Tuning of Traction Power Station Converter Output Characteristics

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***Abstract*— This paper defines the criteria that must be considered when setting the output control characteristics of the static frequency converter (SFC) stations for supplying the 25kV/50Hz railway catenary. The control characteristics must consider many often conflicting requirements and their optimal selection is therefore not a straightforward matter. The second part of the paper shows the search for the optimal control characteristic in terms of losses in the catenary.**

Keywords—Converters for Special Applications, Railway Power Stations, Simulation of Traction Grid

I. INTRODUCTION

The 25kV/50Hz railway traction network in the Czech Republic is a promising system providing a sufficiently sized power supply system suitable for the operation of modern interoperable traction vehicles, meeting the technical specifications for interoperability, which also allows easy recuperation back to the power supply network. [1]--[5] The current solution with conventional transformer stations, brings significant drawbacks, which are furthermore accentuated with increasing demand and the massive uptake of recuperation. [6] First drawback is the asymmetry of the consumption from the public distribution network. Therefore also recuperation to each line to line voltage is not equal. Furthermore, the spectrum of current and drawn reactive power depending on the needs of specific railway vehicles. Also the necessity to divide catenary network into sections fed with different phase shifts. [7][8]

A. Structure of converter substations

A long-term satisfactory solution to the above shortcomings of the conventionally transformer-powered traction network is the use of static frequency converters separating the single-phase 25kV/50Hz traction network from the public distribution 3x 110kV/50Hz by an DC bus [7], according to the diagram in Figure 1 [9].

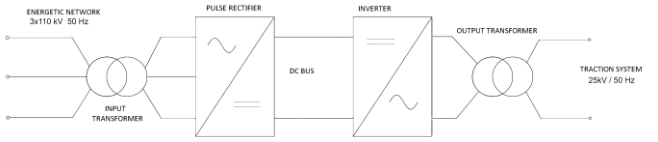

Fig. 1. Block diagram of static frequency converter

This concept, which was used in the Czech Republic for the first time in the Říkovice and Otrokovice substations, allows the parent distribution grid to be loaded evenly in all circumstances, controlling the amount of reactive power while precisely defining the spectrum of current drawn from the distribution grid. In this application in Czech Republic was used rail static frequency converter PCS 6000 for 50Hz manufactured by Hitachi Energy.[10]

On the single-phase (traction) side, it allows to create one phase on the whole line (completely independent of the phase of public distribution grid), to control the amount of reactive energy and at the same time to control the consumption from a given substation by shifting the instantaneous values with respect to a specified reference. [11][12]

The multilevel converters used in 25 kV 50 Hz substations are characterized by their modular architecture [9][13]. A block of the static frequency converter (in this case a three-level block) is shown in Figure 2.

Converters are designed as compact water-cooled containers. Outside the containers are transformers, switchers, circuit breakers and filter elements. Detailed information of the structure and control of the converter is the know-how of the manufacturer and is not publicly available. The converter output characteristic tuning methods discussed in this paper use the options of the converter control layer above, which is open to power station distributors that use converter technology.

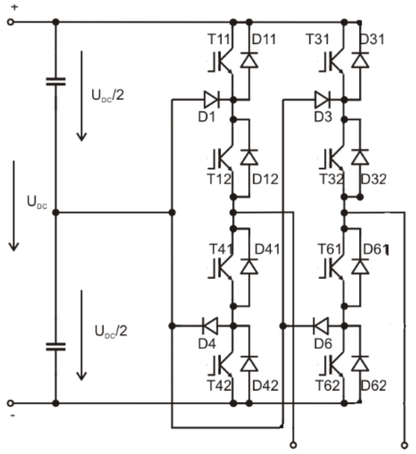

Fig. 2. Schematic diagram of converter block

B. Output characteristics

The converter substation can generally operate in two modes, operating and short-circuit. This paper aims to determine, on the basis of several criteria, the appropriate setting of the substation in the operating mode. Setting can be made by phase shift ε of the substation voltage which controls output active power. ε is phase shift with respect to the reference voltage. Next option is to control output reactive power by the effective value of the substation voltage U. The operational setting of the substation is thus defined by its output characteristics (as per the example in Figure 3). [14]

