Optimal Location of Series FACTS Devices to Control Line Overloads in Power Systems with High Wind Feeding

Arefeh Danesh Shakib, Ervin Spahić, Gerd Balzer

***Abstract*—The planned offshore wind farms in Germany are basically located in North region. For wind integration in Germany, establishing new transmission lines and employing new technologies have become unavoidable. Establishing new transmission lines is very costly and difficult regarding enviromental condition. One of the solutions is the utilization of Flexible AC Transmission Systems (FACTS). This paper discusses a method for determining the placement of series compensation to control line overload in power systems with wind power penetration. By a sensitivity based method critical lines can be identified quickly and accurately, to obtain desired wind feeding into the system. Thyristor Controlled Series Compensator (TCSC) is applied for system stabilization as a typical FACTS devices. This method is applied to realistic scenarios in a test system, which simulates reduced 380 kV network of Germany. Simulation results showed that the proposed method is effective and can enhance the transfer capability margin of existing power systems.**

***Index Terms*--Flexible AC Transmission System (FACTS), load flow controller (LFC), offshore wind farms, optimal location, overload, sensitivity index, wind feeding.**

I. INTRODUCTION

IN the last years the planned capacity of large wind farms in Germany has been increased. Therefore, in the future the wind power will have a large impact in the complete power generation [1]. Due to better wind conditions in North and Baltic Sea the most wind farms are planned offshore [2]. Fig. 1 shows the forecasted expansion of offshore wind power use in Germany. Even now, high load flows appear in the system from the north and east to the south and west regions. With an unfavorable network situation the system can be pushed to the limits of its load capacity. In case of connections of large offshore wind farms this situation will become even more critical and will lead to the overloading of transmission lines [4].

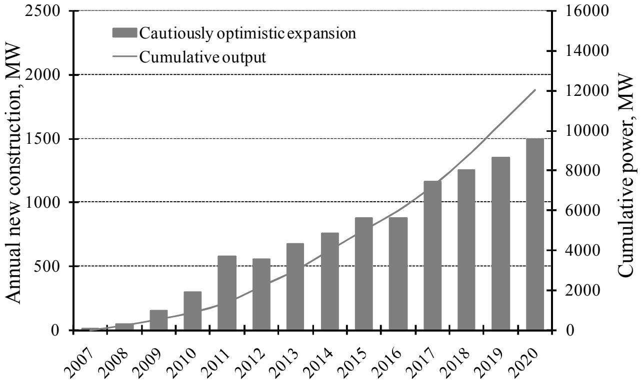

Fig. 1. Forecasted offshore wind power use in Germany up to 2020 [3].

To handle the high additional loading and integrate the wind power generation in Germany, new lines should be added to the system. Due to environmental impact and public opinion the installation of new electric power transmission lines is often restricted [5].

Thereby the development of future generation structures in Germany raise a lot of questions:

- How will be the future energy mix structure in Germany (fossil and renewable energies, power exchange, nuclear power plants, ...)?
- Which projects are currently planned?
- Which projects have the best realization chances?

The use of flexible AC transmission system (FACTS) devices as load flow controller (LFC) can be advantageous for the power systems with high wind power injections from large offshore wind farm. It opens up new opportunities for enhancing the usable capacity of existing transmission lines and provides an alternative to prevent network congestions, e.g. line overloading. FACTS devices may be used for active as well as for reactive power control because of their ability to change the apparent impedance of transmission line.

In this paper, we look for the optimal location of series FACTS devices for power flow control. The location problem needs combinatorial analysis. Several heuristic methods exist which can be used for the solution of each analysis, but for all

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these methods the optimal solution is sought using random process. Here a systematic not random methodology is needed.

In this work, a systematic methodology which can be used to eliminate the weakest network branches depended on future generation models is developed. The model analyzes the possibility to replace a high amount of generation with generation from large offshore wind farms by using a suitable load flow controller in weak branches. With this method the optimal placement of series FACTS devices can be determined. Steady-state simulations are performed on a 12-bus system which is close to German 380 kV network. All load flow calculations are realized by the power system software tool NEPLAN®.

