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A Research on Electric Fluctuation and System Limitation of Wind Power Generation in a Weak Power System

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Abstract: This study provides an applicable process for introducing wind power generaton into a weak power system regarding the fluctuation of electric parameters so as to determine the installable limitation. The static and dynamic operational situation of a Wind Power Turbine (WPT) that relates to terminal output and connection system are detailly explained. Characters of inductive generator under sudden variation of wind speed and short circiut has been introduced. Wind and generation matrixes are applied for regional wind condition. The methods to determine optimal bus are considered by regarding sytem load particularity. The electric fluctuation of system parameters is analyzed in each bus of substation system. installable limitation is tested regarding fluctuation range of target parameters.

Key words: WPT, operational process, electric fluctuation, wind power limitation

INTRODUCTION

In planning of wind power installation in a weak power system, characteristics of WPT and system need be investigated to determine optimal installing procedure. Operational quality of hybrid power system tightly relate to each installing step, such as selection of sites with valid wind speed and optimal connection buses and estimating electric fluctuation so as to estimate the installable limitation of wind power capacity.

Precisely measuring valid wind condition of a region covered by weak power system is important step, result from which directly affects subsequent efficiency of system operation and economy. In this study, Wind Matrix indicates the degree of wind speed that has developable worth in target sites and Generation Matrix shows the averagely electric power that is possibly obtained from Wind Matrix. After having the Generation Matrix, it is possible to determine the wind power fed into all buses of weak power system, this procedure makes the basis for estimating the influence degree of wind power on target system. In estimating influence, appropriate buses to connect WPT should be considered; this step is determined by system indices that result from the operation of weak power system. However, in some cases it is difficult to appraise a weak power system with standard technical stipulations that match for high quality power system, a weak system often operates with condition of crisis load, such as a rural power system usually takes agriculture as main load during irrigation season. Our previous research indicates that existing characteristic of a weak power system is efficient references for searching optimal buses; several system indices have been developed and two of them are therefore introduced, namely Weakness Degree in Energy Supply (WDES) and Endurance Index of Crisis Hours (EICH).

Fluctuations of electric parameters caused by sudden variation of wind speed and sharp current of short circuit are the appraising reference to estimate dynamic stability of inductive generator. Here, short circuit that possible happens on the output terminal of WPT and connection cable is therefore considered. This step is essential for determining the feedback electric current from the system grid and WPT generator. The Electric Fluctuation caused from normal operation and cutting-in process is also explained. Installable limitation of wind power capacity is estimated based on fluctuation range of electric parameters.

ELECTRIC FLUCTUATION IN STABLE OPERATION

Electric fluctuation can be divided into two aspects of stable and dynamic condition of wind power system.

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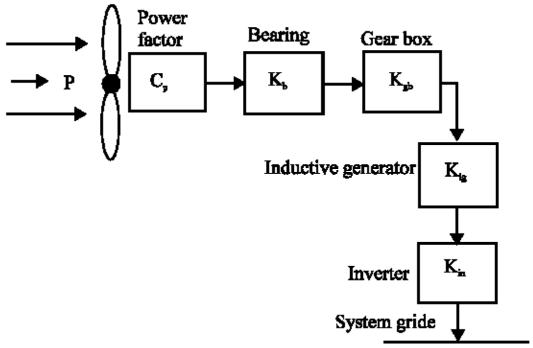

Fig. 1: Coefficient of middle sized WPT without double feed control system

Fluctuation in stable operation is usually ignored; actually fluctuation of active and reactive power in stable state may affect voltage and frequency and also connection system of WPT to grid of a weak power system may cause stability problem.

Estimation wind power generation: In determining the fluctuation and limitation of wind power system, estimation of producible wind power generation is essential, the precision data may assess relative correct simulation result. Power generation from WPT in stable operation is shown in Fig. 1.