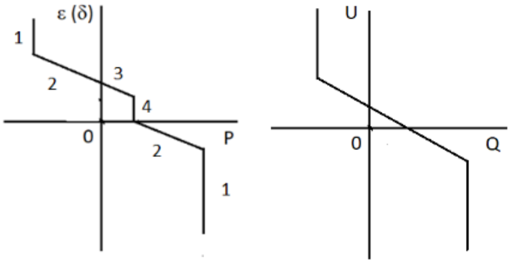

Fig. 3. Output characteristics of converter power station

In the case of double-sided supply of a given section by converter substations, it is necessary to take into account the cooperation of the substations in the setting of the control characteristics. In the case of supplying one end of a double-sided section with a conventional transformer substation, the "control characteristics" are fixed by the characteristics of the transformer used (see Fig. 4). These characteristics are therefore given by the impedance of short circuit transformer.

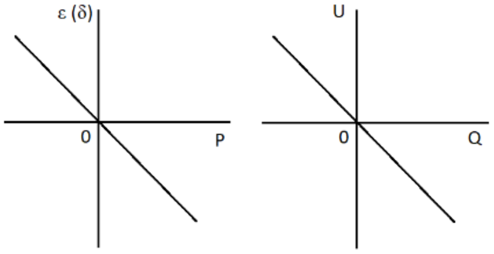

Fig. 4. Output characteristics of conventional transformer power station

Due to the new problem of using converter substations in the 25 kV 50 Hz traction network, the variables for setting the output characteristics of converters have not yet been clearly defined. In the pilot application of these technologies in the Czech Republic, the characteristics of the converters were set on the basis of calculations supplied to the construction contractor by an external supplier. The information about the used setting practices was not provided by the external contractor and is protected as his know-how. Therefore, the University of Pardubice, in cooperation with Elektrizace železnic Praha a.s., is developing original methods of setting the output characteristics of the converters.

The appropriate setting is always a compromise that takes into account many variables. Especially:

- Minimize voltage drops in the catenary (in case of accumulated loads at one substation and its power overload, catenary voltage would drop, but by shifting the control angle of the voltage of the opposite - more distant - substation it is possible to eliminate this drop).
- Minimize losses in the transmission of electricity over the catenary. By changing the phase shift it is possible to supply from more distant substation, but at the cost of increased transmission losses in the catenary. These losses may be justified in certain situations - for example if the closer substation exceeds its contracted power consumption, or if the catenary voltage drops due to its power overload. In other situations it is advisable to prioritize the lowest losses in catenary).
- Minimize the total energy consumption (of all substations) from the overhead 3-phase distribution system. Currently, recuperation to the distribution grid is allowed, but the railway operator is not paid for the recuperated energy. Therefore it is advisable that the control characteristics "force" the recuperated energy to be consumed in the traction network.
- Not to exceed the contracted consumption from the public 3-phase distribution network (maximum power consumption, not to exceed 1/4h max)
- Ensure the greatest possible balance of energy consumption from individual substations. Balanced load of substations, where none of them exceeds the contractual connection conditions, reduces the total cost of traction energy supply.

In the case of supplying one end of the section with a conventional transformer station, only the static converter substation has to provide all the above tasks by its control. In the case of supplying the section by SFCs at both ends, it is possible to set control characteristics in both substations [15][16].

There is still no general methodology for setting these characteristics. This paper attempts to outline a procedure by which this problem can be approached, and how to reach at the simulation level a suitable setting of output characteristics, which can be user-adjusted by the static frequency converter substation and then verified experimentally.

II. DESCRIPTION OF THE COMPUTATIONAL MODEL

In order to investigate and understand how the output characteristics of the static converter can be determined, there is a model created in Simulink. Model is based on following diagram 5, which shows the modelled case of the track and train structure [17][18][19]. Elements in Simulink are from library Simscape Electrical. For model solving is used local solver of type Backward Euler. Simulations has 0.0001 s sample time. Model can be divided into several sub-blocks:

A. Catenary

Each section of the overhead line is represented by an RLC circuit. [20] The parameter values correspond to the real length of the line. The sum of the lengths of the sections represents the same distance as between the substations on the line Nedakonice-Otrokovice on the second transit corridor. For the impedance of all elements of the RLC circuit together, a relative value of 0.26 + 0.55j Ω/km is considered. The capacitance component is practically not reflected in studied phenomena and is therefore not considered further. [21][22]

B. Trains

Trains are represented by impedance without a complex component, which is based on the assumption of modern train units operating with a power factor close to one. Vehicle has active energy draw and reactive component can be neglected.

