Monte Carlo Simulation Techniques for Optimisation of Phase Shifter Settings

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Summary

The Netherlands has installed two phase shifting transformers in order to more evenly distribute the load on the interconnectors with Germany. Belgium is planning to install four devices to tackle the problem of transit flows between France and Germany and to control the flow on the parallel paths between Belgium and France. One phase shifter on the border of the Netherlands and Germany was already installed for a long time. The coordination of all the phase shifters is very important in order to take full advantage of these devices, but also to guarantee a safe situation and not to mutually counteract control actions. In this paper, a new Monte Carlo based approach is proposed to find the optimal settings of different phase shifters. The goal is to maximise the import capacity for both the Netherlands and Belgium.

KEYWORDS: Phase Shifting Transformer, Monte Carlo Simulation, Power Flow Control, Transit Flow, Total Transfer Capacity.

1 Introduction

Due to uneven loading of interconnectors in meshed networks, the total cross-border capacity, available for import and export of electrical energy, is not equal to the capacity one might expect when summing up all the capacities of the different lines. This problem led to the installation of two phase shifting transformers (PSTs) at the Meeden substation in the north of the Netherlands (Fig. 1) [1, 2]. The southern part of the country is closer to the center of the meshed European grid than the northern, which may lead to congestion problems on the southern interconnectors with Germany. The PST can divert power to the northern interconnector, loading the lines more evenly. This is a well-known feature of this kind of devices.

The liberalisation of the electricity market and the increasing use of wind energy in the European power system are two factors that have substantially increased the power flows between countries. Up to one decade ago, international flows were only due to long term contracts and to flows caused by mutual help between control areas at times of lacking generation capacity. Without any means of control, the grid of a country 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

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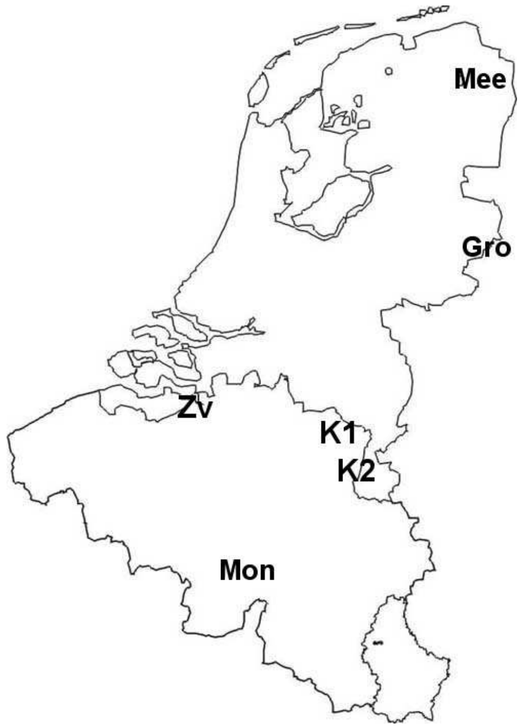


Figure 1: Location of different PSTs in the Netherlands and Belgium

increased trade between Germany and France and loop flows because of surplus of power in noncentral production sites (wind energy in the north of Germany or nuclear energy in the north of France) cause additional loading of the Belgian and Dutch grid, leading to several critical operational situations. It is in this framework that PSTs become a valuable means of control [3, 4, 5].

In response to the growing problem of transit flows, Belgium has decided to install several PSTs, because a single device can only shift power to other lines but not fully control it. The plans are to install one device in Zandvliet and two in Kinrooi, both on the Belgian-Dutch border. Furthermore, a PST will be installed in Monceau, near the French border solving a local problem. Together with the two PSTs in Meeden, this leads to a total of 6 PSTs. In this paper, the PST of Gronau in Germany is taken into account too, and the two devices in Meeden are considered as one, because they are operated in that way. Fig. 1 shows the location of all the devices.

It must be stated that there is no interconnection between Belgium and Germany. So with all the PSTs mentioned installed, the flows on the network between Belgium and the Netherlands can be fully controlled and the same is more or less the case for the flows between the Netherlands and Germany and between Belgium and France.

The use of several PSTs must be studied carefully, because a poor coordination can lead to inefficient use of investments or even to situations where the security of grid operation is no longer guaranteed. The goal of this paper is to study how the PSTs must be controlled in order to obtain an optimal or near-optimal situation for both the Netherlands and Belgium.

