INDICATION OF SAFE TRANSITION PATHS OF PHASE SHIFTER SETTINGS BY GREEDY ALGORITHMS

J.Verboomen(1), D.Van Hertem(2), P.H.Schavemaker(1), W.L.Kling(1), R.Belmans(2)

(1) Electrical Power Systems, Delft University of Technology - (2) ELECTA, KU Leuven

ABSTRACT

In a liberalised market environment, the use of phase shifting transformers (PSTs) or other power flow controlling devices allows the transmission system operator (TSO) to utilise the available grid infrastructure in a more optimal way. In previous work, research has been performed on how to coordinate multiple devices in order to maximise the Total Transfer Capacity. Once the optimal phase shifter settings are determined, the question is how to go from the current setting to this optimal point. In this paper, algorithms are developed to calculate a safe transition between two sets of PST settings. The problem is modelled as a graph in which each combination of PST settings is represented by a vertex (node). Classical shortest path determination algorithms have an unacceptable calculation time for this problem, and an alternative solution must be found. The requirement of the shortest path can be relaxed to a requirement for a good path. This enables the use of a greedy algorithm, which is developed and tested in this paper. Also, an adapted form of the greedy algorithm is proposed, in order to avoid excessive switching between multiple PSTs.

Keywords: phase shifting transformer, total transfer capacity, shortest path, greedy algorithm

INTRODUCTION

Due to uneven loading of interconnectors in meshed networks, the total cross-border capacity, available for import and export of electrical energy in a control area, is not equal to the capacity one might expect when summing up all the capacities of the individual interconnectors. This problem led to the installation of two phase shifting transformers (PSTs) at the Meeden substation in the north of the Netherlands (Fig. 1) [4, 6]. Another Dutch-German interconnector already contained a PST in Gronau. The southern part of the country is closer to the center of the meshed continental European grid (UCTE zone) than the northern part, which could lead to congestion problems on the southern interconnectors with Germany. The PSTs can divert power to the northern interconnectors, loading the parallel lines more evenly. This is the main feature of these kind of devices, and the key reason for installing them.

The liberalisation of the electricity market and the increasing penetration of fluctuating power in the European power system are two factors that contribute to the increase of the power flows between countries (not neccesarily neighbouring countries). Without any means of control, the grid in a control area can become overloaded if it is involved in a power transfer as a third party. This is exactly what is happening to the Netherlands and Belgium. Transit flows induced by trade between Germany and France and loop flows due to the strong concentration of wind energy in the north of Germany cause additional loading of the Belgian and Dutch grid and can lead to critical operational situations. A main reason is the relatively low parallel impedance path through the Benelux. It is in this framework that PSTs become a valuable means of control [1, 2, 7].

Table 1 Nominal power of the different PSTs

PST	Nominal power (MVA)
Meeden	1200
Gronau	1425
Zandvliet	1400
Kinrooi 1	1400
Kinrooi 2	1400
Monceau	400

Belgium has decided to install several PSTs, as a single device can shift power to other lines but can not fully control the power flow. The plans are to install one device in Zandvliet and two in Kinrooi (Van Eyck substation) on the Belgian-Dutch border. Furthermore, a PST will be installed in Monceau near the French border for solving a local problem. Together with the PSTs in Meeden and Gronau, this leads to a total of six PST locations. The two devices in Meeden are considered as one, as they are operated in that way. Fig. 1 shows the location of all the devices, and Table 1 their nominal powers.

There is no direct connection between Belgium and Germany. So with all the PSTs installed, the

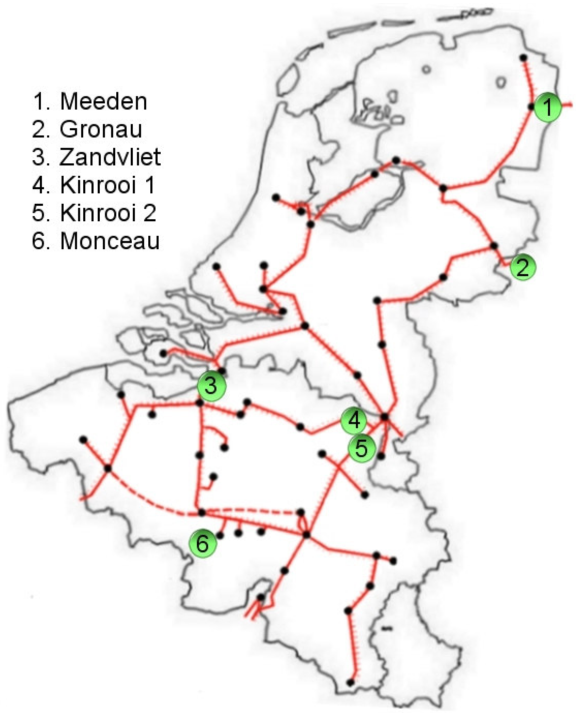


Figure 1 Location of different PSTs in the Netherlands and Belgium in the 400 kV transmission system