C. Power supply stations

The line section is closed on each side by substations, the first one being considered as an converter substation (designation PS_1) and the second one as a conventional transformer substation (designation PS_2). The choice of substations is also identical with Nedakonice-Otrokovice line.

1) The static frequency converter substation is considered an ideal voltage source. This assumption is based on the assumption of accurate internal converter control. If additional parasitic electrical parameters had to be added to the replacement scheme and the converter was not considered as a blackbox, then the output characteristic curve set in the converter would be inaccurate and would not be realistically valid. For the output characteristics of the converter to be effective this must be accomplished and the converter must behave as a complete system whose output characteristics can be adjusted as a system.

2) The conventional transformer substation is represented by a power supply with internal impedance. The internal impedance is set to 0.01 + j7.5 Ω. The dominant part of this impedance is the inductive component.

D. Return path

The above traction circuit impedance includes the catenary and return path. In solving the circuit, the entire impedance has been included in the upper part of the circuit and the voltages are solved assuming a common reference potential for the entire circuit. This has been verified by internal calculations which have confirmed that the simplification does not introduce an error exceeding a maximum of 4%. The assessment of the error caused by the circuit simplification was carried out on five model structures of the traction network. When assessing the error, the effective values of the voltages and currents of the power stations and trains and the active and reactive power of the power stations and trains were compared. In total, several dozen calculated values were compared.

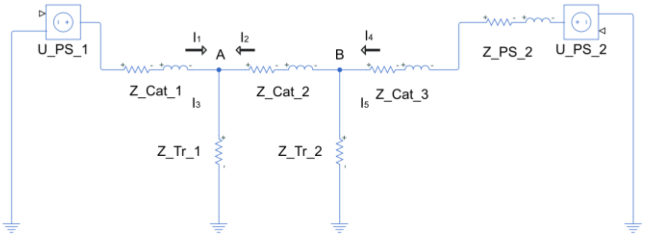

Fig. 5. Schematic of the modelled circuit

The whole circuit in the steady harmonic state can be written analytically using Kirchhoff's laws by the system of equations (1)--(5).

$$\hat{U}_{PS1} = \hat{I}_1 Z_{Cat1} + \hat{I}_3 Z_{Tr1} \qquad (1)$$

$$0 = \hat{I}_2 Z_{Cat2} + \hat{I}_3 Z_{Tr1} - \hat{I}_5 Z_{Tr2} \qquad (2)$$

$$\hat{U}_{PS2} = \hat{I}_4 (Z_{Cat3} + Z_{PS2}) + \hat{I}_5 Z_{Tr2} \qquad (3)$$

$$0 = \hat{I}_1 + \hat{I}_2 - \hat{I}_3 \qquad (4)$$

$$0 = -\hat{I}_2 + \hat{I}_4 - \hat{I}_5 \qquad (5)$$

The change of voltage phase of the converter substation is used to control the active power flow. Thus, we talk about the phase angle of the substation.

If we omit the specific case of the line structure mentioned above and instead consider two power supplies connected via a series RL link, we get the simplest case (Fig. 6) of an unloaded line section where it is possible to demonstrate how phase shift ε can control active power.

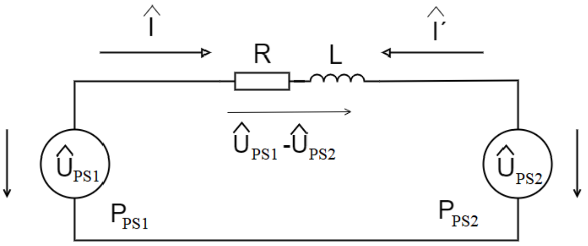

Fig. 6. Schematic of the unloaded two converter power stations

The power is transferred over the overhead line from one substation to the other and returned to the distribution network. The mathematical expression of the active powers (P_{PS1} and P_{PS2}) in this case is defined according to equations (6)(7). The angle ε indicates the phase shift between the voltage phasors U_{PS1} and U_{PS2}. Its value affects the active power of both sources [23].

