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Searching for Efficient Output Characteristics of Railway Power Station

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Abstract **-** This paper aims on new power converter supply stations on railway for 25 kV 50 Hz. Control system through output characteristics is introduced. A new approach of searching effective output characteristics is created and discussed. This approach defines four criteria which evaluate effectivity of railway traction grid. There was created a mathematical model of railway grid to test this criteria. In the last part of the paper there are presented results of simulations, followed by composed output characteristics and their meaning.

Keywords**:** Power Converter Supply Station, Railway Power Stations, Simulation of Traction Grid

1. Introduction

1.1. Converter substations

A railway traction system with a voltage of 25kV and a frequency of 50Hz is a perspective option, providing a sufficiently robust power infrastructure for the operation of modern traction vehicles that satisfy the technical requirements for interoperability. Its advantages include, for example, easy energy recovery back to the distribution grid. [1][2]

However, current solution with conventional substations brings significant drawbacks, which are even worse with increasing load demand and frequent recuperation. One of these disadvantages is the uneven loading of the phases of the public distribution network. This also leads to uneven recuperation. Another problem is the spectrum of the current and reactive power, which is determined by the consumption of different types of rolling stock. Another negative is the need to divide the overhead line network into sections with different phases. [3]-[5]

Single phase is the main advantage of integrating converter substations into the infrastructure. Transformer substations do not have this option. At the same time, converter substations have the possibility of being controlled. This function is performed by the output characteristics. [6][7]

1.2. Converter output characteristics

The converter substation can generally operate in two modes, operating and short-circuit. [8] This paper aims to determine the appropriate setting of the substation in the operating mode. [9][10]

The output characteristics allow to influence the reactive power based on the converter output voltage and the active power due to the phase shift of the output voltage (shift angle δ). Both characteristics are based on a conventional transformer station, which also has them, but are determined by the electrical parameters of the transformer. The converter substation allows the characteristics to be changed during operation. The characteristics of the converter then significantly affect the operation on the railway line at every moment. [11][12]

The process for determining the characteristics is not available in public sources. The most effective output characteristics will be highly dependent on infrastructure. The overall structure of the routes, which can also be operated by multiple substations, is essential. The driving scenario also strongly influences the correct setting of characteristics. If universal output characteristics are deployed, there will only be a reduction in efficiency in a few criteria, but the system as a whole will remain functional. [13] Examples of output characteristic settings can be found in Fig 1.

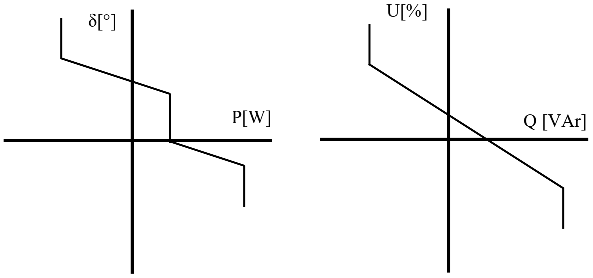

Fig. 1: SFC Active power and reactive power output characteristic

2. Description of computational model

In order to investigate and understand how the output characteristics of single static converter can be determined, there is a model created in Simulink.[16] Model is based on following diagram, which shows the modelled case of the track and train structure.

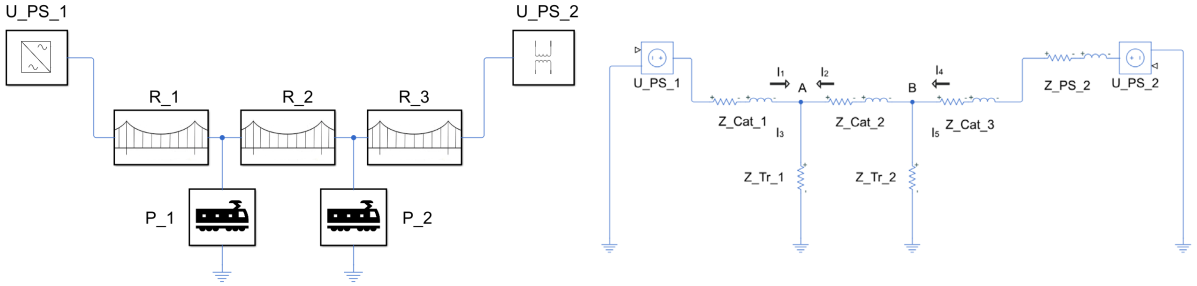

Fig. 2: Graphical and electrical representation of the track configuration

There are catenaries, trains, converter supply station and conventional supply station. This composition makes a circuit for simulations with real parameters of track elements.[17]-[19] More description about model is provided in referenced paper. [16]

3. Simulation

The purpose of the simulations is to determine appropriate output control characteristics of the converter substation. All simulations are performed in single time moment. All simulations are based on the circuit from Figure 2. Figure 2 represents railways structure with trains. Trains are not moving, so the elements which represents length of catenaries has same values throughout the simulation.

