Total Transfer Capability Analysis in Power System including Large-scale Wind Farms

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Abstract

Wind power industry is developing rapidly, more and more wind farms are being connected into power systems. In this paper, a calculation model of continuation power flow in power system containing large-scale wind farms is established by using the detailed π -type equivalent circuit of asynchronous wind turbine. Based on the proposed method, total transfer capability (TTC) is investigated under the static voltage stability constraint. The analysis results show that both the compensation capacity of wind turbine terminals and wind speed have a great influence on TTC.

Keywords: Wind farm; Induction generator; Total transfer capability; Continuation power flow

1. Introduction

As a kind of clean, abundant and renewable energy source, wind energy has been an important part of electrical generation in many countries. By the end of 2005, the installed capacity of wind turbines(WT) all through the world has been 59322 MW, which is 25 percent more than the one of last year. With the increscent scale and amount of wind farms, it is necessary to investigate the influence of WT on transfer capability of power system.

TTC is defined as the amount of electric power that can be transferred over the interconnected transmission network whilst all the reliability requirements are satisfied[1]. When wind farms are connected with system, it is necessary to establish static model of wind turbine to analyze TTC under voltage stability constraint.

[2] adopts a PQ model to represent WT in power flow calculation. [3] first presents RX model and applies the impedance containing slip ratios to be the equivalent of WT. [4] discusses the former method in[3] and presents the idea of unifying the slip ratios in power flow iteration.

Based on [3]~[4], this paper establishes a calculation model of continuation power flow(CPF), which contains slip ratios, by using the detailed π -type equivalent circuit of induction generator(IG). based on the proposed method, this paper analyzes TTC of power system containing large-scale wind farms and investigates the influence of WT terminals' compensation capacity and wind speed on TTC.

2. Model and Calculation Method

2.1. Model of Induction Generator

Induction generators are generally applied in wind farms. The equivalent circuit and the relation of power transmission are shown in Figure 1.

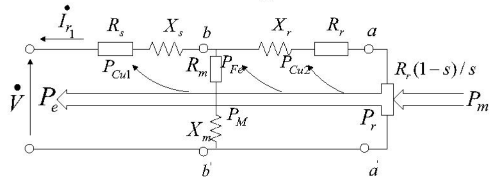

Figure 1. Equivalent circuit of IG and relation of power transmission

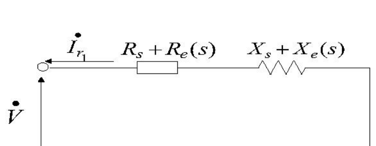

Figure 2. Equivalent circuit of IG after simplifying dextral circuit of bb′ in figure 1

After simplifying dextral circuit of bb′ in Figure 1, we get Figure 2, where, $R_e(s)+jX_e(s)$ represents equivalent impedance. Then power injecting into system can be obtained as:

$$P_e(V,s)=\frac{-(R_s+R_e)V^2}{(R_s+R_e)^2+(X_s+X_e)^2} \quad (1)$$

$$Q_e(V,s)=\frac{-(X_s+X_e)V^2}{(R_s+R_e)^2+(X_s+X_e)^2} \quad (2)$$

Where V is terminal voltage of wind turbine.

After using Thevenin's Theorem to simplify left circuit of aa′ in Figure 1, we get Figure 3:

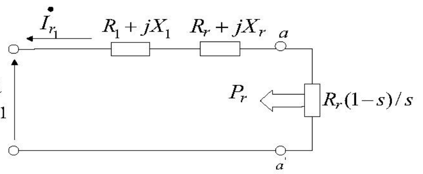

Figure 3. Equivalent circuit of IG after simplifying left circuit of aa′ in figure 1

Where R_1+jX_1 represents the equivalent impedance and V_1 represents the equivalent voltage. Therefore, the electric power on the rotor of generator can be calculated from the following equation:

$$P_r=-\frac{V_1^2 R_r(1-s)/s}{(R_1+R_r/s)^2+(X_1+X_r)^2} \quad (3)$$

2.2. Model of CPF Calculation including WT

When WT are connected with power system and the slip ratios are introduced as new state variables, a group of balance equations should be added to original power flow equations. P_m and P_r, which should be equal according to the power conservation principle, change along with wind speed. By adjusting the slip ratio, these two powers will be equal. Therefore, P_m equals P_r .is brought in as the new balance equation.