The ETSO (European Transmission System Operators) provides definitions and rules for the calculation of the transfer capacities between countries [6]. The maximum amount of power that can be transferred between countries A and B without violating any security criterion is called the Total Transfer Capacity (TTC) between A and B. The aim of the research is to maximise this TTC by coordinating PST control.

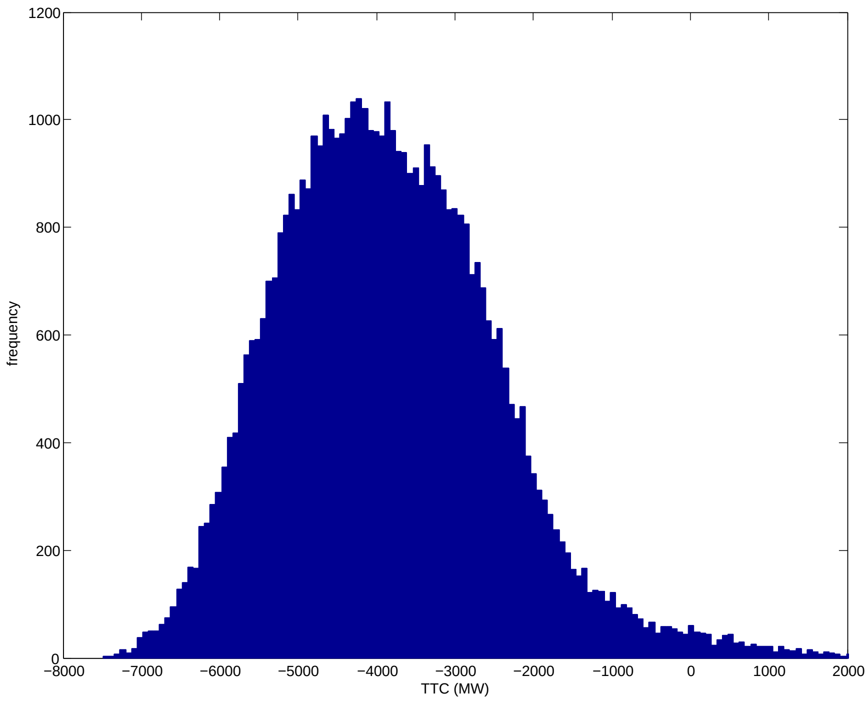


Figure 2: Histogram of a 50000 sample MCS of the import TTC of the Netherlands and Belgium

2 Monte Carlo Simulation

A straightforward approach to the problem of finding the optimal PST settings would be the calculation of the TTC for every combination of phase shifter settings. However, there are so many possible configurations, that this calculation would take years. This is why a Monte Carlo Simulation (MCS) approach is proposed [7].

The TTC is calculated for a number of random combinations of PST settings, and the results are plotted in a histogram. The shape of this histogram converges to a certain distribution, becoming clearer with an increasing amount of samples. A judgement can be made on the maximum attainable TTC and the settings to obtain this value. Conversely, the worst case scenario can also be investigated by looking at the other side of the histogram.

The calculations are performed using PSS/E and controlled by a script written in Python. For every set of random settings, a TTC analysis is performed by using DC load flows to increase the computation speed. The Netherlands and Belgium are considered as one system and France and Germany as another. Calculations are performed on the import TTC from the German-French system to the Dutch-Belgian system.

The model used is the situation of the grid 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.

Fig. 2 shows the results of an MCS with 50000 samples. Favourable TTC values have a negative sign as import is considered as an optimising target. It can be seen that a maximum value of about 7500 MW can be obtained. Furthermore, in the worst case a positive value is obtained. This means that the system can not import any power because of overloading problems. These problems occur when there is a large loopflow passing through the Netherlands and Belgium. This flow, which can become as large as 1500 MW, depends largely on the setting of the Zandvliet and Kinrooi 1 PSTs, or more precisely, on the coordination of both devices.

