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Congestion Management of Transmission Systems Using FACTS

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Abstract - **The efficient utilisation of the existing networks with high penetration of wind power needs more sophisticated control schemes using advanced power flow and voltage control resources, namely power electronic controllers (FACTS) while enhancing voltage security and voltage stability control. In this paper, the application of Static Series Synchronous Compensator (SSSC) for the purpose of congestion management and transfer capability of power systems with high penetration of wind power has been studied. A transfer capability computation approach for congestion management of systems with wind farms using series compensation FACTS i.e. SSSC is proposed in this paper. The approach proposed can simultaneously take voltage, thermal and voltage stability limits into consideration, and may also consider any electricity transaction constraints. Numerical results based on the modified IEEE 30 bus system with/without the SSSC demonstrate the feasibility as well as the effectiveness of the SSSC for congestion management with high penetration of wind power in the network. The results using SSSC to improve system transfer capability and congestion management is encouraging. With the large integration of wind generation into power transmission networks, it can be anticipated that FACTS controllers including the SSSC may be increasingly applied in effective management of transmission network power flows.**

***Index Terms*--Congestion management, Transfer capability, Optimal power flow, Wind generation, Distributed generation, Flexible AC Transmission Systems (FACTS), Series compensation**

I. INTRODUCTION

In recent years, the transmission system of England and Wales has seen considerably increased power transfers across major regional boundaries or interfaces. In the meantime, the policy of the EU is to increase the share of Renewable Energy Sources (RES) in the EU energy supply from 6%, at present, to 12% in 2010, and to 20% in 2020. However, wind energy usually is available and concentrated at some locations away from the load demand centres. For example, it is recognised that the largest prospective source of additional UK renewables in the short to medium term will be wind based plants, which are mainly located along the Western Seaboard running from the North of Scotland and Outer Isles down to the Cornish Peninsula. On the other hand large load demands are centred in the South of the UK. As a result there will be a need to transfer large amount of renewable energy mainly wind power to the mainland demand centres. This means that some large wind farms may be connected with transmission network and wind power concentrated at some locations may be transferred to load centres where it is needed.

It can be anticipated that high penetration of wind power in the network will further push the transmission tie-lines to their power transfer limits and cause likely problems such as network congestion, voltage security or even voltage stability where the network is already under stressed due to the uncertainty of generation and demand and power market transactions. In fact, in some countries and regions wind power is already reaching penetration levels where operational problems are being experienced such as network congestion and voltage security or stability problems created by concentration of wind farm proposals on certain high potential sites.

Environment considerations usually restrict opportunities to reinforcement through the construction of new transmission routes. The new trading arrangements used for the electricity market would further increase the already considerable challenges faced by the operator of the transmission system of England and Wales. In order to facilitate the fair competition of generators and secure the transactions of long distance power transfers between different regions, the transmission system owner and operator must operate and plan the system to ensure that its transmission infrastructure is such that no transmission security constraints on the intact system will prevent any generator from operating when the system's demand is at its peak. In such a situation, it is very important to boost the transfer capability of the transmission system while improving the utilisation of transmission assets to accommodate high penetration of wind power on the network.

The efficient utilisation of the existing networks with high penetration of wind power needs more sophisticated control schemes of the advanced power flow and voltage control resources, namely power electronic controllers (FACTS) [1]

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while enhancing voltage security and voltage stability control. In this paper, we will in particular look at the application of Static Series Synchronous Compensator (SSSC) [2] for the purpose of congestion management and transfer capability of power systems with high penetration of wind power. The paper investigates and demonstrates how, at regional transmission level, effective FACTS based power flow control can be applied to relieve the transmission congestion and improve the transfer capability of the network with high penetration of wind power while voltage security and voltage stability constraints are satisfied and transmission assets can be effectively utilised.

II. MODELLING OF FACTS CONTROLLERS

A. Modelling of SSSC

As shown in Fig. 1, a SSSC usually consists of a coupling transformer, an inverter and a capacitor. However, the SSSC is series connected with a transmission line through the coupling transformer. Operation principle of a SSSC can be found in [2]. In principle, the inserted series voltage can be regulated to change the impedance (more precisely reactance) of the transmission line. Therefore the power flow of transmission line can be controlled.