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 R1, R2 and R3. The trains are designated as P1 and P2. Effective voltage for both substations is 27 kV. During simulation converter station is controlled either by voltage phase shift δ (P/δ characteristic) or voltage level (U/Q characteristic).

Many simulations were performed with different configurations of each parameter (R1, R2, R3, P1, P2). The only condition of configuration was that length of the railway remained always the same (R1 + R2 + R3 = R = 24 km). Train powers P1 and P2 were chosen randomly. Highest occurred power of one train was 9 MW and lowest (recuperative state) was negative 6.5 MW. These power levels are only for simulations variability since it is not common to have such high train load. The highest power output of the converter station in the performed simulations was unlimited. Anyway in real application there must be a limitation in the situation if the installed power of the converter station is smaller. In such a case, it is necessary to modify (cut) the edges of modelled characteristic.

4. Criteria

Each criterion is defined by its function and throughout the simulations specific working point is searched.

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

4.1. Lowest losses

Determining the lowest loss criterion is the first step. It is clear that the losses in the system should always be the lowest.

Criterion definition: Function for loss criterion p_{loss} (δ) is defined as sum of losses on each catenary p_{cat_n} (δ). Working point X is located in minimum of the function.

$$p_{loss}(\delta) = \sum p_{cat\_n}(\delta) \tag{1}$$

$$X = min(p_{loss}(\delta)) \tag{2}$$

Criterion function: An example for this criterion can be seen in the following figure.

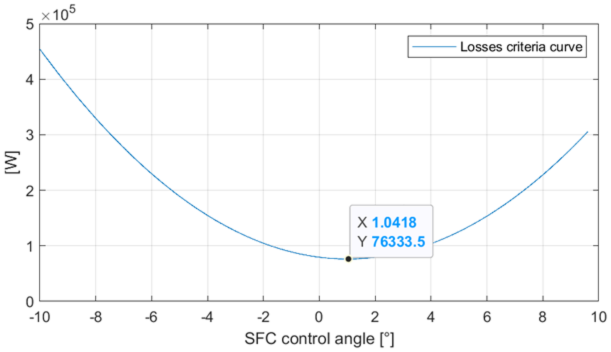

Fig. 3: Loss criterion

In this particular case, the ideal point is at voltage phase shift angle of about 1°. The loss curve was always observed as a parabola. For each simulation, the minimum of losses will belong to a different phase shift 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. The positive angle lightens the converter power station, on the other hand negative phase shift angle puts more load on converter station.

4.2. 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 financial benefit for rail transport. 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.

Criterion definition: For energy drawn we consider only consumed power $p_{cons\_ps\_n}$ (δ) of each supply station p_{ps_n} (δ). Sum of these powers creates function p_{cons} (δ) where the working point X is minimum.

$$p_{cons\_ps\_n}(\delta) = p_{ps\_n}(\delta) > 0 \tag{3}$$

$$p_{cons}(\delta) = \sum p_{cons\_n}(\delta) \tag{4}$$

$$X = min(p_{cons}(\delta)) \tag{5}$$

In some simulations we may encounter the minimum as a set of points. This is the range of voltage phase shift for which the function has the same value, which is the minimum. Finding the working point X in these cases is defined being the mean in the given interval.

4.3. 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 and 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. The voltage requirement is to have the most stable voltage level and at the same time as close as possible to the voltage reference value, which is the output voltage value of the substations.