As demonstrated, an approximation of the maximum TTC can be obtained by looking at the

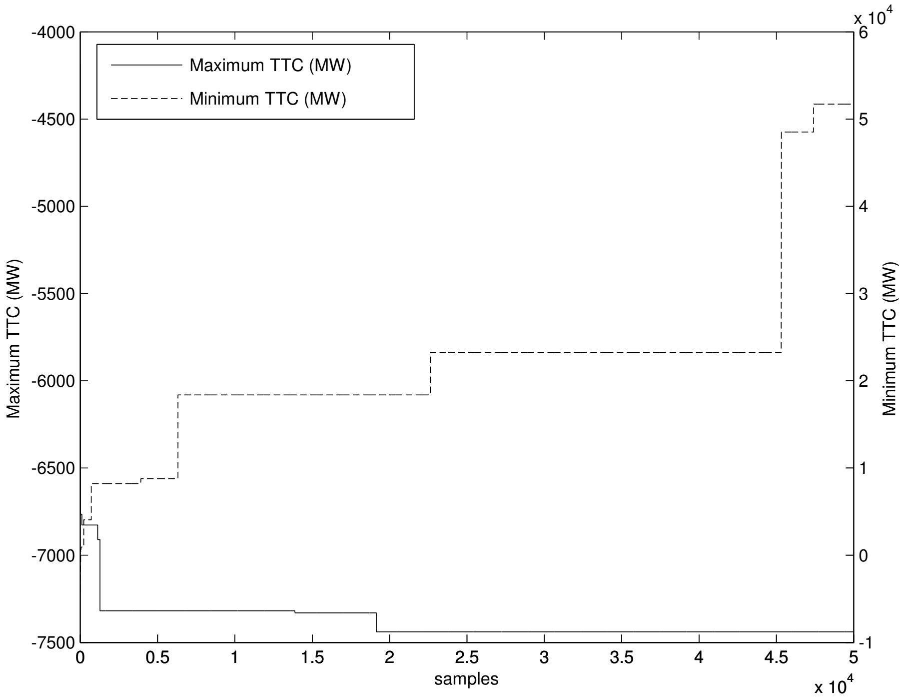


Figure 3: Evolution of the minimum and maximum TTC values with an increasing amount of samples

histogram. An important question is how many samples are needed to find a good approximation. In Fig. 3, the minimum and maximum TTC values with an increasing number of samples can be seen. From the figure, it becomes clear that 20000 samples are enough to reach the maximum value in this simulation. It is also evident that the absolute minimum value is very sharp, as it is only reached with a large amount of samples. It can be concluded that the amount of samples needed depends on the area of interest.

3 Multistage Monte Carlo Simulation

In the classical MCS approach, samples are generated in a certain multidimensional search volume SV:

$$SV = \prod_{i=1}^{d} (max_i - min_i) \tag{1}$$

In this expression, min_i and max_i are the minimum and maximum values respectively of variable i. The larger the range of the variables, the larger the SV becomes. In the case of this research, the dimension d is 6. A high dimension leads to a large SV, which in its turn leads to a high required amount of samples. Furthermore, from the MCS it is not clear which PST settings are the best, as the information on the optimal region of the histogram is not sufficiently detailed. In order to reduce the search volume and increase the accuracy, the Multistage Monte Carlo Simulation (MMCS) is introduced.

Fig. 4 shows the principle of the technique. In the first step, the minimum and maximum settings of each phase shifter are used as boundaries of the initial SV (indicated by a_{min} and a_{max}). A random number generator (RNG) is used within this interval to produce random configurations. The best fraction of the resulting TTC values is selected and the minimum and maximum settings of each