A series FACTS device, for example thyristor-controlled series capacitor (TCSC), can be installed in the lines which have larger load due to transport of high wind power from North and Baltic Sea to the load centre in south of Germany. The TCSC has a high speed switching capability which provides a mechanism for controlling line power flow. This allows rapid changes of the line power flow in response to various contingencies. Furthermore TCSC can also regulate steady-state power flow within its rating limits [6, 7].

II. BASIC THEORY

In this section the details of functions and constraints of a typical series FACTS device (TCSC), which is applied for system stabilization, are shown. A typical TCSC can provide continuous control of power flow on the transmission line with a variable series capacitive reactance. TCSC will be connected at a transmission line as shown in Fig. 2.

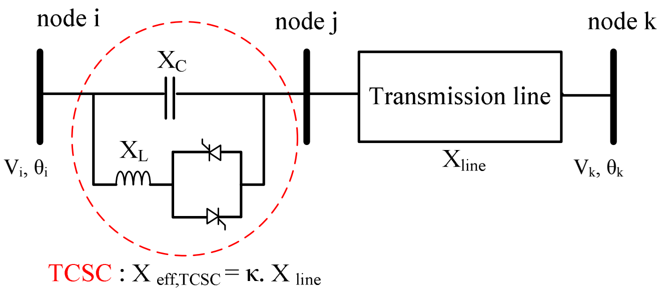

Fig. 2. A typical TCSC.

The basic TCSC module comprises a fixed series compensator (X_C) in parallel with a thyristor-controlled reactor (X_L) [6].

Depending on the system conditions inductive or capacitive reactive power may be needed. To meet this requirement the variable inductor is usually connected in parallel with a fixed capacitor. With the changes of the $X_{eff,TCSC}$ the power flow through the transmission line can be regulated. Thereby the effective reactance of TCSC can be varied as:

$$-0{,}2 \cdot X_{line} < X_{eff,TCSC} = \kappa \cdot X_{line} < 0{,}8 \cdot X_{line} \tag{1}$$

where κ is the compensation degree of TCSC.

Firing angles are allowed to vary between 90° and 180°. For a certain firing angle the variable inductive reactance equals in absolute value the capacitive reactance of the fixed capacitor X_C causing a resonance. Thyristors are fired sufficiently far away from the resonance value to avoid problems with control (*resonance region* limits).

A TCSC can either operate in the capacitive or in the inductive region. It means that X_{min} and X_{max} must be entered both as negative (capacitive operation) or both as positive (inductive operation) values.

In practical applications the TCSC may be used for the control of the active power flow and impedance of the transmission line (installed as shown in Fig. 2). The mathematical descriptions of the control functions of the TCSC are presented as follows:

$$P_{ik} - P_{ik}^{spec} = 0 \tag{2}$$

$$X_{eff,TCSC} - X_{eff,TCSC}^{spec} = 0 \tag{3}$$

where P_{ik}^{spec} and $X_{eff,TCSC}^{spec}$ are the specified active power flow control reference and the specified impedance control reference, respectively. The both control parameters can be changed by variation of κ. The constraint enforcement of equations (2) and (3) can be generalized as:

$$\Delta F(x) = F(x) - F^{spec} = 0 \tag{4}$$

where $x = [\theta_i, V_i, \theta_k, V_k, \kappa]^T$. θ and V represent the magnitude and the phase angel of the voltage, respectively.

A Newton power flow algorithm with simultaneous solution of power flow constraints and power flow control constraints of the TCSC may be represented as follows:

$$\left[\begin{array}{c:cccc}
\frac{\delta F}{\delta \kappa} & \frac{\delta F}{\delta \theta_i} & \frac{\delta F}{\delta V_i} & \frac{\delta F}{\delta \theta_i} & \frac{\delta F}{\delta V_k} \\
\hdashline
\frac{\delta P_i}{\delta \kappa} & \frac{\delta P_i}{\delta \theta_i} & \frac{\delta P_i}{\delta V_i} & \frac{\delta P_i}{\delta \theta_i} & \frac{\delta P_i}{\delta V_k} \\
\frac{\delta Q_i}{\delta \kappa} & \frac{\delta Q_i}{\delta \theta_i} & \frac{\delta Q_i}{\delta V_i} & \frac{\delta Q_i}{\delta \theta_i} & \frac{\delta Q_i}{\delta V_k} \\
\frac{\delta P_k}{\delta \kappa} & \frac{\delta P_k}{\delta \theta_i} & \frac{\delta P_k}{\delta V_i} & \frac{\delta P_k}{\delta \theta_i} & \frac{\delta P_k}{\delta V_k} \\
\frac{\delta Q_k}{\delta \kappa} & \frac{\delta Q_k}{\delta \theta_i} & \frac{\delta Q_k}{\delta V_i} & \frac{\delta Q_k}{\delta \theta_i} & \frac{\delta Q_k}{\delta V_k}
\end{array}\right] \cdot \left[\begin{array}{c}
\Delta \kappa \\ \hdashline \Delta \theta_i \\ \Delta V_i \\ \Delta \theta_k \\ \Delta V_k
\end{array}\right] = \left[\begin{array}{c}
\Delta F \\ \hdashline \Delta P_i \\ \Delta Q_i \\ \Delta P_k \\ \Delta Q_k
\end{array}\right] \tag{5}$$

In (5) the system Jacobian matrix is split into four blocks by the dotted lines. The bottom diagonal block is the system Jacobian matrix of conventional power flow without TCSC. The other three blocks are TCSC related.

Thus, a TCSC can change the structure of system Jacobian matrix and leads to a controlled active power flow through the transmission line.

III. CHOISE OF LOCATION METHODS

A. Heuristic methods

Heuristic methods are a first approach to find optimal location of FACTS devices in electrical networks. Several heuristic methods exist: Tabu Search method [8], Simulated Annealing [9] and Genetic Algorithms [10]. For all these methods the optimal solution is sought using random processes. These methods can be used to solve problem of combinatorial analysis for example for the optimal location of a given number of FACTS. The goal of this work is to find an optimal number of series FACTS devices, their locations and setting values for variable generation patterns. It needs methods which systematic, but not random find an optimal solution.

B. Other methods

A lot of proposals from diverse authors can be found in the literatures. The most of them are a modification of the heuristic methods which are not discussed in this paper. In [11] a Mixed Integer Linear programming (MILP) find optimal position of thyristor controlled phase shifter transformer (TCPST). Authors of [12] and [13] use methods which determine the weak places in the system using eigenvalue analysis of the system admitance matrix. They suggest these places as optimal location of shunt FACTS devices for reactive power and voltage regulation, respectively.

C. Developed method

In this work a methodology which is used for the optimal location of series FACTS devices in the system is developed. With this sensitivity based method it is possible to determine the lines sensitivity for all possible future generation strategies in a grid and to detect the most sensitive branches against generation replacement. The advantage of this method is the determination of line senstivity by very simple matrix calculation for all possible generation strategy combinations without extra long simulation and complex computation process.

All methods for the optimal location of series FACTS devices, which are developed by other authors, are to enhance the stability margin of existing power systems. This means that new analyses are needed for all other generation-load patterns.

The goal of the proposed method is to determine a line, which is highly sensitive to the new generation strategies, i.e. the integration of offshore wind energy. In Germany the majority of the offshore wind farms will be located on a relatively small area at the North Sea and this will lead to the large changes of line power flows. This method determines the line sensitivity for every load-generation scenario and for all individual combinations. A TCSC will be installed at the line, which has the highest sensitivity and largerst load respectively. This TCSC will provide the most efficienty power flow control in the system for the new generation strategy (replacement of the conventional generation by offshore wind farms).

The procedure of the optimal location of FACTS devices based on wind integration sensitivity index (*WISI*) can be described further on.

The first step is to consider a set of scenarios including load growth, import reduction, cancellation of nuclear power and CO_2 reduction by decrease of conventional generation. For all these scenarios it is assumed that the outage power is replaced by wind power generation.