Regarding a single WPT, power P on blades and power P_{sg} on system grid can be expressed by Eq. 1:

$$\begin{cases} P = 0.5\rho A\, V^3 \\ P_{sg} = C_p\, k_b\, k_{gb}\, k_{ig}\, k_{in} \end{cases} \quad (1)$$

Where, V and A are wind speed and area swept by blades, ρ and C_p coefficient in Fig.1. In application, average wind speed derived from minute scale of random wind speed, which make it available to obtain average wind speed with different interval, like hourly, daily and monthly or yearly. Possible wind generation is easily realized using Particularity Curve of Wind and Generation of a defined WPT. However, regarding a region covered by weak power system, Wind and Generation Matrixes (Zulati *et al*., 2006) are efficient method. If area has n sites S_{11}, S_{12}….$S_{1n,}$ that are worth to investigate, supposing hourly wind speed v_{11}, v_{12}…v_{1n} are relate to all numbered sites, then for each site, wind speed on one defined direction v_k can be obtained from 10 min data x_1, x_2, …, x_r as shown in Eq. 2. And also for site i, wind speed on m directions can be presented by a raw of wind matrix through v_0, v_6, v_{12},…, $v_{int(r/6)}$ as shown in Eq. 2:

$$\begin{cases} v_k = \left(x_{k+1} + x_{k+2} + x_{k+3} \ldots + x_{k+6}\right)/\,6 \\ V_{ij} = \left(v_0 + v_6 + v_{12} + \ldots + v_{int(r/6)}\right)/\mathrm{Int}(r/6) \end{cases} \quad (2)$$

Where, k×0, 6, 12,…, int(r/6), j×1, 2, 3, … , m, i×1, 2, 3,…,n. Numeral Wind speed Matrix for n sites and m directions is therefore expressed by Eq. 3:

$$V = [v_{N\times M}] \quad (3)$$

Use kk' to indicate wind direction with 15 degree's interval and r_{ij} to indicate the ratio of occurred valid wind speed on direction kk' for element v_{ij} and then the Vector Wind Speed Matrix for n sites and m directions can be expressed by (4).

$$\vec{V} = \vec{v}^{\,kk'_{ij}}_{N\times M}\left(r_{ij}\right) \quad (4)$$

However, if the region covered by weak power system can be divided into several areas, same number of vector matrixes is needed. If sites with wind direction less than m, the related elements equal to zero.

Two methods namely precision and ratio methods are used to determine Generation Matrix as shown in (5):

$$\begin{cases} g_{ij} = C_1 v_{ij}^1 + C_2 v_{ij}^2 + \ldots + C_s v_{ij}^s \\ G = K\dfrac{V}{V_0} = KVV_0^{-1} \end{cases} \quad (5)$$

Where, v_{ij} and matrix V relate to Eq. 3 and 4, V_0 and V_0^{-1} relate to matrixes of rated wind speed and its inverse, K is constant with unit kW. C is constant determined by Output Character Curve under wind speed v_{ij}. Hence, the Generation Matrix may be obtained and shown by (6):

$$G = [g_{N\times M}] \quad (6)$$

Equation 6 provides the power amount that can be obtained from all sites of area; it is an essential basis to continue the following researches.

The concept of weak power system: Weak power system widely exists in terminal of power system, here, weak means substation grid is not stiff enough; the voltage can not be well controlled and affected easily by manipulation activities. In rural power system, voltage is allowed to vary in a certain degree due to load condition. However, wind power farm is usually connected to substation system and fluctuation range caused by WPT relates tightly to bus quality. Since there are several buses in substation system, it is therefore necessary to determine optimal bus for connecting to WPT. Our research shows that Domain-link Methods (Zulati *et al.*, 2003) is efficient for large power system, WDES (Zulati *et al.*, 2003) and EICH (Zulati *et al.*, 2007) are efficient for weak power system. This study only deals with the method used for weak power system.

