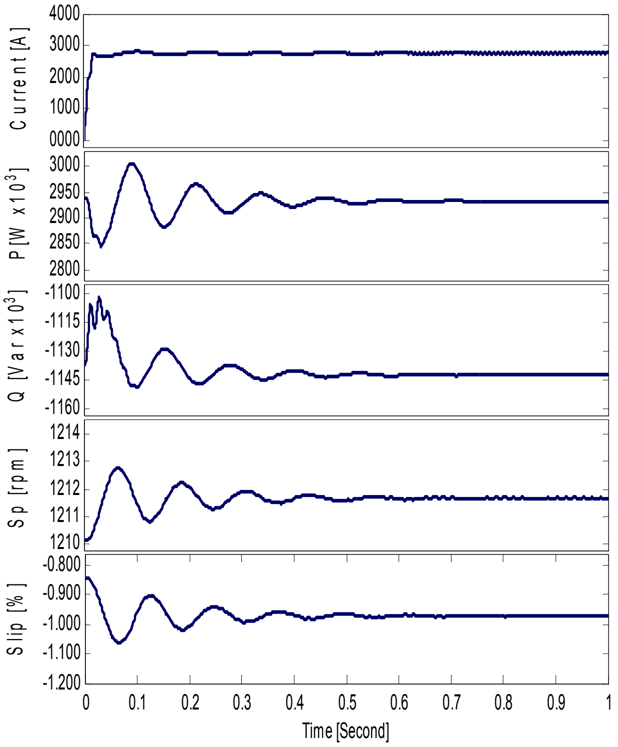

Fig.13. Simulation result of five 600kW fixed speed WPTs at the defined installation site

The simulation result also shows that 7 WPTs provides the maximum wind power generation capacity allowed at this targeted installation site. The WF -bus voltage falls outside the ±5% range when 8 WPTs are installed at the site (Fig.14.), and this is not acceptable according to our defined stability standard of power systems.

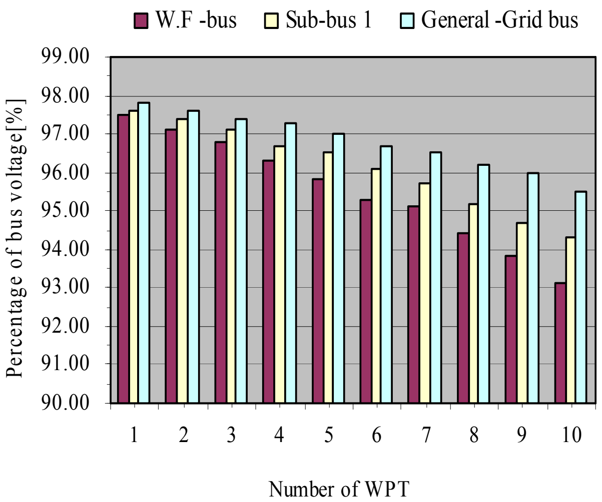

Fig.14.Percentage of bus voltage when difference number of WPT at the defined installation site

4 Conclusion

The WPT installation process may be summarised in three steps. The first step is the estimation of Wind Matrix and Generation Matrix that are available for any region such as complex shaped land. The second step is to select the optimal bus for WPT to connect to the power system. The final step is to determine the fluctuation of electric parameters so as to estimate the introducible limitation of wind power capacity. The installation process is essentially the same for both large and small scaled system, with a minor difference in step two.

Lastly, this installation process is based on numerical simulations. Therefore, it is essential to ensure that the practical operation data and calculations are compared on a regular basis, and revised when necessary.

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Biographies

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