For the base case, the load flow calculation (LFc) will be performed and the current of all transmission lines for the base case will be calculated.

$$I_{base,L} = \begin{bmatrix} I_{base,L1} \\ I_{base,L2} \\ \cdot \\ \cdot \\ \cdot \\ I_{base,Ln} \end{bmatrix}_{n\times 1} \text{, } n\text{: total number of transmission lines of interest.}$$

In the next step the line currents $I_{sc,L}$ and the line current differences $\Delta I_{sc,L}$ related to the basic scenario will be separately calculated for different generation scenarios.

$$I_{sc,L} = \begin{bmatrix} I_{sc1,L} & I_{sc2,L} & \cdots & I_{scm,L} \end{bmatrix}_{n\times m}$$

and

$$\Delta I_{sc,L} = \begin{bmatrix} I_{sc1,L} - I_{base,L} & I_{sc2,L} - I_{base,L} & \cdots & I_{scm,L} - I_{base,L} \end{bmatrix}_{n\times m} \tag{6}$$

where *m* is the total number of scenarios of interest. These represent the influence of the offshore wind integration on the line currents for the analyzed scenarios.

The wind integration sensitivity index (*WISI*) for the *i*-th line (L_i) is defined as:

$$WISI_{Li} = \frac{I_{\sup,Li}}{I_{r\max,Li}} - 1 \tag{7}$$

where $I_{r\,max,Li}$ is the maximal rated current of the *i*-th line and $I_{\sup,Li}$ is the line current for defined scenarios combination and can be calculated as following:

$$I_{\sup.} = \begin{bmatrix} I_{\sup,L1} \\ I_{\sup,L2} \\ \cdot \\ \cdot \\ \cdot \\ I_{\sup,Ln} \end{bmatrix}_{n\times 1} = \Delta I_{sc,L} \cdot B_{sc} + I_{base,L} \tag{8}$$

Array B_{sc} is an (m×1) binary array whose entries are „1“ or „0“ depending whether the scenario is considered or not. Therefore, it is possible to study (2^m- 1) superposition of scenarios. Fig. 3 shows the block diagram of the method.

This computation process allows determination of the line sensitivity for all possible scenario combinations by variation of B_{sc} elements.

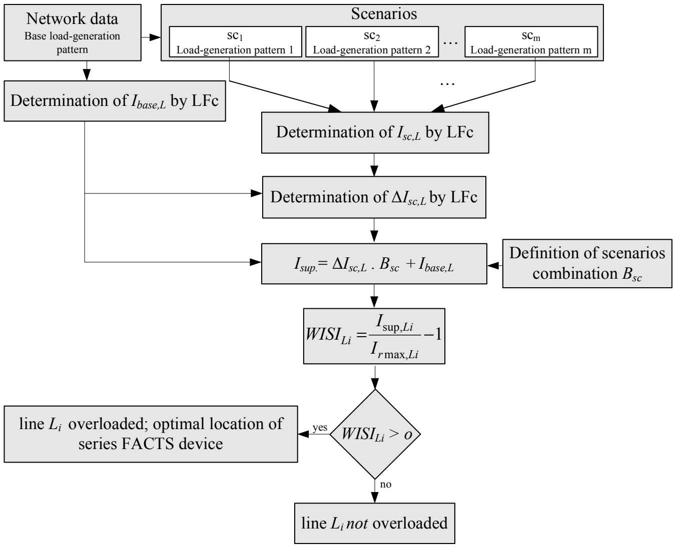

Fig. 3. Block diagram of method to determinate the optimal location of series FACTS devices in power system with high wind feeding.

The values of $WISI_{Li}$ are calculated for a specific load-generation pattern. If this approach is used for power system planning, the $WISI_{Li}$ values should reflect all typical load-generation patterns, e.g. summer or winter [14]. Thus, a composite value weighted by seasonal variations of load-generation patterns can be expressed as:

$$S_{Li} = g_w \cdot WISI_{Li,w} + g_s \cdot WISI_{Li,s} \tag{9}$$

where g_w and g_s are the weighting factors and $WISI_{Li,w}$ and $WISI_{Li,s}$ the calculated sensitivity values for winter and summer load-generation patterns, respectively.

Sensitivity index will be calculated for every line using (9). Lines with large S_{Li} values will be the weakest lines with the highest loading. These lines are the best location for the installation of series FACTS devices, e.g. TCSC [15]. A positive sensitivity value means that the line will be overloaded in case of applied scenarios combination. For this case, the load flow through the line must be kept within maximal allowed values using a load flow controller. The difference between expected and maximum acceptable power flow has to be shifted and carried out by other lines.