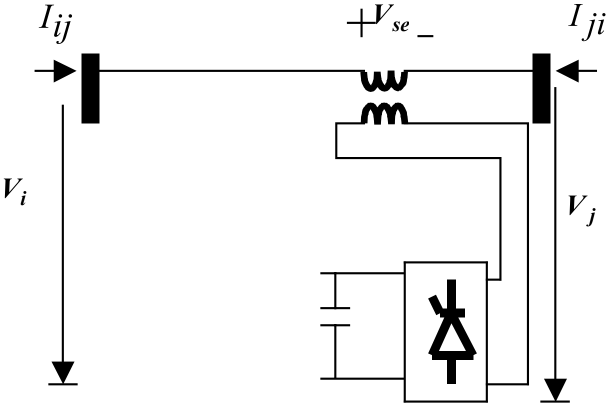


Fig. 1. The schematic representation of SSSC

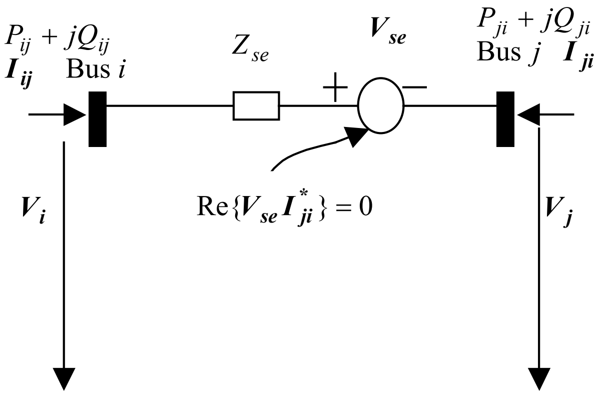


Fig. 2. The equivalent circuit of SSSC

The equivalent circuit of a SSSC as shown in Fig. 2 can be derived based on the operation principle of the SSSC. According to the equivalent circuit, suppose $\boldsymbol{V_{se}} = V_{se}\angle\theta_{se}$, $\boldsymbol{V_i} = V_i\angle\theta_i$ $\boldsymbol{V_j} = V_j\angle\theta_j$, then the power flow equations of the SSSC can be established:

$$\begin{aligned}P_{ij} = {} & V_i^2 g_{ii} - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) \\ & - V_i V_{se}(g_{ij}\cos(\theta_i - \theta_{se}) + b_{ij}\sin(\theta_i - \theta_{se}))\end{aligned} \tag{1}$$

$$\begin{aligned}Q_{ij} = {} & -V_i^2 b_{ii} - V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}) \\ & - V_i V_{se}(g_{ij}\sin(\theta_i - \theta_{se}) - b_{ij}\cos(\theta_i - \theta_{se}))\end{aligned} \tag{2}$$

$$\begin{aligned}P_{ji} = {} & V_j^2 g_{jj} - V_i V_j (g_{ij}\cos\theta_{ji} + b_{ij}\sin\theta_{ji}) \\ & + V_j V_{se}(g_{ij}\cos(\theta_j - \theta_{se}) + b_{ij}\sin(\theta_j - \theta_{se}))\end{aligned} \tag{3}$$

$$\begin{aligned}Q_{ji} = {} & -V_j^2 b_{jj} - V_i V_j (g_{ij}\sin\theta_{ji} - b_{ij}\cos\theta_{ji}) \\ & + V_j V_{se}(g_{ij}\sin(\theta_j - \theta_{se}) - b_{ij}\cos(\theta_j - \theta_{se}))\end{aligned} \tag{4}$$

where

$$g_{ij} + jb_{ij} = 1/Z_{se}$$

$$g_{ii} = g_{ij}$$

$$b_{ii} = b_{ij}$$

$$g_{jj} = g_{ij}$$

$$b_{jj} = b_{ij}$$

Operating constraint of the SSSC (active power exchange via the DC link) is:

$$\begin{aligned}PE &= \mathrm{Re}(\boldsymbol{V_{se}}\boldsymbol{I_{ji}^*}) \\ &= -V_i V_{se}(g_{ij}\cos(\theta_i - \theta_{se}) - b_{ij}\sin(\theta_i - \theta_{se})) \\ &\quad + V_j V_{se}(g_{ij}\cos(\theta_j - \theta_{se}) - b_{ij}\sin(\theta_j - \theta_{se})) = 0\end{aligned} \tag{5}$$