Criterion definition: The voltage on the panthographs of the trains (u_{ti_n} (δ)) is limited in the criterion calculations from above to the reference value u_{ref}, which is 27 kV. We obtain the adjusted voltage on the collector trains $u_{adj\_ti\_n}$ (δ).

$$u_{adj\_ti\_n}(\delta) = u_{ti\_n}(\delta) < u_{ref} \tag{6}$$

First, the mean value of the train voltage u_{avg} (δ) is determined. The criterion function (u_x (δ)) is equal to the sum of the two components u_{ref_diff} (δ) and u_{avg_diff} (δ). Where u_{ref_diff} (δ) is the difference between the reference value and the mean value of the voltage trains $u_{adj\_ti\_n}$ (δ). And u_{avg_diff} (δ) is the mean of the absolute values of the differences between u_{avg} (δ) and $u_{adj\_ti\_n}$ (δ).

$$u_{avg}(\delta) = \frac{1}{n}\sum_{i=1}^{n}(u_{adj\_ti\_n}(\delta)) \tag{7}$$

$$u_x(\delta) = u_{avg\_diff}(\delta) + u_{ref\_diff}(\delta) \tag{8}$$

$$u_{ref\_diff}(\delta) = u_{ref} - u_{avg}(\delta) \tag{9}$$

$$u_{avg\_diff}(\delta) = \frac{1}{n}\sum_{i=1}^{n}\left|u_{avg}(\delta) - u_{adj\_ti\_n}(\delta)\right| \tag{10}$$

$$X = min(u_x(\delta)) \tag{11}$$

Finally, the minimum of the criterion function is searched. It is necessary to find appropriate the result, because the searched minimum may be on the set of points.

4.4. Equal power distribution

The last criterion takes into account the distribution of the energy consumed between the substations. We can say that this criterion should 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 all substations compared to the case where single substation is dominantly loaded for a longer time interval. Such behavior is operationally undesirable.

Criterion definition: As with the lowest power criterion, only the positive power consumption of the stations $p_{cons\_ps\_n}$ (δ) is determined. The mean p_{avg} (δ) of these readings is then determined. Variable p_{diff} (δ) is then the sum of the absolute values from the difference of p_{avg} (δ) and $p_{cons\_ps\_n}$ (δ). Point X is the minimum of p_{diff} (δ).

$$p_{cons\_ps\_n}(\delta) = p_{ps\_n}(\delta) > 0 \tag{12}$$

$$p_{avg}(\delta) = \frac{1}{n}\sum_{i=1}^{n} p_{cons\_ps\_n}(\delta) \tag{13}$$

$$p_{diff}(\delta) = \sum \left| p_{avg}(\delta) - p_{cons\_ps\_n}(\delta) \right| \tag{14}$$

$$X = min(p_{diff}(\delta)) \tag{15}$$

5. Active power control characteristic

From the criteria described above, it is then necessary to find and determine the most suitable working points. 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.

5.1. Lowest losses

Each criterion is analyzed separately, where first criterion considered is a loss criterion. The graph 4a shows the calculated X points. Each simulation is represented by one point. The various configurations form virtual curves. Simulations with the same train load but different positions move on the apparent line. Overall, the densest region of points is in the region of positive voltage phase shift angle and with positive power.

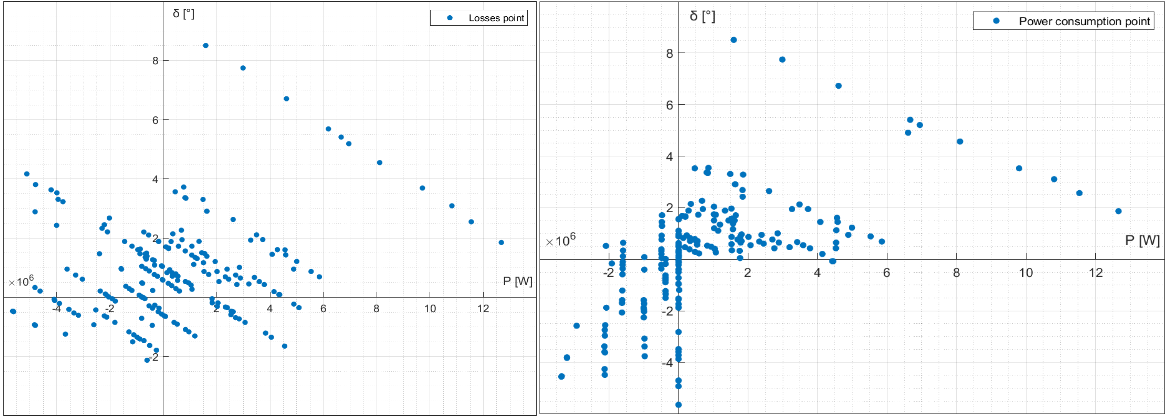

Fig. 4: a) Working points for loss criterion b) Working points for lowest power consumption

5.2. Lowest power consumption

For the lowest power consumption another set of X points was calculated. In this case working points for each configuration are on Figure 4b. This criterion is close to the loss criterion. The calculated working points correspond to this criterion. In the first quadrant, the results are similar. On the other hand, the other quadrants are different. The change is due to the fact that the recuperated power to the distribution network is not considered and the power curves from the stations are cut.