Let N_w represent the set of nodes connected with WT, and (θ_i , V_i , s_i) is the state variable of node i $(i\in N_w)$. Then the power flow equations, corresponding to the node i, can be represented as:

$$\begin{cases} f_{1i}=P_{ei}-P_{iL}-V_i\sum_{j\in i}V_j(G_{ij}\cos\delta_{ij}+B_{ij}\sin\delta_{ij})=0 \\ f_{2i}=Q_{ei}-V_i\sum_{j\in i}V_j(G_{ij}\sin\delta_{ij}-B_{ij}\cos\delta_{ij})=0 \\ f_{3i}=P_{mi}-P_{ri}=0 \\ i\in N_w \end{cases} \quad (4)$$

To the system with WT, the simplified representation of the power flow equations containing load parameter λ is:

$$\boldsymbol{f}(\boldsymbol{X},\lambda)=0 \quad (5)$$

Where $\boldsymbol{X}\in\boldsymbol{R}^n$ represents the state variables vector containing bus voltage magnitudes $\boldsymbol{V}$ 、 bus voltage angles $\boldsymbol{\theta}$ and slip ratios $\boldsymbol{s}$ of induction generators.

(1)Predictor

A、 Calculating tangent vector

The tangent vector $(d\boldsymbol{V},d\boldsymbol{\theta},d\boldsymbol{s},d\lambda)$ is derived in the following equation:

$$\begin{bmatrix} \boldsymbol{J}_{f_1\theta} & \boldsymbol{V}\cdot\boldsymbol{J}_{f_1V} & \boldsymbol{J}_{f_1s} & \boldsymbol{J}_{f_1\lambda} \\ \boldsymbol{J}_{f_2\theta} & \boldsymbol{V}\cdot\boldsymbol{J}_{f_2V} & \boldsymbol{J}_{f_2s} & \boldsymbol{J}_{f_2\lambda} \\ \boldsymbol{J}_{f_3\theta} & \boldsymbol{V}\cdot\boldsymbol{J}_{f_3V} & \boldsymbol{J}_{f_3s} & \boldsymbol{J}_{f_3\lambda} \\ & \boldsymbol{e}_p^T & & \end{bmatrix} \begin{bmatrix} d\boldsymbol{\theta} \\ \boldsymbol{V}^{-1}d\boldsymbol{V} \\ d\boldsymbol{s} \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \pm 1/V_p \end{bmatrix} \quad (6)$$

Where row vector $\boldsymbol{e}_p=[00\cdots0\vdots00\cdots010\cdots0]^T\in\boldsymbol{R}^{N_B+N_V+1}$, of which all the elements are zero, except that the (N_B+p) th element is 1. p indicates the location of continuation parameter, which can be $1,2\ldots N_V+1$.

B、 Choosing continuation parameter

To choose p to fulfill the following equation:

$$|dV_p|=\max_{j=1}^{N_V}\{|dV_j|\} \quad (7)$$

C、 Predicting the next solution

The update of state variables can be updated by the following equations, and step size σ is chosen as 0.005～0.02.

$$\begin{cases} \boldsymbol{\theta}^{(k+1)}=\boldsymbol{\theta}^k+\sigma\cdot d\boldsymbol{\theta} \\ \boldsymbol{V}^{(k+1)}=\boldsymbol{V}^k+\sigma\cdot d\boldsymbol{V} \\ \boldsymbol{s}^{(k+1)}=\boldsymbol{s}^k+\sigma\cdot d\boldsymbol{s} \end{cases} \quad (8)$$

(2) Corrector

Add an arc length formula as corrected equation:

$$\Delta S^2=\sum_{j=1}^{n}(x_j-x_j^0)^2+(\lambda-\lambda^0)^2-[\sum_{j=1}^{n}(x_j^{(1)}-x_j^{(0)})^2+(\lambda^{(1)}-\lambda^{(0)})^2]=0 \quad (9)$$

The process can be achieved as follows [5]:

①let $k=0$

②judge the convergence condition:

$$\begin{cases} \left\|\boldsymbol{f}(\boldsymbol{X}^{(k)},\lambda^{(k)})\right\|<\varepsilon_1 \\ \Delta S^{2(k)}<\varepsilon_2 \end{cases} \quad (10)$$

Where ε_1 and ε_2 are convergence threshold. If (10) is satisfied, exit; otherwise, continue.