IV. TEST SYSTEM AND SYMULATION RESULTS

For the analysis of the methodology and its application, a reduced model of German 380 kV transmission system is used [16]. This 12-bus test system takes into account all major features of the German system: wind generation in north, high consumption in south, offshore generation, conventional generation, exports and imports (see Fig. 4). For the base case, the load-generation situation in Germany in 2005 is assumed.

For two load-generation patterns, light load and peak load situation, the sensitivity factors of the lines will be calculated using the methodology, mentioned in section III.

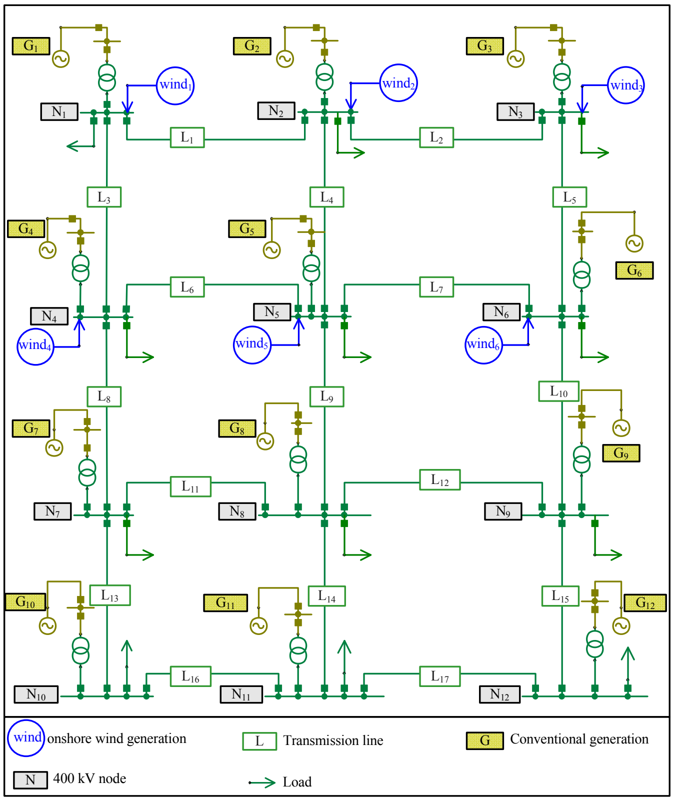

Fig. 4. Reduced simulated network of the 380 kV power system of Germany.

Four different scenarios are analyzed:

- **Scenario 1:** Load increase at 1,6% per year until 2010.
- **Scenario 2:** Reduction of import power from neighboring country up to 50%.
- **Scenario 3:** Canceling of nuclear power (80% thereof will be replaced by new conventional power plants).
- **Scenario 4:** Reduction of CO_2 emissions by decreasing the generation from lignite up to 20%.

It is assumed that in each case the outage power is replaced by offshore wind farms, which are connected to buses N_1, N_2 and N_3. These connections should simulate the planed offshore wind farms in the North and Baltic Sea. Depending on the occurrence of scenarios, different sensitivity values will be calculated. In this paper, it is considered that all scenarios occur simultaneously. For the peak load situation the wind generation (app. 45,6% onshore and 54,4% offshore) amounts about 32% of the total generation in the test system. Fig. 5 and Fig. 6 show the load-generation patterns of the test system for the base case, four studied scenarios and the superposition of the scenarios (end case) for peak load and light load situation in the test system, respectively.

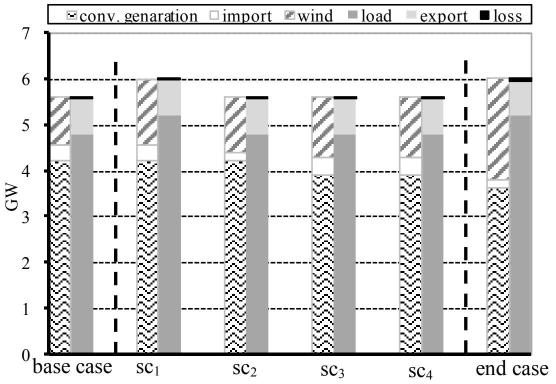

Fig. 5. Load-generation pattern of base case, four studied scenarios and end case for ***peak load*** situation in the test system.