The equivalent voltage injection $V_{sh}\angle\theta_{sh}$ bound constraints:

$$V_{se}^{\min} \le V_{se} \le V_{se}^{\max} \tag{6}$$

$$\theta_{se}^{\min} \le \theta_{se} \le \theta_{se}^{\max} \tag{7}$$

B. Modelling of VSC HVDC

The success of application of VSC technologies in FACTS has inspired interests to apply such technologies in HVDC transmission. It was reported recently that VSC based HVDC systems have been successfully installed in several electric utilities in European Countries and U.S. However, it should be pointed out that these HVDC systems are basically used for back-to-back power transmission. The detail modeling of the VSC HVDC in power flow and optimal power flow analysis has been discussed in [4]. In comparison to the SSSC, the VSC HVDC can provide independent active and reactive power flow control and also bus voltage control. In principle, the VSC HVDC should be more powerful than the SSSC in terms of control capability.

III. FORMULATION OF TRANSFER CAPABILITY COMPUTATION PROBLEM INCLUDING FACTS AND WIND FARMS

A. Representation of Wind Farm

In the transfer capability calculations, a wind farm at the connection point can be equivalently represented by active and reactive power injections P_{wind} and Q_{wind} with a constant power factor:

$$P_{wind} = \alpha P^0_{wind} \tag{8}$$

$$Q_{wind} = \alpha Q^0_{wind} \tag{9}$$

where P^0_{wind} and Q^0_{wind} are base case active and reactive power injections of the wind farm while P_{wind} and Q_{wind} are the actual active and reactive power injections as functions of the load increase parameter. α represents the load increase factor.

B. Representation of Load

A load in the transfer capability calculations is defined by

$$Pd_k = \alpha * Pd^0_k \tag{10}$$

$$Qd_k = \alpha * Qd^0_k \tag{11}$$

$$k \in \Omega_k$$

where

Pd^0_k, Qd^0_k - base case active and reactive load of bus *k*

Pd_k, Qd_k - active and reactive load of bus *k*

Ω_k - a set of buses which have variable loads

C. Formulation of Transfer Capability Computation Problem

Mathematically, the transfer capability may be formulated as,

$$\text{Objective:} \quad \text{Max } f(x) = \alpha \tag{12}$$

Subject to the following constraints:

$$g(x) = 0 \tag{13}$$

$$h^{\min} \le h(x) \le h^{\max} \tag{14}$$

where $x = [\theta sh, Vsh, V, \theta, T, Pg, Qg, \alpha]^T$

P_{ij} - sum of the interface active power flows

Ω_I - the set of the interface tie lines

g(x) - equality constraints including bus power flow equations, operating and control constraints with incorporation of the FACTS controllers

h(x) - inequality-constraints including line flow constraints, simple inequality constraints of variables such as voltage-magnitudes, generator active power, generator reactive power, transformer tap ratio and bound constraints of SSSC variables, wind farm reactive power injections and load increase factor

θse - angle of series voltage source of SSSC

Vse - magnitude of series voltage source of SSSC

θ - bus angle

V - bus voltage magnitude

T - tap ratio vector of transformer

Pg - bus active generation

Qg - bus reactive generation

α -load increase parameter

The nonlinear optimisation problem of the transfer capability in (12) – (14) can be solved by the Nonlinear Interior Point Methods [3]. The Newton equation may be expressed as the following compact form,

$$\begin{bmatrix} -\Pi l^{-1} Sl & 0 & -\nabla h & 0 \\ 0 & \Pi u^{-1} Su & -\nabla h & 0 \\ -\nabla h^T & -\nabla h^T & H & -J^T \\ 0 & 0 & -J & 0 \end{bmatrix} \begin{bmatrix} \Delta \pi l \\ \Delta \pi u \\ \Delta x \\ \Delta \lambda \end{bmatrix} \tag{15}$$

$$= \begin{bmatrix} -\nabla_{\pi l} L_\mu - \Pi l^{-1} \nabla_{Sl} L_\mu \\ -\nabla_{\pi u} L_\mu - \Pi u^{-1} \nabla_{Su} L_\mu \\ -\nabla_x L_\mu \\ -\nabla_\lambda L_\mu \end{bmatrix}$$

$$\Delta sl = \Pi l^{-1} (\nabla_{sl} L_\mu - Sl \Delta \pi l) \tag{16}$$

$$\Delta su = \Pi u^{-1} (-\nabla_{su} L_\mu - Su \Delta \pi u) \tag{17}$$

where

μ - barrier parameter and $\mu > 0$

sl and su are slack variables for inequalities. πl and πu are dual variables for inequalities. λ are dual variables for equalities