flows on the interconnectors between Belgium and the Netherlands can be fully controlled and the same is more or less true for the flows between the Netherlands and Germany and between Belgium and France (within the control possibilities of the PSTs).

The use of multiple PSTs in a rather limited geographical area must be studied carefully, because a poor coordination can lead to inefficient use of the infrastructure or even to situations where the security of supply is no longer guaranteed. In previous research, work has been done in order to calculate the optimal phase shifter settings. This paper aims to find a safe way to reach these optimal settings, avoiding unfavourable intermediate states.

TRANSFER CAPACITIES

ETSO (the organization of European Transmission System Operators) provides definitions for the transfer capabilities between countries [5]. The maximum amount of power that can be transferred between control areas A and B without violating any security criterion (for example the (n-1) criterion) is called the Total Transfer Capacity (TTC) between A and B. The definition of the TTC assumes that all future network conditions are perfectly known or foreseeable.

However, the exact operating conditions can not be predicted with total accuracy. The information that a transmission system operator (TSO) receives (be it from market players or measurements) and uses to predict future conditions is mostly uncertain and hard to guarantee. Hence, a security margin is introduced: the Transmission Reliability Margin (TRM). The TRM is determined by the TSOs. It is mostly a fixed value, but it can be adapted according to seasonal variations or network configuration changes.

The transfer capacity that can be offered to the market is the Net Transfer Capacity (NTC). It is the maximum amount of power that can be transferred across a border without violating any security constraint and taking into account the uncertainty in the planning process:

$$NTC = TTC - TRM \tag{1}$$

The aim is to maximise the capacity that can be offered to the market by the TSO. Hence, the goal is to maximise the NTC by choosing the best settings for the PSTs. However, the value of the NTC depends on the TRM. TSOs can have a different vision on how to choose this value. This is why the TTC is more appropriate to make transfer capacity calculations. Of course, in practice, the NTC should be used for operation, but for planning analysis the TTC is a more objective parameter.

For the calculation of the TTC, a base-case is used, corresponding to a certain amount of base-case exchange (BCE) between control areas. In order to increase the power flow at the border, the generation in one area is increased and decreased by the same amount in the other. This is the principle of power shift (PS). This process is repeated until a security constraint is violated. The maximum increase in generation in country A is designated as ΔE^{+}_{max}. The maximum decrease is ΔE^{-}_{max}. A graphical representation of the transfer capacities can be seen in Fig. 2.

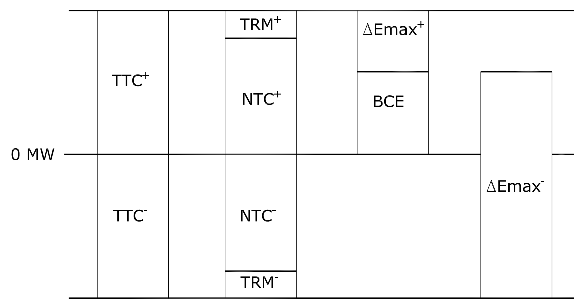


Figure 2 Transfer capacities according to ETSO

For TTC calculation, the linear projection technique is applied. The sensitivity s_l of every line flow is measured for a certain PS (typically 100 MW) and these values are assumed to be constant for every value of the PS. The power on every line can be expressed as a function of the power shift ΔP:

$$P_l = P_{l,0} + s_l \Delta P \qquad (2)$$

Furthermore, the line powers can not exceed the rated power:

$$\forall l : |P_l| \leq P_{l,r} \qquad (3)$$

From these two equations, the maximum allowable PS can be determined, and hence the maximum transmission between the two areas. If this is done for all contingencies, the (n-1) secure value for the TTC can be derived.