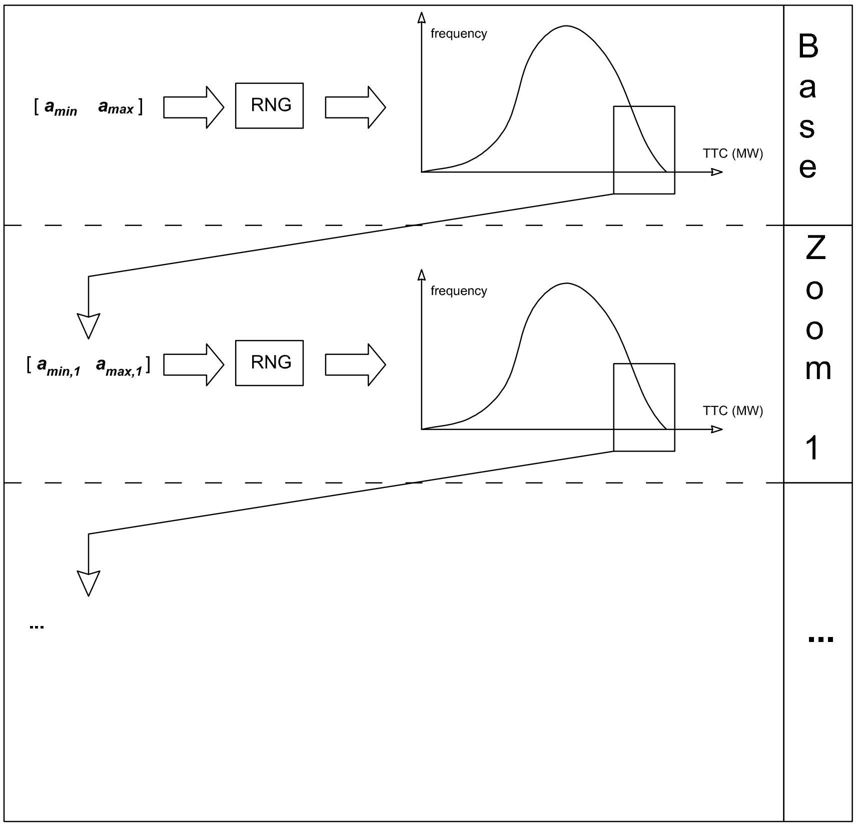


Figure 4: Principle of the Multistage Monte Carlo Simulation technique

variable within this fraction define the boundaries of the SV of the next MCS. The new SV is smaller than the previous one and still contains the optimal point. This process of zooming can be repeated several times. The SV in the MMCS can be described by:

$$SV_z = \prod_{i=1}^{d} (max_{i,z} - min_{i,z}) \quad (2)$$

where z is the zoomlevel (ZL).

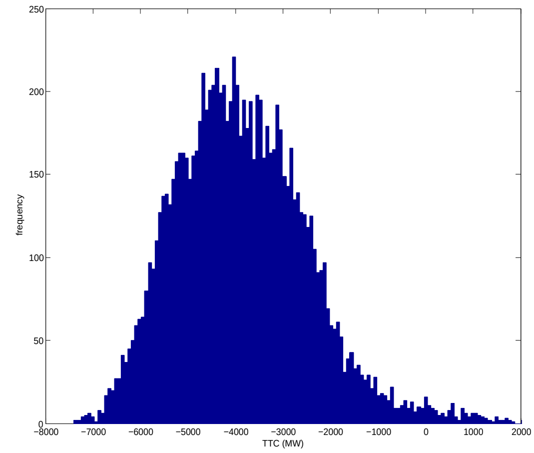
Fig. 5 shows the histograms for different zoomlevels. In this simulation, 10000 samples per zoomlevel are used and the 20 best are selected for the definition of the new SV. It is clear from the picture that the range of the TTC values decreases with each ZL, especially from the base case to ZL 1. At ZL 5, the range has decreased to less than 300 MW.

After ZL 5, the minimum and maximum settings of the 20 best TTC values are used as boundaries for a final MCS with 50000 samples. From this calculation, it appears that a TTC between 7750 and 7500 MW can be expected if the final PST setting intervals are respected.

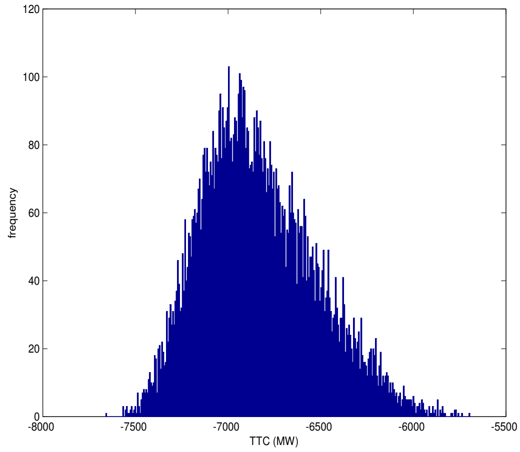
4 Transit Flow Analysis with MMCS

4.1 Simulation results

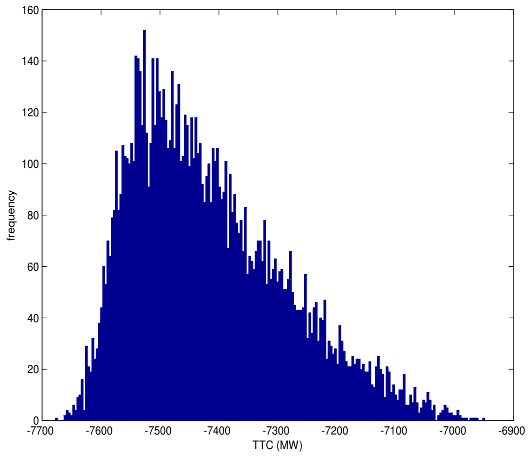
The MMCS is also used to investigate how the coordination of PSTs should be under transit flow (TF) conditions. In order to obtain a transit flow between France and Germany, a power shift (PS)