③calculate $(\Delta\boldsymbol{X}^{(k)},\Delta\lambda^{(k)})$ by the following equation:

$$-\begin{bmatrix} f_X(X^{(k)},\lambda^{(k)}) & f_\lambda(X^{(k)},\lambda^{(k)}) \\ \sum_{j=1}^{n} 2(x_n^{(k)}-x_n^{(0)}) & 2(\lambda^{(k)}-\lambda^{(0)}) \end{bmatrix} \begin{bmatrix} \Delta X^{(k)} \\ \Delta\lambda^{(k)} \end{bmatrix} = \begin{bmatrix} f(X^{(k)},\lambda^{(k)}) \\ \Delta S^{2(k)} \end{bmatrix} \quad (11)$$

④correct X , λ

$$\begin{cases} X^{(k+1)} = X^{(k)} + \Delta X^{(k)} \\ \lambda^{(k+1)} = \lambda^{(k)} + \Delta\lambda^{(k)} \end{cases} \quad (12)$$

⑤ $k \leftarrow k+1$, back to step②.

3. TTC Analysis in Power System containing wind farms

The IEEE 118-bus system has been used to analyze TTC. As shown in Figure 4, the system is divided into area A of receiving power and area B of supplying power by a dashed line. Through the transformer and 110KV line, the wind farm containing 20 WT, whose rated power is 600KW, is connected with either Bus 117 in area B, or Bus 118 in area A. The input-output shunt capacitor bank has been installed on the WT terminal. The unit of capacitor bank is expressed by reactive power supplied by capacitor when terminal voltage is 1.0pu(mvar/p.u.v).

(1)The influence of WT terminals' compensation capacity on TTC

Since induction generators cannot produce reactive power and have to absorb reactive power from system to build up excitation, WT terminals' compensation capacity has influence on the output characteristic of WT and TTC. CPF program is run while connecting wind farm with Bus 117 and assuming wind speed to be 10m/s. Under different compensation capacity, the voltage curves of WT varying with load are shown in Figure 5 and TTC is shown in Table 1.

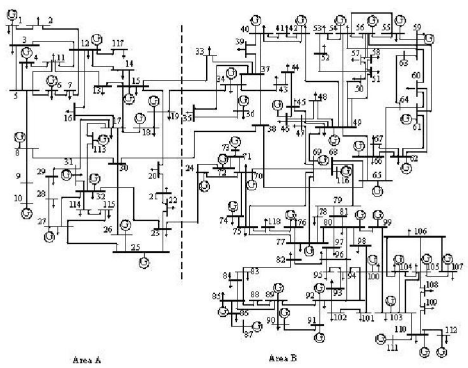

Figure 4. Figure of IEEE 118 system

From Figure 5 and Table 1, it can be concluded that, the increment of compensation capacity has improved WT terminals voltage and increased TTC of system. But it is improper to use too large magnitude of compensation capacity, considering the restriction of asynchronous machines' auto-excitation phenomena and voltage instability caused by using abundant capacitors in status of heavy load and low voltage. Generally speaking, it is proper to compensate the power factor of WT to 0.98.

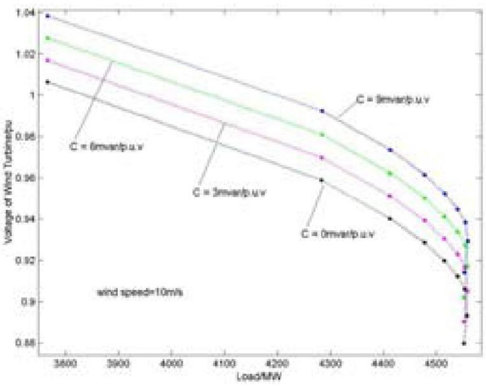

Figure 5. Voltage curve of WT varying with load under different compensation capacity

Table 1. TTC under different compensation capacity

Compensation Capacity / (mvar/p.u.v)	TTC / MW
0	885.7363
3	886.3718
6	887.0120
9	887.6440

(2)The influence of wind speed on TTC

Wind speed, which is uncontrollable, affects output power of WT directly. Therefore, it is necessary to analyze the influence brought by wind speed on TTC. Wind farm is connected with both Bus 118 and Bus 117, and TTC is calculated under different wind speed. The result is shown in Table.2.