WDES is defined as the criterion to weight redundancy of system service demanded by the maximum load. Here, system service represents available power supply including system reserve corresponding to dispatching plan and the experienced maximum load demand. WDES reflects the margin of system service for a critical load, based on such idea WDES is expressed mathematically by Eq. 7:

$$\mathrm{WDES} = 1 - \frac{\left[\sum_{i=1}^{n} W_{G.i} - \left(\sum_{r=1}^{s} \Delta W_{1r} + \sum_{j=1}^{m} W_{ML.j}\right)\right]}{\sum_{j=1}^{m} W_{ML.j}} \qquad (7)$$

Where, n, m and s are, respectively the number of generator buses, load buses and transmission lines. W_{Gi} is regular and potential energy supplied from generator i, $W_{ML\,j}$ is system load demand on bus j, ΔW_{1r} is energy loss on line r. For a system, WDES relates to cumulated $W_{G\,i}$, $W_{ML\,j}$ and $\Delta W_{1\,r}$ in same period of time T_a. Define T_a as a sum of fraction period of time during which the maximum load (or critical load) is existing, then T_a can be expressed by a series of operational time sections of $a_1+a_2+\ldots a_r\ldots+a_{r-1}+a_s$. On the other hand, EICH is defined as a criterion to indicate elongation level of crisis time on the target bus. Unstable power sources existing in power system, such as hydro and solar power sources, may increase enduring period, system generation should therefore, be evaluated by EICH as shown by Eq. 8;

$$\mathrm{EICH} = \sqrt{\frac{N_{1.c.h}}{N_{op.h}}} \qquad (8)$$

Where, $N_{1.c.h}$ and $N_{op.h}$ are integer number summing from each crisis's time and operating hours during which load crisis occurred as given by (9):

$$\begin{cases} N_{1.c.h} = \mathrm{int}\left(\sum_{i=1}^{n} \frac{\Delta t_{1.c.i}}{60}\right) \\ N_{op.h} = \mathrm{int}\left(\frac{T_{op.h}}{60}\right) \end{cases} \qquad (9)$$

Where, $\Delta t_{1.c.i}$, i = 1,2,..,n, is time section in which the crisis load of number i is occurred. In unit of minute, if $\Sigma\delta t_{1.c.i}$< 60 min, it is counted as 1 h, if $\Sigma\Delta t_{1.c.i}$=60 min, it is divided by 60 to take integer and complement parts as integer hours. $T_{op.h}$= $t_{1.c.1}$ - $t_{1.c.n}$ is period containing all crisis time, $t_{1.c.1}$ and $t_{1.c.n}$ are starting and finishing time of all crisis condition. The mentioned 2 methods are feasible and applicable for any small sized weak power system; the main idea of two methods is same that to determine optimal buses in according to the particularities of weak power system itself. Anyway, the selected buses should be verified by the stability and reliability demand.

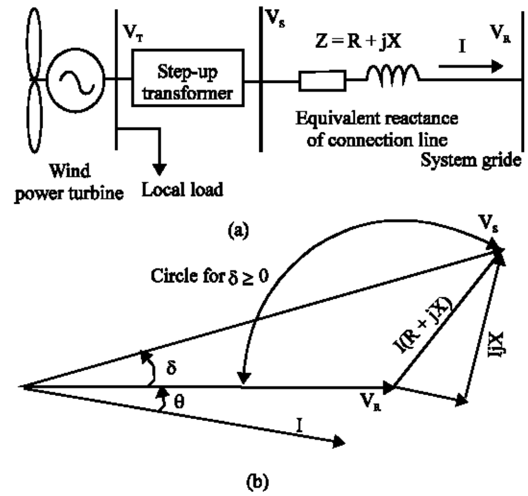

Fig. 2: Equivalent circuit (a) and stability limit circle (b) in wind power connection system

Stability in connection system: Connection part of wind power system may cause electric fluctuation and stability problem in stable operation, voltage regulation and stability limit have therefore, to be considered in connection circuit. The equivalent reactance resulted from load and connection line should satisfy the stability limit, otherwise the connection cable need to be replaced and the power factor of load need to be improved. Figure 2a and b show the equivalent circuit and voltage vector used for the connection circuit.

In voltage regulation, the voltage at receiver terminal is defined in according to power system demand; it can be expressed by Eq. 10:

$$\begin{cases} V_S = V_R + I(R + jX) \\ V_d\% = \frac{V_S - V_R}{V_R} \times 100 \end{cases} \qquad (10)$$

The stability limit of connection circuit may be easily obtained from the diagram of voltage vector as shown in (b) of Fig. 2. If ignore the resistance R, the mathematic relatinship of connection circuit can be expressed by the Eq. 11:

$$P_R = V_R I\cos\theta = \frac{V_S V_R}{X}\sin\delta \tag{11}$$

It is obvious that negative angle δ may cause the power feedback to wind power side, when δ = 90, connection line may transfer maximum power, when angle δ beyond 90 degree, connection line loses its stability and falls out of synchronous operation. In application, power angle δ is maintained below 20 degree so as to remain enough power degree for big transient power causing from dynamic process, by this way the dynamic stability is kept.