$$\begin{aligned} P_{PS1} &= Re\left[\widehat{U_{PS1}} \cdot \hat{I}^*\right] = Re\left[\widehat{U_{PS1}} \cdot \left(\frac{\widehat{U_{PS1}} - \widehat{U_{PS2}}}{R + j\omega L}\right)^*\right] \\ &= Re\left[\widehat{U_{PS1}} \cdot \left(\frac{U_{PS1} - U_{PS1} \cdot \cos\varepsilon + j \cdot \sin\varepsilon}{R + j\omega L}\right)\right] = \\ &= \frac{U_{PS1}^2}{R^2 + (\omega L)^2}\left(R \cdot (1 - \cos\varepsilon) - \omega L \sin\varepsilon\right) \end{aligned} \qquad (6)$$

$$\begin{aligned} P_{PS2} &= Re\left[\widehat{U_{PS2}} \cdot \hat{I}^*\right] = Re\left[\widehat{U_{PS2}} \cdot \left(\frac{\widehat{U_{PS2}} - \widehat{U_{PS1}}}{R + j\omega L}\right)^*\right] \\ &= \frac{U_{PS1}^2}{R^2 + (\omega L)^2}\left(R \cdot (1 - \cos\varepsilon) + \omega L \sin\varepsilon\right) \end{aligned} \qquad (7)$$

III. SIMULATION

The purpose of the simulations is to determine appropriate output control characteristics of the converter substation.

All simulations are based on the circuit from diagram 5. Diagram represents railways structure with trains. Trains are not moving, so the elements which represents length of catenaries has same values throughout the simulation.

In the first simulation, an operational action was performed in the form of changing the phase of the voltage of the converter station (its voltage phase angle) over time and observing the effect on the system. There are two trains on the line with P_{vl1} = 2 MW and P_{vl2} = 3 MW, the first train is at a distance of 4.8 km from the SFC and the second train is at a distance of 9.6 km from the conventional transformer substation. The section between the trains is 9.6 km long. The effective voltage for both substations is 27 kV. The total distance between stations for all simulations performed in this document is 24 km.

The first graph (Fig. 7) shows active power as a function of the phase angle. It can be seen that a negative angle puts more load on the converter substation and, on the contrary, lightens the conventional transformer substation. At the extremes of the voltage phase angle, power transfers also occur between substations (one of the substations is recuperating). Therefore, these angles are unsuitable for the configuration. Inefficient power transfer is also reflected in the total power curve.

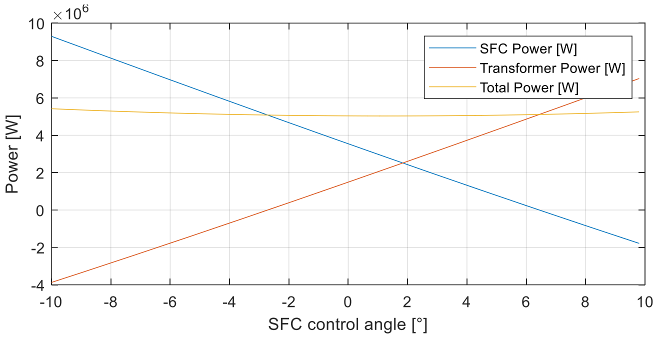

Fig. 7. Operating powers of power station

The lines of losses and total losses on the Figure 8 confirm that the extreme values of the control angle voltage are not effective. Effective voltage for both substations is still 27 kV. The lowest losses of the system are at positive control angle in range around 1° to 2°. Individual line sections then have minima at different angles depending on how much they are loaded. Losses are ideally in the order of a kW, but can be many times higher for a poorly set control angle.

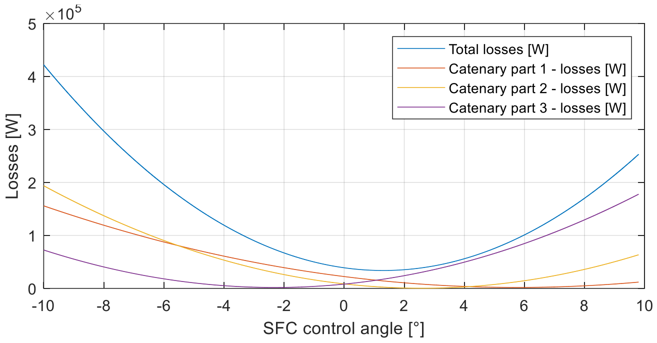

Fig. 8. Total losses and losses of individual line sections

The next two graphs 9 and 10 compare three simulations with the same configuration as the previous one, except for the effective voltage level of the converter substation. This assumes values of 25 kV, 27 kV and 29 kV.