PROBLEM DEFINITION

Once the optimal phase shifter settings are determined, the question is how to go from the current settings to this optimal point. For technical reasons, this is a stepwise process which takes some time due to the limited speed of the mechanical tap changer of PSTs. One strategy could be to set one PST to its optimal position, then the second one, and so on. However, it is possible that some of the intermediate states are (very) unfavourable. Those states must be prevented as they can have a serious impact on the system. As an illustration of this problem, Fig. 3 shows the evolution of the TTC for different switching sequences (starting from a random initial configuration and moving to the optimal point). The import TTC is considered, which is a negative value by convention. Clearly, sequence 2 should be avoided at all times, as the import TTC becomes even positive for some intermediate states, indicating very unfavourable conditions.

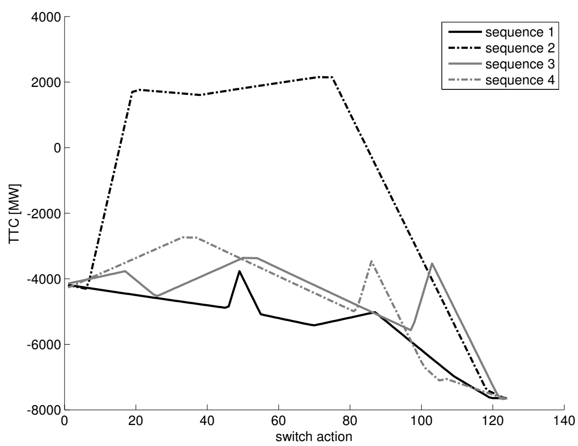


Figure 3 Evolution of the TTC for different switching sequences (negative values indicate import TTC)

The problem can be described as a directed graph $D = (V, A)$ with vertices V and arcs A. Each vertex v_i is represented by a state vector with the phase shifter settings:

$$\mathbf{x}_i = [x_i^1, x_i^2, \ldots, x_i^n]^T \qquad (4)$$

For the phase shifter settings, only integer numbers are used.

An arc is represented by a_{ij}, which designates that it goes from vertex v_i to v_j. The graph is constructed in such a way that vertices which differ only one degree in only one phase shifter setting are connected by an arc:

$$a_{ij} \in A \iff \exists!\, x_j^k \in \mathbf{x}_j : x_j^k = x_i^k \pm 1 \qquad k = 1 \ldots n \qquad (5)$$

This is of course only valid for phase shifter settings within the limits of the devices.

Every arc a_{ij} has a cost c_{ij}. This cost can for example be defined as:

$$c_{ij} = TTC_j - TTC_i + w \qquad w \geq 0 \qquad (6)$$

where w is a penalty factor that is strictly positive when the TTC deteriorates from vertex i to vertex j. The value of this parameter can be tuned depending on how severe a TTC deterioration should be penalised. The problem of avoiding unfavourable transitional states reduces to the determination of the shortest path in the graph described above.

SOLUTION STRATEGIES

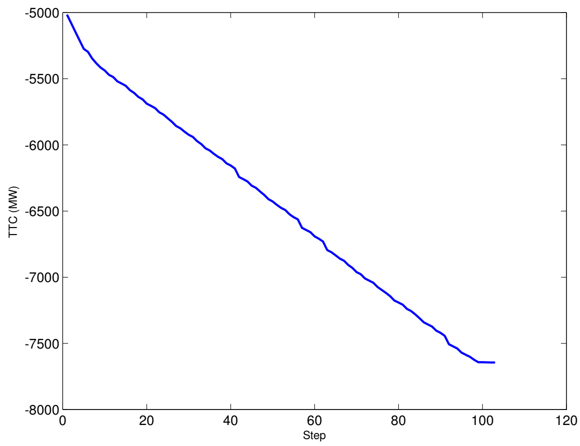
Shortest Path Algorithms

Shortest path problems are very common in optimisation theory [3]. The most basic method of solving them is Dijkstra's algorithm. The running time of this method is $\mathcal{O}(|V|^2)^*$. However, in the original version of this method, no negative arc lengths are allowed, making it unsuitable for the particular problem stated in this paper. The Bellman-Ford algorithm is designed to deal with negative arc lengths, with a running time of $\mathcal{O}(|V||A|)$. Next to these two classic methods, a whole array of other algorithms has been developed, but the aim of this paper is not to give an extensive overview of those. Even with modern methods, the calculation time can become very large, because the graph considered here is immense: there are over 5E^9 vertices and even more arcs.