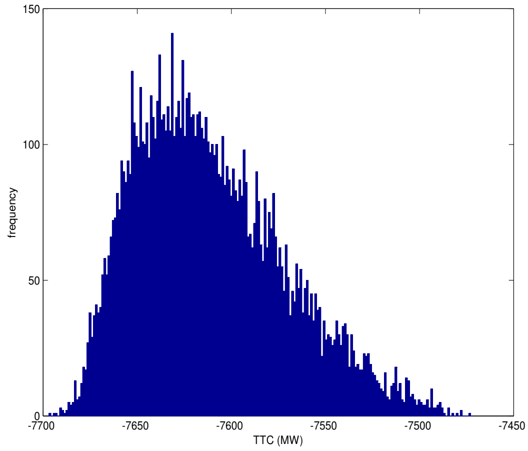
(a) Base



(b) zoom 1x



(c) zoom 3x



(d) zoom 5x

Figure 5: Histograms for different zoomlevels at 10000 samples for the import TTC from France and Germany to Belgium and the Netherlands

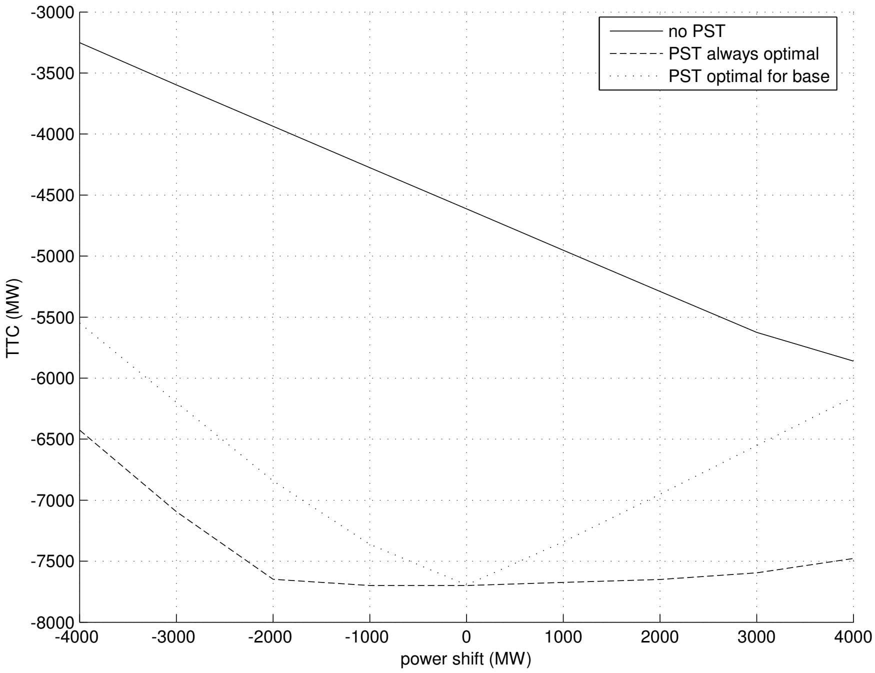


Figure 6: TTC for different PS levels for MMCS with 10000 samples and ZL 5

is applied. This means that the generation is increased in one country and decreased by the same amount in the other. A part of this PS passes the Netherlands and Belgium. A positive PS means that generation is increased in Germany, resulting in a TF to France.

The MMCS method is used with 10000 samples per ZL up to ZL 5. The results can be seen in Fig. 6.

In order to obtain a reference situation, all PSTs are set to zero degrees initially. This situation is roughly that of a scenario without PSTs. As can be seen in Fig. 6, the no-PST situation suffers from a significant loss of TTC for a TF in a particular direction. More precisely, if the power shift is negative for Germany, the resulting flow coming from France causes a decrease in TTC for the Netherlands and Belgium. In the reverse case, the situation improves in comparison with the base case. This can be explained by the fact that a TF from Germany to France decreases the loading of the interconnectors at the Belgian-French border, resulting in a higher import TTC.