The following graph shows how the reactive power consumption changes when the voltage changes. At lower voltages, the curve shifts to inductive power.

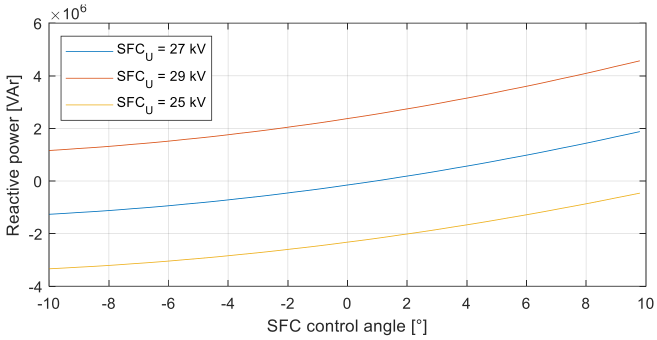

Fig. 9. Reactive power for different converter output voltages

The next chart compares the losses. In this configuration, the losses are lowest when converter's effective voltage value is equal to the transformer which is 27 kV. For voltages different from transformer voltage losses are higher.

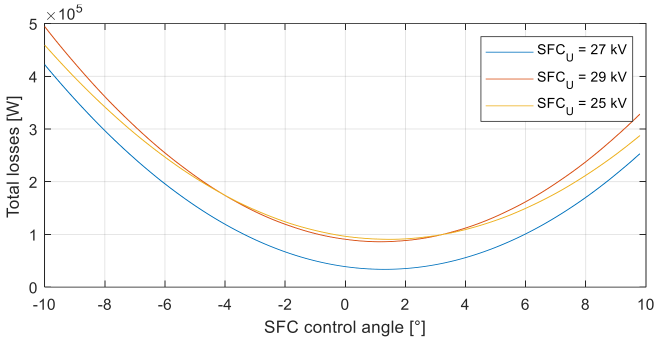

Fig. 10. Losses for different converter output voltages

IV. CRITERIA

Based on variables in the introduction, criteria are defined:

- Lowest loss criterion
- Lowest energy drawn from distribution grid criterion
- Catenary voltage stability criterion
- Equal power distribution between stations criterion

A. Loss minumum

The previous graphs mainly evaluate system-wide losses. Thus, the criterion of lowest losses can be defined in general. This criterion will be described in more detail below. However, in order to evaluate the most efficient output characteristics, it is necessary to consider other variables that affect the energy transfer characteristics. Losses are not always the priority indicator for ideal choice of the converter's operating point in the designing of the output characteristic.

B. Energy drawn from the grid

The total energy drawn from the distribution network is naturally required to be as low as possible. This criterion is also related to losses, but the way the energy is transferred from the recuperating trains also has an impact. In most cases, recuperation into the energy network has no benefit for rail transport. The grid operator does not provide any financial compensation for the energy that is returned. For this reason, it is a much more economical option to consume all the energy from the recuperating vehicles inside the traction network, even at the cost of higher overall losses and lower efficiency of energy transfer. The impact of recuperated energy on this criterion may change in the future depending on the commercial conditions of the electricity distributor.

C. Voltage stability

The voltage criterion considers the voltage levels at the trains pantographs and at the outputs of the substations. In case of large voltage fluctuations, it is necessary to start considering this criterion as well and to adjust the power flow so that trains and substations do not have very different voltage levels. The voltage level is related to the currents drawn by trains and thus to the power losses in traction circuit.

D. Equal power distribution

The last criterion takes into account the distribution of the energy consumed between the substations. Again, it will only apply when there are significant imbalances between substations. An even distribution of power is essential for the distribution network and it is preferable to have at least approximately equal power consumption of both substations compared to the case where one substation is dominantly loaded for a longer time interval. Such behaviour is operationally undesirable.