ELECTRIC FLUCTUATION IN DYNAMIC PROCESS

There are many reasons to lead to electric fluctuation of WPT; fluctuation may be resulted from the transient process so as to affect system frequency and voltage. Some transient processes are occurred by system manual connection activities of large equipments in system and animal action caused short circuit. From the view of wind speed, small variation in wind speed may be absorbed by WPT blades and inertia without happening transient process, when large and sharp variation of wind speed happened in relative long time, WPT may reach new operation point through transient process by tracking. However, WPT that capacity less than 100kW usually without pitch control, sudden variation in wind speed causes electromagnetic fluctuation in stator and rotor coils. Simulation results of current and electromagnetic fluctuation are the important references to judge the dynamic character of devices in connection system.

Equations for transient process: Fluctuation simulation is based on the transient equations (Zulati *et al*., 2005) derived by basic inductive generator theory as shown in Eq. 12:

$$\left.\begin{aligned} p\psi_d &= R_1 i_d + \omega\psi_q + V_d \\ P\psi_q &= R_1 i_q - \omega\psi_d + V_q \\ p\psi_D &= -R_2 i_D + (\omega-\omega_1)\psi_Q \\ p\psi_Q &= -R_2 i_Q - (\omega-\omega_1)\psi_D \end{aligned}\right\} \tag{12}$$

Where, p = d/dt, I, ψand V are currents, magnetic linkages and voltages, R_1 and R_2 are resistances of stator and rotor. Based on (12), three standard equations that can be used for transient simulation are expressed by matrix Eq. 13, where; p = d/dt, I, ψ 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.

$$\begin{cases} p\psi = A\psi + BV \\ pE = AE + BI \\ pI = AI + BV \end{cases} \tag{13}$$

Equation 13 can be feasibly used in according to the simulation target and it can be also expressed by (14):

$$\left.\begin{aligned} \Delta pX_i &= \frac{\partial f_i}{\partial X_1}\Delta x_1 + \ldots + \frac{\partial f_i}{\partial X_n}\Delta x_n + \frac{\partial f_i}{\partial U_1}\Delta u_1 + \ldots + \frac{\partial f_i}{\partial U_r}\Delta u_r \\ \Delta Y_j &= \frac{\partial F_j}{\partial X_1}\Delta x_1 + \ldots + \frac{\partial F_j}{\partial X_n}\Delta x_n + \frac{\partial F_j}{\partial U_1}\Delta u_1 + \ldots + \frac{\partial F_j}{\partial U_r}\Delta u_r \end{aligned}\right\} \tag{14}$$

Here, n is the order of system and r is the number of input, above equation can be written as (15):

$$\left.\begin{aligned} \Delta pX &= A\Delta X + B\Delta U \\ \Delta Y &= C\Delta X + D\Delta U \end{aligned}\right\} \tag{15}$$

Here, C is output constant matrix; D is constant matrix related to input. Equation 15 is linearization state of (13) and it enable in defined time range to represents the states denoted by (13), two states are therefore, equivalent states. Equation (15) is able to be linked to SIMULINK program and calculated by numeral method. The linearization form of Eq. 15 can be realized by Eq. 16:

$$\left.\begin{aligned} \dot{X} &= AX + BU \\ Y &= CX + DU \end{aligned}\right\} \tag{16}$$

Then, the simulation block related to (16), which used for suddenly wind variation can be shown by Fig. 3:

In these transient equations, some parameters were given as input from the input terminal of blocks, the value of initial value can be determined based on the operational condition as mentioned in this study.