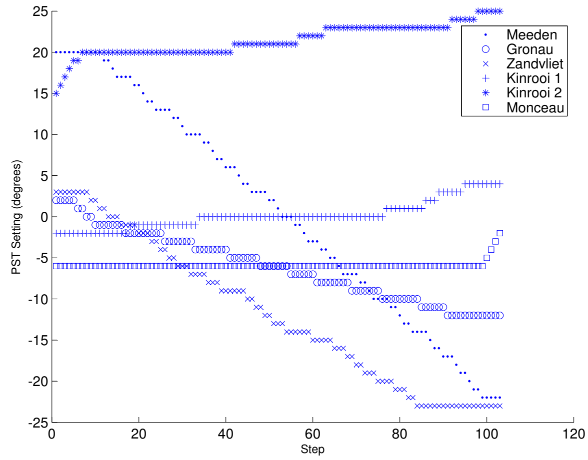
Greedy Algorithms

The requirement of the *shortest* path can be relaxed to a requirement for a *good* path. This enables the

$^*f(n) = \mathcal{O}(g(n))$ means there are positive constants c and k, such that $0 \leq f(n) \leq cg(n)$ for all $n \geq k$. The values of c and k must be fixed for the function f and must not depend on n. (source: Dictionary of Algorithms and Data Structures, `http://www.nist.gov/dads/HTML/bigOnotation.html`)



(a) TTC



(b) Settings

Figure 4 Evolution of the TTC and the PST settings for the Simple Greedy Algorithm

use of a greedy algorithm. This kind of method only looks in the direct neighbourhood of the current state and picks the apparent best solution at that time. For the implementation of a greedy algorithm for the problem considered in this paper, a few conventions are made:

- The cost of an arc is equal to the difference in TTC between the two vertices it connects.
- From the candidate arcs, the one that results in the biggest improvement is selected for the path.

The proposed Simple Greedy Algorithm (SGA) has the advantage of simplicity and limited calculation time, but it results in excessive switching between different PSTs, which is undesirable in practice. This problem can be tackled by using the Penalised Greedy Algorithm (PGA). In this approach a penalty factor P is added to the cost function:

$$c_{ij} = TTC_j - TTC_i + \lambda \cdot P \tag{7}$$

$$with:$$

$$\lambda \in \{0, 1\} \qquad P \geq 0 \tag{8}$$

The cost of an arc is increased by a constant P if it leads to a change in a setting of another PST than the previous one. This makes the control curves more smooth, but allows for a small deterioration in TTC. If the penalty factor is not too large, this should not be a problem.

SIMULATIONS

For the simulations, the grid model is that of the Netherlands, Belgium, and the neighbouring countries on the 19$^{\text{th}}$ of January 2000, at 10h30, representing a typical state of the grid. All phase shifters mentioned in the introduction are incorporated in this base-case. The Netherlands and Belgium are considered as one system and France and Germany as another. Calculations are performed on the import TTC of the Dutch-Belgian system opposed to the German-French system.

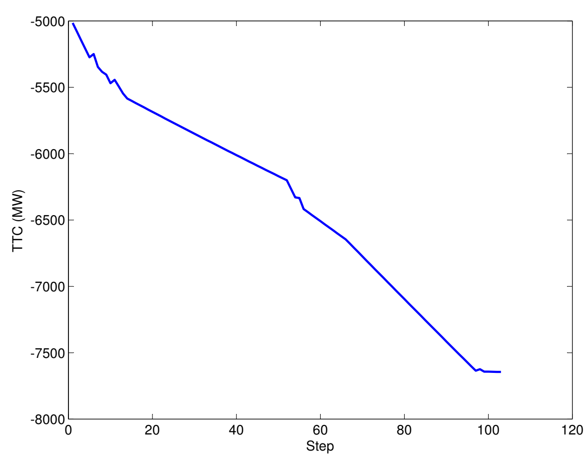
TTC values are calculated with PSS/E, and controlled by a script written in Python. For testing purposes, 10 random initial combinations of PST settings are generated, and the greedy algorithms are tested for each of these cases. The PGA method is tested with penalty factors of 100, 200, 300 and 400 MW.
Fig. 4 shows the evolution of the TTC and the PST settings when the SGA is applied in one specific case. The TTC improves in a monotonic way. However, there is constant switching between the different PSTs. This behaviour is also observed in all the other random situations.

Fig. 5(a) and 5(b) represent the results of a PGA calculation with a penalty factor of 100 MW. Clearly, a large improvement is made regarding the switching behaviour, but the TTC does no longer improve in a monotonic way. Fig. 5(a) shows that this non-monotonic behaviour is very limited, and it does not impose any problems.