$$H(x, \lambda, \pi l, \pi u)$$
$$= \nabla^2 f(x) - \lambda \nabla^2 g(x) - (\pi l + \pi u) \nabla^2 h(x)$$

$$J(x) = \left[\frac{\partial \Delta P(x)}{\partial x}, \frac{\partial \Delta Q(x)}{\partial x} \right]$$

$$g(x) = \begin{bmatrix} \Delta P(x) \\ \Delta Q(x) \end{bmatrix}$$

$$\lambda = \begin{bmatrix} \lambda_p \\ \lambda_q \end{bmatrix}$$

$$Sl = diag(sl_j)$$

$$Su = diag(su_j)$$

D. Solution Procedure of the Transfer Capability Problem

The solution procedure for the nonlinear interior point optimization algorithm for the transfer capability problem is summarized as the following:

1) Set iteration count $K = 0$, $\mu = \mu 0$, and initialize the optimization solution
2) If KKT conditions are satisfied & complementary gap is less than a tolerance, output results. Otherwise go to step 3)
3) Form and solve Newton equation in (12) – (14)
4) Update Newton solution
5) Compute complementary gap
6) Determine barrier parameter
7) *K*=*K*+1, go to step 2)

IV. NUMERICAL EXAMPLES

A. Test System

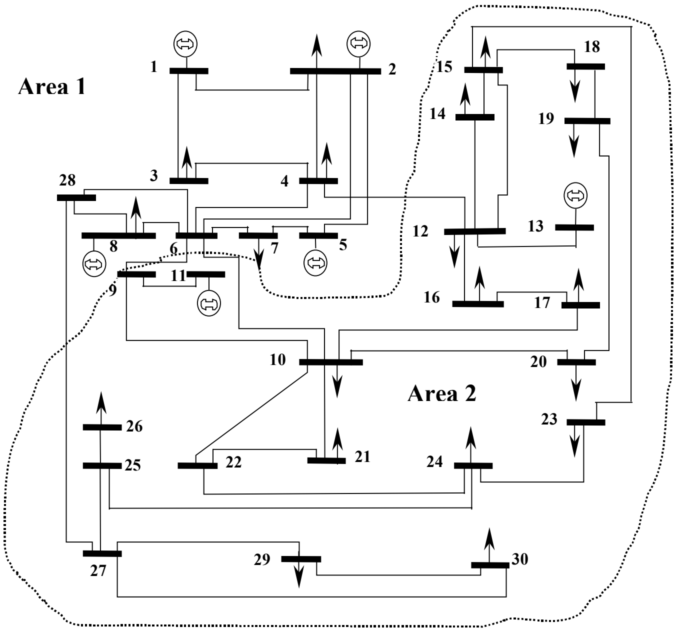


Fig. 3. The modified IEEE 30-bus system

Test cases in this paper are carried out on a modified IEEE 30 bus system. In the system, there are 6 generators, 4 OLTC transformers and 37 transmission lines. G3-G6 and G1 are conventional generating plants while G2 is a wind farm. In the study, the modified IEEE 30 bus system was divided into two areas, which are interconnected by intertie lines: 4-12, 6-9, 6-10, and 28-27 where buses 4, 6, 28 belong to the area 1, and buses 9, 10, 12, 27 belong to area 2. With the loads in area 1 being kept constant, the power transfer from the area 1 to the area 2 will be investigated in the following section.

B. Case Studies

In order to investigate the transfer capability of the system in Fig. 3, the following case is presented

Case 1: This is a base case for transfer capability computation without SSSC where the wind farm is connected with bus 1.

The transfer capability computation results of Case 1 are summarised in Table 1. The transfer capability of a system is characterised by the maximum load increase parameter $\alpha_{\max}$. In Table 1, the total generation of system is 340 MW while 60 MW of the power generation is from the wind farm generation, which represents 18% of the total generation. This Case can be considered as a case with high penetration of wind power in the system. It is found that at the maximum load increase parameter of 1.43, transmission line 2-6 is congested where the transmission limit is 65 MVA. In this situation, it is impossible to further increase the transfer capability of the system using the system control resources available.