Fluctuation caused by short circuit: For any sized WPT it is necessary to test the dynamic and thermal stability when there is a short circuit at terminal connecting equipments or on connection system. WPT and system provide big amount of electric current to short connection point, all devices in connection system should be able to bear this current without breakdown. Short circuit of WPT system includes two aspects; one is short circuit inside

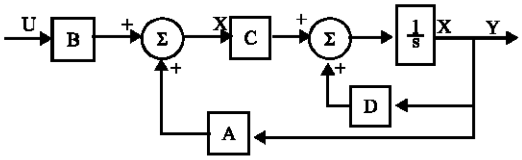

Fig. 3: Diagram of transient states after linearization

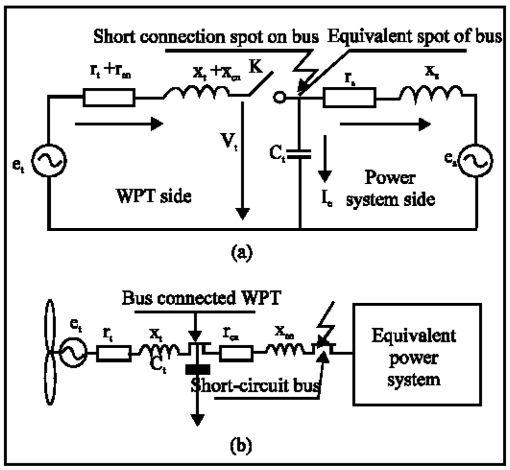

Fig. 4: (a) Equivalent circuit of connection system, (b) typical connection system of WPT and system

WPT related to stator coil, this problem can be easily done by using Eq. 13 or directly solved by Matlab block circuit. The other one relates to short circuit on connection system from WPT terminal to system main grid. Comparing with WPT, grid feed bigger current to short circuit dot. Simultaneously grid voltage will be dropped down in a large range. To estimate dynamic particularity of connection system, the range of short circuit current should be determined. Equivalent circuit used for simulation is shown in Fig. 4.

When short circuit occurs on any part of connection system, current range mainly depends on remained reactance from generator to short circuit point. Regarding to high frequency of current, impedance of compensating capacitor can be ignored. General short circuit power and current may be expressed by Eq. 17:

$$\begin{cases} S_{gsc} = k_1 \dfrac{U_s^2}{Z_s} + k_2 \dfrac{U_{wpt}^2}{Z_{wpt}} \\ I_{gsc} = S_{gsc} \big/ \sqrt{3} U_{ar} \end{cases} \tag{17}$$

Where; S_{gsc} and I_{gsc} is short circuit power and current, Z_s and U_s are remained reactance and voltage on system grid, Z_{wpt} and U_{wpt} are remained reactance and rated voltage of WPT. Related to Fig. 4,

$$Z_s = r_s + j x_s \text{ and } Z_{wpt} = r_s + r_{cn} + j(x_s + x_{cn})$$

Short circuit happens on output terminal, then

$$Z_{wpt} = X_d'' = x_d'' \cdot U_{wpt}^2 \big/ S_{wpt.s}$$

U_{ar} is average rated voltage on power line. K_1 and K_2 are constant, k =1.1 or 1.05 in according to high or low grid voltage.

It is necessary to indicate that in short circuit process electric current is main reference to verify thermal and dynamic quality of connection system; influence caused by variation of active and reactive power is ignored due to very short transient process.

Fluctuation caused by connecting activities: WPT Connection activities cause transient process that affect voltage and frequency, reactive and active power respectively drag down frequency and voltage. Active power relates to defined load that does not change so much in process, so that the frequency varies without bigger fluctuation. Voltage drops down following variation range of reactive power. In the fluctuation calculation, for the small and middle sized WPT that capacity is smaller than 100kW, it is convenient to use equivalent circuit shown in Fig. 4. For large sized WPT that capacity is larger than or equal to 100kW, the software circuit is efficient way. However, experiment data is necessary in determining initial condition of target circuit. Bus of wind power farm can be regarded as a dot to determine the initial value of fluctuation, initial value of active power on WPT and inductive generator may be expressed by Eq. 18:

$$\begin{cases} P_{wpb} = \sum_{i=1}^{n} f_i(V) \\ P_{idg} = I_{ro}^2 R_{ro} \dfrac{1-s}{s} \end{cases} \tag{18}$$