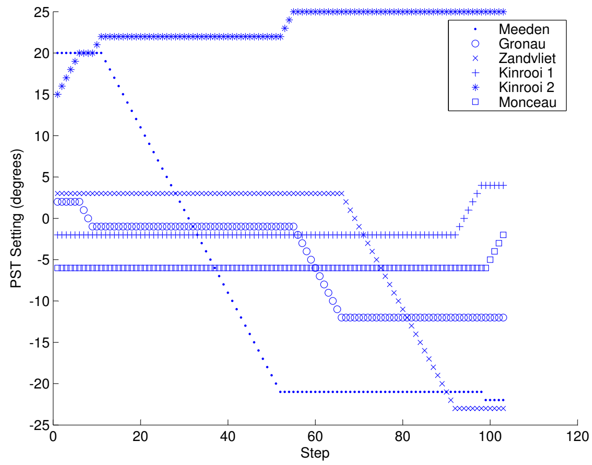
Fig. 5(c) and 5(d) show the results from the PGA calculation with a penalty factor of 400 MW. The temporary deteriorations of the TTC have become more pronounced, but the switching between PSTs has been reduced dramatically.

CONCLUSIONS

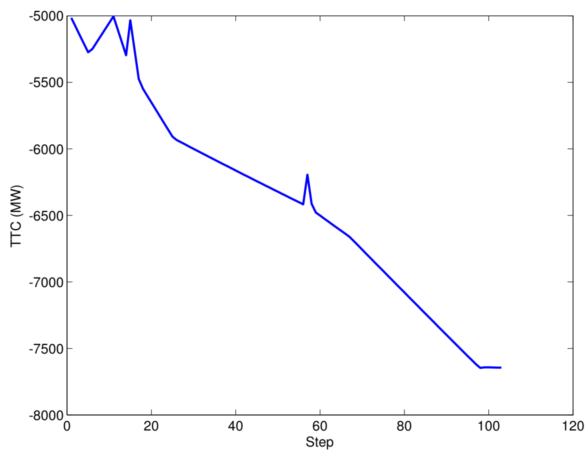
If multiple Phase Shifting Transformers (PSTs) are installed in a limited geographic area, coordination is required in order to make full use of the devices but also to guarantee a safe operating situation and to



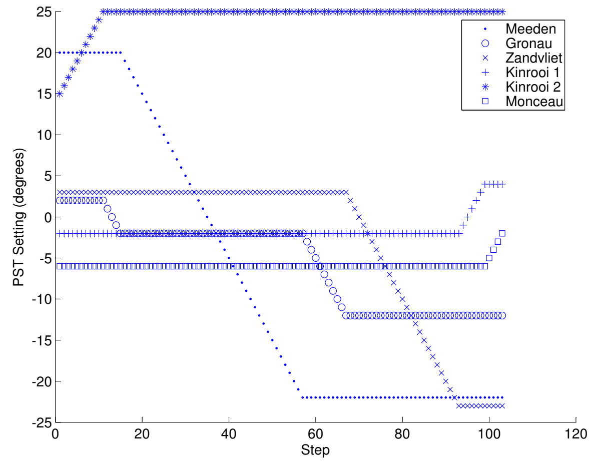
(a) TTC penalty 100 MW



(b) Settings penalty 100 MW



(c) TTC penalty 400 MW



(d) Settings penalty 400 MW

Figure 5 Evolution of the TTC and the PST settings for the Penalised Greedy Algorithm with a penalty factor of 100 (a and b) and 400 MW (c and d)

prevent control actions that counteract each other. The Total Transfer Capacity (TTC) is used as a target indicator, and the optimal PST settings can be found by using optimisation methods. Once these optimal settings are determined, the question is how to go from the current setting to this optimal point. In this paper, algorithms are developed to calculate a safe transition between two sets of PST settings. The problem is modelled as a graph in which each set of PST settings is represented by a vertex (node). Classical shortest path determination algorithms have an unacceptable calculation time for this problem, but the requirement of the shortest path can be relaxed to a requirement for a good path. This enables the use of a greedy algorithm. The Simple Greedy Algorithm (SGA) determines a good path, but at the cost of excessive switching between PSTs. The Penalised Greedy Algorithm (PGA) offers reduced switching behaviour at the cost of temporary deterioration in TTC.

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AUTHOR'S ADDRESS

The first author can be contacted at

Power Systems Laboratory
Delft University of Technology
Mekelweg 4
2628 CD Delft
The Netherlands
j.verboomen@tudelft.nl