Table 2. Mechanical power of WT and TTC under different wind speed

Wind Speed / (m/s)	Mechanical Power of WT / MW	Compensation Capacity / (mvar/p.u.v)	TTC / MW Connecting Bus 118	TTC / MW Connecting Bus 117
0~3, 20~	0	0	855.1636	855.1636
4	0.1423	2	879.7636	879.5517
7	2.4053	4	879.9550	882.2962
10	6.8415	6	880.1951	887.0120
13.5~20	12.1840	7.5	880.3462	891.9888

When wind speed is either less than 3m/s (cut-in wind speed) or more than 20m/s (cut-out wind speed), WT will stop working and be cut off system. When wind speed arrives at 13.5m/s (rated wind speed), WT will work stably and mechanical output will stand. From Table.2 it can be concluded that, no matter with which side been connected, WT will markedly increase TTC by at least 20MW even under low wind speed. Since wind speed has a great influence on TTC, it is necessary to take the variety of future wind speed into consideration in calculating TTC. Specially, when WT is cut out for either too low or too high wind speed, TTC will decrease remarkably.

Although mechanical power of WT only relates to wind speed, active power generated by WT varies with the increment of system load. When wind farm is connected with Bus 118, Figure 6 and Figure 7 represent active power output and terminal voltage curves of WT varying with load under different wind speed.

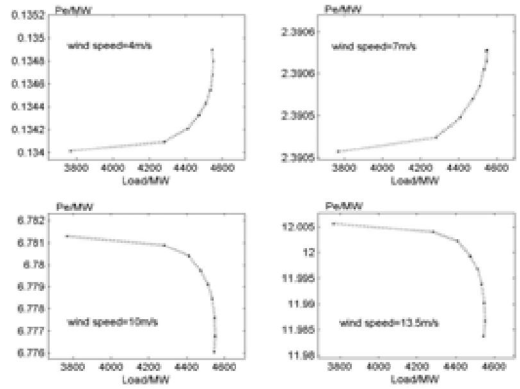

Figure 6. Active power output curve of WT varying with load under different wind speed

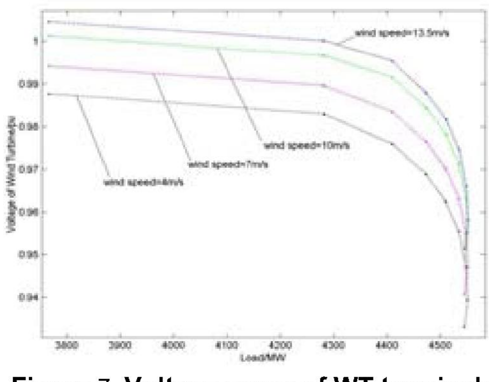

Figure 7. Voltage curve of WT terminals varying with load under different wind speed

From Figure 6 and Figure 7 it can be concluded that, under the same wind speed, WT terminals voltage continue decreasing with the increment of load, while active power output may either increase or decrease. Amply speaking, with the increment of load, the active power output of WT increases slowly under low wind speed, while decreases slowly under high wind speed. From formula (2), this phenomenon can be explained by the reason that active power output relates to not only WT terminals voltage, but also WT inner equivalent impedance. Since the equivalent impedance has consanguineous relationship with slip ratio, and slip ratio change differently under low wind speed and high wind speed, so it results in different active power output curves.

4. Conclusions

This paper establishes a calculation model of continuation power flow in power system connected with wind turbines. In this model, asynchronous wind turbines' slip ratios are introduced as new state variables. Through this method, TTC of power system containing large-scale wind farms is investigated. The analysis results show that the increment of WT terminals' compensation capacity can improve WT terminals voltage in order to increase TTC. Moreover, the wind speed has a notable influence on TTC. Specially, when WT is cut off system for either too low or too high wind speed, TTC will decrease sharply. When WT work normally, TTC will increase with the accretion of wind speed. Therefore, to the operation personnel, it is beneficial to take the reasonable distribution of WT terminals' compensation capacity and the forecast of wind speed into consideration to accurately calculate TTC in the future.

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