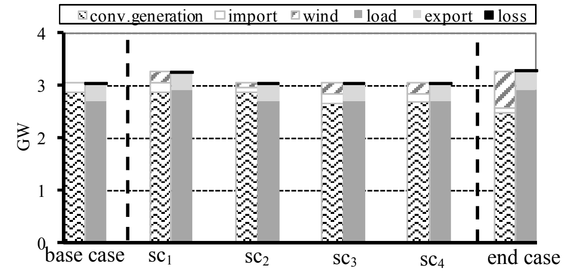

Fig. 6. Load-generation pattern of base case, four studied scenarios and end case for ***light load*** situation in the test system.

Using the developed method it can be estimated which lines will be overloaded when all these scenarios occur simultaneously (end case). TCSC are installed at the overloaded lines to limit their current flows. So, the number of needed TCSC in the test system and their optimal placement and setting value can be determined, if wind energy amounts 32% of the system generation. At first the current flows for base case and for four defined scenarios are calculated and then by using (6) and (8) the current flows for the end case are determined. Finally, line sensitivities $WISI_{Li}$ are calculated for each line and are listed in Table I for the case winter and in Table II for the case summer, respectively.

TABLE I
CALCULATED LINE CURRENTS, CURRENT VARIATIONS, AND SENSITIVITY FACTORS FOR PEAK LOAD SITUATION (WINTER)

Line	$I_{base,L}$ **[pu]**	$\Delta I_{sc1,L}$ **[pu]**	$\Delta I_{sc2,L}$ **[pu]**	$\Delta I_{sc3,L}$ **[pu]**	$\Delta I_{sc4,L}$ **[pu]**	$I_{sup.}$ **[pu]**	$WISI_w$
L_1	0,2261	0,0130	-0,0290	0,0000	0,0391	0,2493	-0,7507
L_2	0,1809	-0,0135	0,0011	-0,0169	-0,0067	0,1449	-0,8551
L_3	0,2760	0,2919	0,1026	0,1720	0,2399	1,0824	0,0824
L_4	0,3382	0,1854	0,0472	0,1101	0,1303	0,8112	-0,1888
L_5	0,3115	0,2654	0,0827	0,1750	0,1962	1,0308	0,0308
L_6	0,1020	0,0010	-0,0010	0,0000	0,0320	0,1340	-0,8660
L_7	0,3442	0,0423	-0,0077	0,0212	0,0135	0,4135	-0,5865
L_8	0,2442	0,0575	0,0433	0,0850	-0,0158	0,4142	-0,5858
L_9	0,7050	0,1941	0,0843	0,1784	0,0725	1,0824	0,3800
L_{10}	0,2620	0,0880	0,0570	0,0770	0,0340	0,5180	-0,4820
L_{11}	0,3897	0,0138	0,0000	0,0138	0,0207	0,4379	-0,5621
L_{12}	0,5040	0,0840	-0,0280	0,0320	0,0160	0,6080	-0,3920
L_{13}	0,6842	0,0395	0,0368	0,0316	0,0079	0,8000	-0,2000
L_{14}	0,4560	0,0560	0,0200	0,0840	0,0500	0,6660	-0,3340
L_{15}	0,2760	0,0640	-0,0160	0,0880	0,0360	0,4480	-0,5520
L_{16}	0,2700	-0,0075	0,1125	-0,0250	-0,0075	0,3425	-0,6575
L_{17}	0,5600	0,0617	-0,0100	0,0300	0,0250	0,6667	-0,3333

TABLE II
CALCULATED LINE CURRENTS AND CURRENT VARIATIONS AND SENSITIVITY FACTORS FOR LIGHT LOAD SITUATION (SUMMER)