TABLE 1 THE TRANSFER CAPABILITY RESULTS OF CASE 1

Maximum load increase parameter $\alpha_{\max}$	Total Generatio (MW)	Wind farm generation (MW)	Percentage of wind farm generation (%)	Network congestion at the maximum load factor
1.43	340	60	18%	Transmission line 2-6 is congested with a transfer limit of 65 MVA

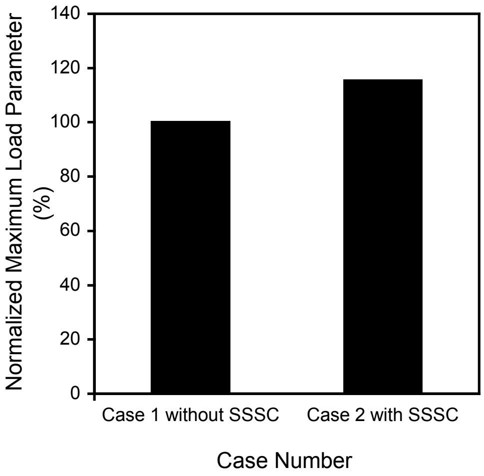
It has been recognised that the series FACTS controllers can be used to control power flows of transmission lines and hence to control power flow distribution of the network. In order to improve the transfer capability of the system of Case 1, the following Case was investigated:

Case 2: This is similar to Case 1 except that a SSSC is installed in line 2-6.

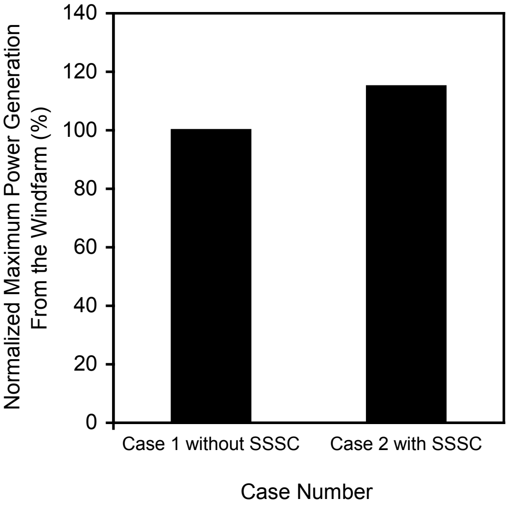
As discussed in Case 1, transmission line 2-6 is congested at the maximum load increase parameter of 1.43, in Case 2, a SSSC is installed in line 2-6 to manage the congestion and increase the network transfer capability. The transfer capability computation results of Case 2 are shown in Table 2.

TABLE 2 THE TRANSFER CAPABILITY RESULTS OF CASE 2

Maximum load increase parameter $\alpha_{\max}$	Total generation (MW)	Wind farm generation (MW)	Percentage of wind farm generation (%)	Network congestion at the maximum load factor
1.65	364	69	19%	Transmission line 2-6 is congested with a transfer limit of 65 MVA



(a) Transfer capabilities



(b) Wind farm outputs

Fig. 4. Comparison of transfer capability calculations of Case 1 and Case 2

Comparing Table 2 with Table 1, it can be found that using the SSSC, the transfer capability of the network with high penetration of wind power can be significantly increased from the maximum load factor 1.43 to 1.65. This is because a SSSC can be basically used to manage the network power flows effectively by changing the distribution of power flows of the network. The normalised maximum load increase parameters and wind farm outputs of Case 1 and Case 2 are also shown in Fig. 4. From Fig. 4, using the SSSC, the significant increase of the transfer capability and penetration of wind power in 15% can be clearly seen.

V. CONCLUSIONS

A transfer capability computation approach for systems with wind farms using series compensation FACTS i.e. SSSC has been proposed in this paper. The approach proposed can simultaneously take voltage, thermal and voltage stability limits into consideration, and may also consider any electricity transaction constraints. It should be mentioned that with the recent development of VSC HVDC technologies [4], VSC HVDC may be alternatively applied in the effective management of network congestion while enhancing the transfer capability of networks.

Numerical results based on the modified IEEE 30 bus system with/without the SSSC demonstrate the feasibility as well as the effectiveness of the SSSC for congestion management with high penetration of wind power in the network. The results using SSSC to improve system transfer capability and congestion management is encouraging. With the large integration of wind generation into power networks, it can be anticipated that FACTS controllers including the SSSC may be increasingly applied in effective management of network power flows.

Further research work is required to investigate the installation of SSSC in practical networks and the coordinated FACTS control techniques through the EMS such as the AREVA Network Energy Management System technology to implement the transmission network operation control and congestion management.

VI. REFERENCES

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VII. BIOGRAPHIES

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