Where, V is wind speed on blades of WPT, I_{ro} and I_{ro} are current, resistance and slip on the rotor of inductive generator. It is necessary to indicate that for a wind power farm, general active power from different types of WPT should be, respectively summed and power from same type of WPT can be directly summed. Direction of reactive power transformed into bus of wind power farm is determined by range of voltage between system grid and wind power farm bus. Initial value of fluctuation can be estimated through active power and voltage of wind farm bus P_{wpb} and U_{wpb}, general reactance of wind power farm X_{wpf} and also the reactance of compensating capacitor X_{cc}. Reactive power on wind power bus can be approximately expressed by (19):

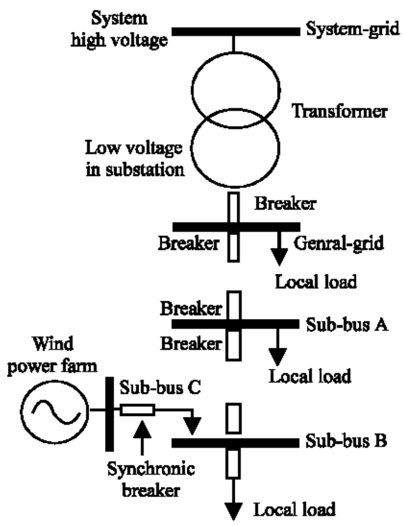

Fig. 5: The typical inter-connection of wind power farm at terminal of a weak power system

$$Q_{wpb} = U_{wpb}^2 \frac{X_{cc} - X_{wpf}}{X_{cc} X_{wpf}} + P_{wpb}^2 \frac{X_{wpf}}{U_{wpb}^2} \qquad (19)$$

In calculation, just as active power, reactive power of entire wind power farm should be managed by considering type of WPT. Resulting from random wind speed and different operational characteristics of each WPT, there is a difference of power angle between each wind power generator. It is therefore, necessary to consider influence caused by the type and wind speed, usually the influence of wind speed is ignored since it is difficult to obtain a regulative method in calculation. Anyway, influence caused by type of WPT is able to be estimated. General reactive power is the sum one accumulated from different type of WPT and concrete value is statistic results under different wind speed. Contribution of reactive power tightly depends on voltage limitation as shown in Fig. 2. By mentioned method, the initial value of active and reactive power is determined. It is need to be mentioned here, voltage is regarded as nominal in mentioned calculation, this supposing is practically available and allowed.

With obtained initial value, electric fluctuation in dynamic process can be determined easily. Research experiment shows that wind power farm often connects to the system substation in order to achieve valid wind energy and directly serve the system load. A typical inter-connection of wind power farm and substation of a weak system and also the investigation procedures are shown in Fig. 5 and 6.

This transient process can be approximately solved by power flow calculation (Zulati *et al.*, 2006); the

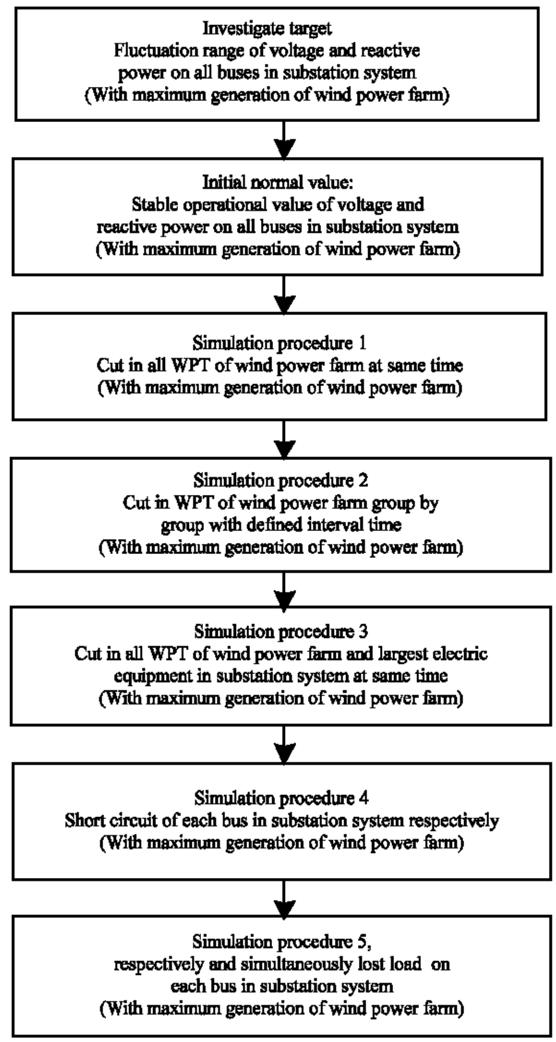

Fig. 6: The procedures for investigating situation of wind power system in stability and limitation