Line	$I_{base,L}$ **[pu]**	$\Delta I_{sc1,L}$ **[pu]**	$\Delta I_{sc2,L}$ **[pu]**	$\Delta I_{sc3,L}$ **[pu]**	$\Delta I_{sc4,L}$ **[pu]**	$I_{sup.}$ **[pu]**	$WISI_s$
L_1	0,2899	-0,0290	0,0058	0,0145	0,0029	0,2841	-0,7159
L_2	0,2270	-0,0124	0,0011	-0,0056	-0,0022	0,2079	-0,7921
L_3	0,2688	-0,1373	-0,2283	-0,1922	-0,1387	-0,4277	-0,5723
L_4	0,0910	0,0831	0,0315	0,0584	0,0685	0,3326	-0,6674
L_5	0,1077	0,0942	0,0308	0,0788	0,0865	0,3981	-0,6019
L_6	0,2640	-0,0400	0,0020	0,0070	-0,0170	0,2160	-0,7840
L_7	0,3308	-0,0269	0,0038	0,0019	0,0019	0,3115	-0,6885
L_8	0,0558	0,0600	0,0700	0,0775	0,0067	0,2700	-0,7300
L_9	0,4050	-0,1000	-0,0675	-0,1225	-0,0450	0,0700	-0,9300
L_{10}	0,1490	-0,0470	-0,0340	-0,0550	-0,0220	-0,0090	-0,9910
L_{11}	0,7000	-0,0759	0,0000	0,0138	0,0103	0,6483	-0,3517
L_{12}	0,4200	-0,0220	0,0040	-0,0040	0,0000	0,3980	-0,6020
L_{13}	0,3658	0,0079	0,0026	0,0079	0,0026	0,3868	-0,6132
L_{14}	0,3280	-0,0400	-0,0020	-0,2340	0,0000	0,0520	-0,9480
L_{15}	0,3640	-0,0360	-0,0020	-0,0300	-0,0080	0,2880	-0,7120
L_{16}	0,2475	0,0175	0,0075	-0,0050	-0,0025	0,2650	-0,7350
L_{17}	0,0117	0,0350	0,0050	0,0100	0,0167	0,0783	-0,9217

The lines with positive sensitivity index are overloaded and are consequently proper for TCSC installation. It can be seen that the winter load situation is more critically than the summer. In this case, a superposition of the four scenarios leads to three positive sensitivity factors (for L_3, L_5, L_9) where in light load situation all sensitivity factors are negative. The following weighting factors are assumed for the calculation of S_{Li}:

$$g_w = 0{,}6,\ g_s = 0{,}4$$

Therewith the sensitivity factors of the lines can be determined when considering the weighting factors and typical load-generation pattern in winter and summer according to (7). Hence Table III shows the ranking list of the line for the optimal placement of TCSC.

TABLE III
RANKING LIST OF THE LINES FOR THE LOCATION OF TCSC´S

Line	**ranking list (winter)**	**ranking list (sommer)**	S_{Lj}	**ranking list (final)**
L_1	15	9	-0,7368	15
L_2	16	13	-0,8299	16
L_3	2	2	-0,1795	2
L_4	4	6	-0,3802	5
L_5	3	3	-0,2223	3
L_6	17	12	-0,8332	17
L_7	13	7	-0,6273	11
L_8	12	10	-0,6435	12
L_9	1	15	0,4294	1
L_{10}	9	17	-0,6856	13
L_{11}	11	1	-0,4779	7
L_{12}	8	4	-0,4760	6
L_{13}	5	5	-0,3653	4
L_{14}	7	16	-0,5796	9
L_{15}	10	8	-0,6160	10
L_{16}	14	11	-0,6885	14
L_{17}	5	14	-0,5687	8

According to the results in Table III the line L_9 is selected as the most sensitive line. Therefore, this line is chosen as the best location to place the first TCSC followed by L_3 and L_5. A TCSC can be installed in this line, if there is minimum one parallel unregulated branch to this line. If this is not the case; then a construction of a new transmission line should be made.

With a suitable setting of TCSCs, the current flow through the weak lines can be limited at their maximal rated current. The setting can be performed by using (1). Depending on the line reactance the maximal and minimal reactance of the TCSC will be selected. The TCSCs operate inductive because they have to limit the line currents at the maximal acceptable current. Table IV shows the setting parameters of the installed TCSCs.

TABLE IV
SETTING PARAMETERS OF THE INSTALLED TCSCS

No.	line	$X_{ind\ min}$ [ohm]	$X_{ind\ max}$ [ohm]	$X_{eff,\ TCSC}$ [ohm]	number of module
1	L_9	1	40	54,73	2
2	L_3	1	40	24,47	1
3	L_5	1	40	38	1

Under consideration of the TCSCs, which are installed in the weak branches in the test system, no overloaded line appears in the system for the critical load-generation case (winter). Fig. 7 shows that after installing of these three TCSCs the line current flows are changed so that current flow of the critical lines are reduced and in opposite the current flows of the uncritical lines are partially increased.