Coordination of PSTs can make the system more robust. In the base case, this means that the bottleneck located at the Belgian-French border is alleviated. Any deviation from the base case causes a deterioration in TTC because the PST settings were optimised specifically for the base case. It can be seen in Fig. 6 that the curve is well below that of the no-PST scenario.

If the PSTs are optimised for every power shift level, the curve of the TTC becomes much flatter, as shown in Fig. 6.

Fig. 7 shows the best settings found for each PS level. The Gronau PST setting remains more or less constant over the whole range of power shifts. This is also true for the Monceau setting, although the curve is less smooth. The Kinrooi 1 PST setting shows the most radical change; this device seems to be the most important control entity in the optimisation process under various power shift levels.

4.2 Convergence of the simulation

The MMCS method decreases the SV with every ZL. However, during the simulations, it became clear that the speed of convergence is not the same for all PSTs. After the calculations of the previous

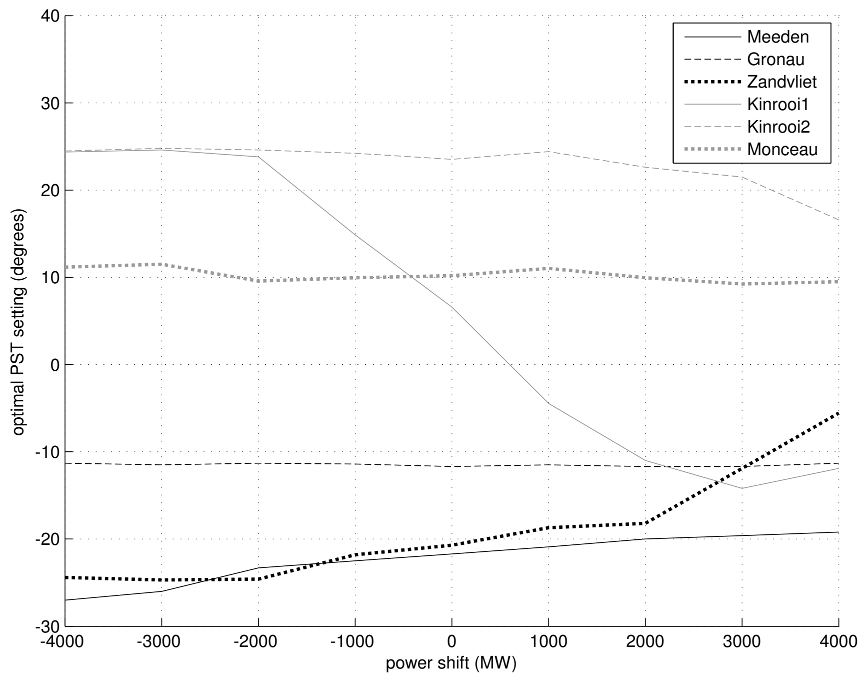


Figure 7: Optimal PST settings for different PS levels calculated with MMCS with 10000 samples and up to ZL 5

paragraph, the range in the settings of the best 20 samples is examined and scaled as a percentage of the total range of that particular PST. This action is performed for every PS level. The results can be seen in Fig. 8.

Clearly, the range of the Meeden, Gronau and Kinrooi 2 PST settings is smaller than 10%, indicating that these devices converge reasonably fast in the MMCS calculations. The other PSTs however show a significant larger setting range, especially for additional flows from Germany to France.

For the Monceau PST setting, this can be explained from the fact that this device is not very important in the optimisation proces. A sensitivity analysis shows that the TTC only varies a few MW per degree of change in the setting. This means that the optimum value is not very well defined, and that convergence is slow.

For the Kinrooi 1 and Zandvliet PST settings, a similar sensitivity analysis is performed. The results show a variation of a few tens of MW per degree of deviation from the calculated optimal setting. A correlation analysis between the PST settings of Kinrooi 1 and Zandvliet shows that the correlation coefficient of the best 20 values reaches values of up to 0.99, indicating that the optimal settings of these devices are highly dependent. This is the reason why these PSTs do not converge very fast to one optimal setting.

5 Conclusions

A method for the optimisation of settings of multiple phase shifters is developed. This algorithm is applied for the situation in the Netherlands and Belgium, where multiple devices are installed. The parameter that is optimised is the TTC.