fluctuation range of electric parameters is able to be easily determined. On the other hand, simulation using tool boxes shows much efficient and precision; simulation circuit of block net can provides detail fluctuation diagrams.

In simulation, the notes of Sub-bus A, Sub-bus B and Sub-bus C is the target to be investigated. Here, the synchronic breaker and other breakers in substation system operate switching on and off the wind power farm and load from system following the procedures shown in Fig. 6. If fluctuation range of hybrid system within allowed margin in all simulation procedures shown in Fig. 6, the hybrid system of wind power is regarded as a safety system. However, procedures in Fig. 6 are not limited, there are the possibilities to add or reduce some necessary simulation methods in according to system operational particularities.

Limitation of wind power capacity: Limitation of wind power capacity in a power system may result from two operational aspects of power system. One is the limitation under stable operation and the other is limitation under dynamic state of substation system.

Limitation in stable operational mainly depends on the voltage and reactive power to avoid connection activity caused sharp current, voltage and reactive power lost. Voltage and reactive power can be solved by procedure shown in Fig. 6. Sharp current result from connection activities need to be solved by investing dynamic stability of connection devices. Fluctuation range of sharp current related to Fig. 5 can be expressed by (20):

$$\begin{cases} i_s = (A_s + B_s e^{-\tau_s t})\sin(\omega t + a_s) \\ i_t = (A_t + B_t e^{-\tau_t t})\sin(\omega t + a_t) \end{cases} \quad (20)$$

Where

$$\alpha = 2L_t/R_t \text{ and } \omega = 1/\sqrt{L_t C_t}$$

and A and B are constants that can be determined by the initial value mentioned in this study. Here, the limitation of wind power capacity depends on current i_s and i_t, however, start current should be limited under 5-7 times of nominal current. Current t_c can be used to estimate last time of sharp current in compensation capacitor, actually i_c may be expressed by (21):

$$i_c(t) = A_1 \exp(S_1 t) + A_2 \exp(S_2 t) \quad (21)$$

Where, A 1 and A2 are determined by initial value and

$$S_1 = -\alpha + \sqrt{\alpha^2 - \omega^2}, S_2 = -\alpha - \sqrt{\alpha^2 - \omega^2}$$

Define $i_c(t) = 0$ with different time t, then $i_s = i_t$, this method can be used to simulate the fluctuation range of connection current.

Installable limitation in normal operational condition depends on reactive power absorbed by WPT from power system. Anyway, this problem usually solve by installing compensation capacitor on wind farm bus. Installable limitation in dynamic operational condition, such as connection and other dynamic process caused by system manufacture depends on not only reactive power but also voltage of each bus in substation system as shown in Fig. 5. Dropping range of voltage relates to fluctuation range of reactive power provided by compensating capacitor and also the cut in time of capacitor. In simulation, the voltage on all buses in substation system need to be investigated, fluctuation range of voltage should be controlled within ±5%, otherwise, it is necessary to increase capacity of compensation capacitor and reduce the cut in time.

CONCLUSION

Overall, the installation process may be concluded by the three steps, the first step is estimation of Wind Matrix and Generation Matrix that are available for any region such as complex shaped land. The next step is to select optimal bus inside weak power system for connecting to WPT. The third step is to determine the fluctuation of electric parameters so as to estimate the introducible limitation of wind power capacity. The procedures introduced in this paper can be applied for large and small scaled system, the only difference of small and large scaled system in application relates to step two as mentioned in this study. Since entire research bases on numeral simulation, calculation precision is therefore, very important, the constant comparison and revision with practical operation data in all calculation steps is generally recommended.

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