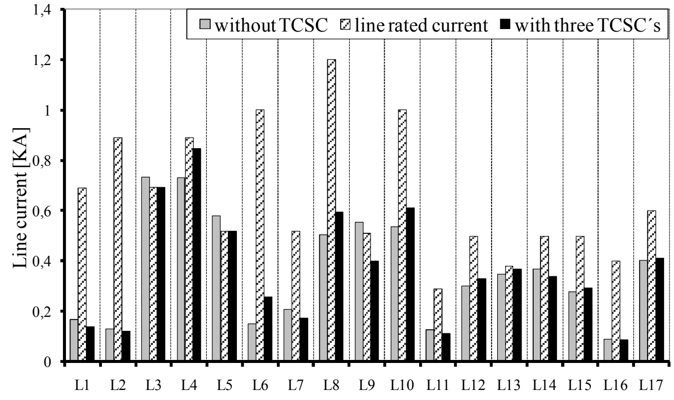

Fig. 7. Comparison of line currents with and without TCSCs installations.

Fig. 7 clearly illustrates that the system transfer capability can be enhanced by optimal using of series FACTS devices as TCSC. In addition, it is possible to feed about 1200 MW (32% of total generation) wind power from offshore wind farms into the system by using only three TCSCs with optimal allocation and suitable setting.

V. EVALUATION OF PROPOSED METHOD

To examine the validity of the proposed method for an optimal solution of TCSC placement an example is tested. The solutions for the 12-bus test system by the proposed algorithm are given in Table V. The solutions accuracy is compared with the solution obtained by load flow calculation using software program NEPLAN®. It is named as "Exact" solution. The values are determined for the more critical load-generation situation (winter) in the test system in the case of simultaneous occurrence of the scenarios (end case).

TABLE V
COMPARISON THE SOLUTIONS OF THE PROPOSED METHOD AND THE EXACT LOAD FLOW CALCULATIONS FOR THE END CASE

Line No.	line loading (%)		Error (%)
	Porposed method	Exact	
1	24,93	24,35	2,38
2	14,49	14,61	0,77
3	108,24	106,07	2,04
4	81,12	82,13	1,23
5	103,08	109,55	5,91
6	14,00	15,00	6,67
7	41,35	40,38	2,38
8	41,42	41,92	1,19
9	138,00	138,00	0,00
10	51,80	53,50	3,18
11	43,79	44,14	0,78
12	60,80	60,20	1,00
13	80,00	81,00	1,23
14	66,60	68,00	2,06
15	44,80	46,00	2,61
16	34,25	36,52	6,22
17	66,67	67,00	0,50

It can be seen that the solution errors are limited within 6,67%. Furthermore, the exact load flow calculation for the end case shows three lines overloading for L_3, L_5 and L_9. This agrees with the results of the porposed method.

VI. CONCLUSIONS

This paper presented a new methodology for allocation of series FACTS devices as the power flow controllers to eliminate overloads and to increase transfer capabilities for the power system with high wind feeding penetrations. The proposed method can select the optimal locations of TCSCs, which enable more transfer capability in the system. It is analyzed whether it is possible to replace a high amount of conventional generation with the generation from large offshore wind farms by using a suitable load flow controllers in weak branches.

TCSCs controllers stabilize the system under heavy load and unfavorable generation conditions (more generation in north because of wind feeding and high load concentration in south). It is shown that TCSC improve the stability and power transmission capability of the system.

In this paper the optimal locations and required capacity of TCSCs for a test system with high wind feeding are determined. The simulations are performed for checking the validity of the porposed method using a test system whose structure is closed to the 380 kV network of Germany. It has been shown that the line overloads are eliminated by the optimal allocation and the size of TCSCs while keeping the balance of the supply and demand. The test system is in a critical situation for the base case because of the unfavoreable load-generation condition. The current flow of several lines is closed to their limits and it is expected that with additional wind feeding in North region these lines will be overloaded. It is shown that with the utilization of three TCSCs the additional feeding of about 1200 MW from offshore wind farms into the system is possible without appearance of line overloading.

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