A classical Monte Carlo Simulation offers an estimate of the best and worst import TTC values, and the number of samples needed can be relatively limited for this purpose. However, the settings required to obtain optimal or near optimal results do not come out of this approach with an accuracy

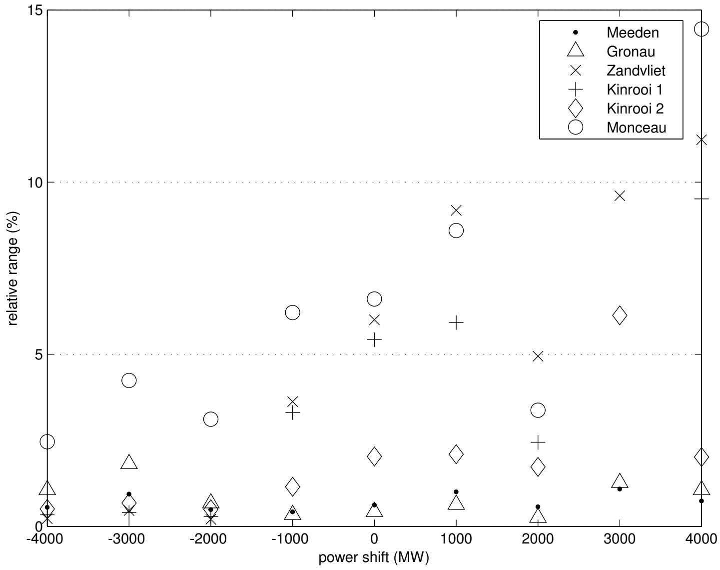


Figure 8: Procentual range of the best 20 samples at ZL 5 for MMCS with 10000 samples

that is sufficiently high.

Therefore, a new approach is developed in which the search volume of the MCS is narrowed in several subsequent steps. In this way, the optimal settings for each phase shifter are defined in detail.

Calculation of transit flow conditions indicates that a good coordination of the PSTs leads to a more robust system: the sensitivity to these flows is greatly reduced.

6 Abbreviations

CDF	Cumulative Distribution Function
ETSO	European Transmission System Operators
MCS	Monte Carlo Simulation
MMCS	Multistage Monte Carlo Simulation
PS	Power Shift
PST	Phase Shifting Transformer
RNG	Random Number Generator
SV	Search Volume
TF	Transit Flow
TTC	Total Transfer Capacity
ZL	Zoomlevel

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Biographies

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Jean-Marie Delincé obtained his M.Sc. in Electromechanical Engineering in 1970 and a complementary diploma in applied mathematics in 1971, both from the University of Liège, Belgium. During his career, he has been involved in several aspects of electrical power engineering. Currently, he is responsible for grid development at Elia, the Belgian TSO.

Ronnie Belmans received the M.S. degree in electrical engineering in 1979, the Ph.D. in 1984, and the Special Doctorate in 1989 from the K.U.Leuven, Belgium and the Habilitierung from the RWTH, Aachen, Germany, in 1993. Currently, he is full professor with K.U.Leuven, teaching electrical machines and variable speed drives. He is appointed visiting professor at Imperial College in London. He is also President of UIE. He was with the Laboratory for Electrical Machines of the RWTH, Aachen, Germany (Von Humboldt Fellow, Oct.'88-Sept.'89). Oct.'89-Sept.'90, he was visiting associate professor at Mc Master University, Hamilton, Ont., Canada. During the academic year 1995-1996 he occupied the Chair at the London University, offered by the Anglo-Belgian Society. Dr. Belmans is a fellow of both the IEEE and the IEE (United Kingdom). He is the chairman of the board of Elia, the Belgian transmission grid operator.

Wil L. Kling received his M.S-degree in electrical engineering from the Technical University of Eindhoven in 1978. Since 1993 he has been a (part-time) professor with the Department of Electrical Engineering at Delft University of Technology, in the field of Power Systems Engineering. In addition, he is with the Operations department of TenneT (the Dutch Transmission System Operator). Since 1999, he has also been a part-time professor at the TU Eindhoven. His area of interest is related to planning and operations of power systems. He is the project leader of the research programme 'Intelligent Power Systems', sponsored by SenterNovem, an agency of the Dutch Ministry of Economic Affairs. Prof. Kling is involved in scientific organizations such as CIGRE and the IEEE. As Netherlands' representative, he is a member of CIGRE Study Committee C1 System Development and Economics, and the Administrative Council of CIGRE. Furthermore, he is involved in several international working groups in the field of network planning and system studies, within UCTE, Eurelectric and other bodies.