V. CONVERTER OUTPUT CONTROL CHARACTERISTIC

From the criteria described above, it is then necessary to find a suitable intersection and determine the most suitable working point. Each criterion will be defined by its weight, and at the same time this weight, in the evaluation of the criteria as a whole, will vary depending on the magnitude of the deviation from the ideal state. This means that even though the selected work point will satisfy the three criteria, but the last criterion will be very far from the ideal state, this criterion must be preferred and the operating point found elsewhere. It is very likely that for different configurations of trains on the line the ideal working points of each criterion will be different.

After finding suitable operating points, these points are transferred to the control characteristic. From their positions, the output characteristic of the converter is determined, considering different configurations and mentioned criteria.

A. Loss criterion

In the current state of modelling, each criterion is analysed separately, where first criterion considered is a loss criterion.

In order to ensure a larger number of modelled variants, it was necessary to define the individual cases of train placement on the track and the power of each train. The track section under study was divided into three parts, designated R_1, R_2 and R_3. The trains are designated as P_1 and P_2. Everything is described graphically in Figure 11.

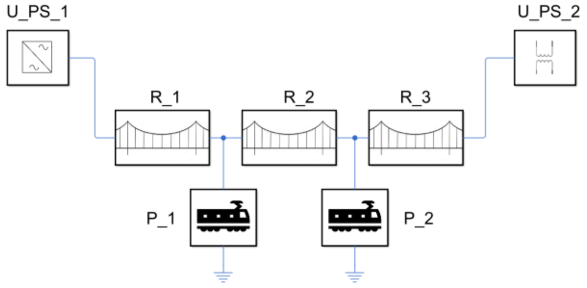

Fig. 11. Graphical representation of the track distribution

Track configurations were defined according to the following tables. The numerical configurations define one specific definition of the train placement, thus determining the lengths of the sections. The letter configurations, on the other hand, define the train loadings. A different letter defines a different train load. Combining these cases gives twelve variants. which have been simulated.

TABLE I. TRACK CONFIGURATION

Distances from the total length of the section			
Configuration	***R_1***	***R_2***	***R_3***
1	$\frac{4}{8}$	$\frac{3}{8}$	$\frac{1}{8}$
2	$\frac{2}{8}$	$\frac{3}{8}$	$\frac{3}{8}$
3	$\frac{1}{11}$	$\frac{3}{11}$	$\frac{8}{11}$
4	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{5}{7}$

Fig. 12. Track configuration

The length of the section is set in the simulation script as a product of the total length of the powered section to make it clearer. The sum of the coefficients R_1, R_2 and R_3 is always equal to one. Similarly, the vehicle consumption is a product of the reference value (from Table II) of 5 MW.

TABLE II. TRAINS POWERS

Power multiplier of the 5 MW reference value		
Configuration	***P_1***	***P_2***
A	1,6	0,3
B	0,4	0,5
C	1,3	1,8

Fig. 13. Trains powers

The train loads are chosen for modelling purposes and the nominal value used for the simulation may not be within the load ranges of the real vehicles. The train positions were chosen to allow the cases to include the higher load cases of both the converter station and the conventional transformer substation. Thus, three simulations with each train location having different train power draws (i.e., Simulations 1A, 1B, and 1C) are performed.

Each simulation has its own loss curve, which will have a shape reminiscent of the convex loss curve already observed in the first simulation above. For each simulation, the minimum of losses will belong to a different control angle of the converter substation voltage. The losses will of course vary in nominal values, but this is not important for finding the optimum point.

By evaluating the optimum point for each simulation, a set of the most efficient operating points is created. Plotting these points on the control characteristic gives a graph 14.

The graph shows the points for the different variants of train loads divided by colour. The letters correspond to the definition in Table II. On y-axis there is control angle and on x-axis there is active power drawn from converter substation. It can be noticed that the coloured points move along an apparent curve. The individual points on this curve then represent different train positions. Cases 3 and 4 have similar train locations and therefore the working points are close to each other. In these cases the trains are closer to the converter substation. The opposite is configuration 1, where the trains are located closer to the conventional transformer station. In these cases, the optimum point belongs to the higher positive values of the voltage phase angle of the converter station, for variant C phase angle reaches almost 7°.

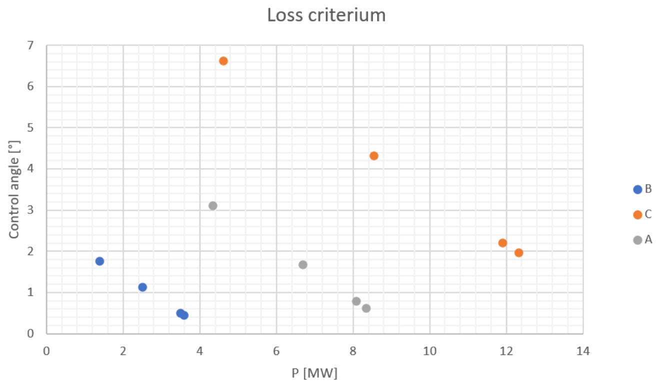

Fig. 14. Operating points determined by loss criteria

The positive angle lightens the converter power station and was considered the ideal condition for all simulations performed. The converter substation is considered (unlike a conventional transformer substation) as an ideal voltage source and therefore the unloading makes sense and the result can be considered correct in this sense.

These simulations were performed for a voltage level of 27 kV for both substations. After the phase angle of the voltage, the next possible action of the converter is to change the output effective voltage value. Therefore, another simulations were performed with different converter voltages, keeping the same way of evaluating the results. The voltage of the conventional transformer station remained 27 kV, as in the previous simulations. For the converter, voltage levels of 22 kV, 27 kV and 29 kV were chosen to demonstrate the voltage effect on the optimum operating points of the loss criterion.

The Figure 15 shows the operating points again, but now they are colored according to the converter output voltage. Axes stand for same variables as in previous graph. You can see the analogy of the individual levels, which form similar curves, but shifted by voltage. At higher voltage levels, the converter station is more loaded and the phase angle of the voltage is reduced. On the other hand, at a lower voltage level, the converter station becomes less loaded and the phase angle increases. At a voltage level of 22 kV (gray dots), the difference is more noticeable. Therefore, if there is intervention in the converter output voltage, this must be taken into account when constructing the ideal control characteristic.

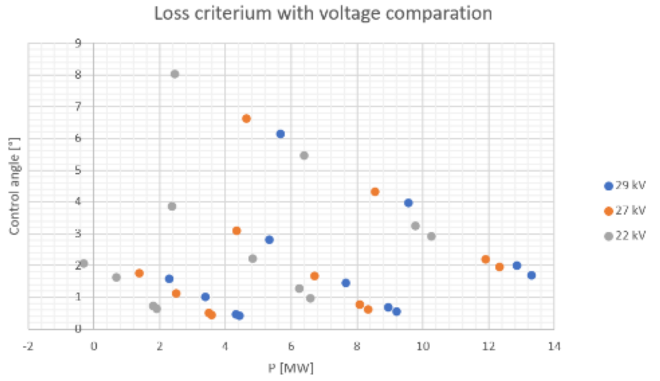

Fig. 15. Operating points based on loss criteria at different converter voltage

It can also be seen in the last graph that although an optimum point of the loss criterion was found for one case at the time of converter substation recuperation, this point cannot be considered ideal because this operating point will be undesirable from the point of view of the minimum energy drawn from the distribution network criterion.

At the same time, the highest power output in the simulations performed was over 13 MW. Also here there must be a limitation in the situation if the installed power of the converter substation is smaller. In such a case, it is again necessary to modify (trim) the modelled characteristic.

VI. CONCLUSION

As already outlined, it is necessary to first determine firmly each criterion separately and then proceed to the combination on the basis of predetermined criteria weights. There will almost always be a conflict between ideal operating points and the resulting curve must be a compromise not only in considering the criteria but also in selecting the most common operating situations.

Modelling loss criterion can be seen as first step to create complex model to generate suitable SFC output characteristics. The simulations showed that criteria of losses has to take part when creating correct output characteristic for SFC substation. If the other criteria are omitted, we can shape output characteristic based on models results in graphs 14 and 15. The final curve would consider all the calculated points.

In the next steps of the research, simulations will be performed for each criterion separately and then the search for an optimum for most operational situations. In the same way, another control characteristic will be approached, namely the dependence of the converter output effective voltage on the reactive power.

The output characteristic of the converter can be changed operatively. Therefore, it is possible to assume regular traffic, for example, within a week, and on this basis vary the characteristic according to the model output for the expected load. However, the characteristic should be resistant to any line conditions and thus ensure the operation of the system without the need for intervention. The only sacrifice will be lower efficiency for the criteria mentioned.

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