5.3. Voltage stability

The third criterion is voltage criterion. The working points form a group of points moving mostly in the second and third quadrants of the output characteristic. It is clear that the best conditions for stability and voltage drops are the moments when the trains recuperate and, due to this, the converter substation recuperates.

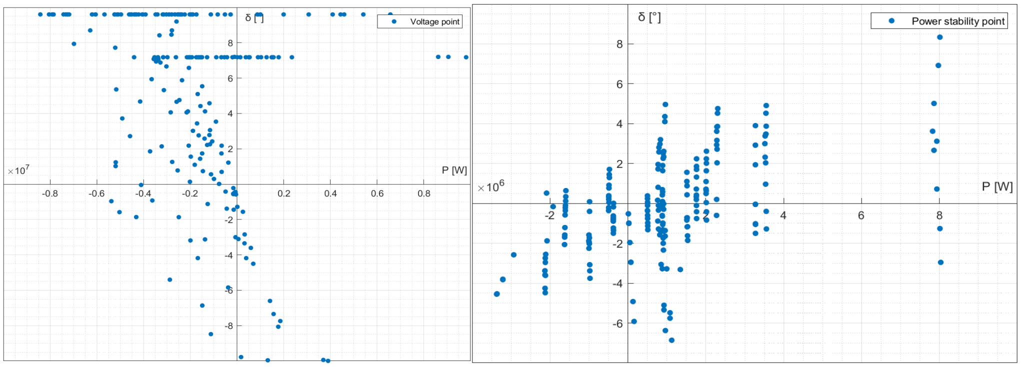

Fig. 5: a) Working points for voltage stability b) Working points for power draw stability

5.4. Power draw stability

The last criterion in the list is the criterion of equal power draw of stations. This criterion favors the configuration in time of equal power supply stations. The characteristic (Figure 5b) thus marks the points where the power outputs of the substations intersect. This does not apply in cases where the intersection would occur at negative powers (both stations recuperate). In these situations there are multiple operating points, the mean of the interval of operating points is considered for plotting in the characteristic.

5.5. All criteria

At first sight, the characteristic is difficult to determine, but the points of each criterion have a meaningful value for the construction of the characteristic.

Each criterion could be defined by its weight, and when evaluating the criteria as a whole, this weight 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 working point has to be found elsewhere. The output characteristic will be constructed from such defined points.

6. Reactive power control charatericitic

For the characteristic of reactive power with voltage, the criteria with the same definition as in the previous cases will be used. In these simulations, the converter output voltage changing over time in the range of approximately from 24 kV to 29 kV. Two cases of converter station voltage phase shift angle (0° and 2°) were chosen to compare the effect of angle. Simulations were performed for both cases and evaluated in the same way using the criteria presented previously with changed action parameter (not voltage phase shift angle but output voltage) of converter.

6.1. Lowest losses

Plots of the voltage/reactive power characteristic for voltage phase shift angles of 0° and 2° are shown in the Figure 6. Lowest losses working points are represented with blue colour. Most of the working points are concentrated near 27 kV and above. If we compare effect of the different angles, we can notice a slight shift of the working points as a whole.

6.2. Lowest power consumption

Just as in the case of the active power characteristic and the voltage phase shift angle, we can see common features as with the loss criterion. Comparing the graphs with different angles, we again see a slight offset of the imaginary curve that crosses the voltage axis at lower levels. Simulations were again performed for both voltage phase shift angles of the converter station.

6.3. Voltage stability

The voltage criterion cannot be applied because the converter's action is the output voltage and therefore there is no specific voltage reference.

6.4. Power draw stability

The last criterion is the equal power draw of the stations. If we compare the different voltage phase shift angles, the offset of the line axis of the group of working points is also visible here. The offset is at first sight less noticeable compared to the other criteria. Although the effect of the different angle can be observed, it is not a major change in the characteristic.

6.5. All criteria

All points for the simulated configurations form a zone in which the resulting characteristic should be.

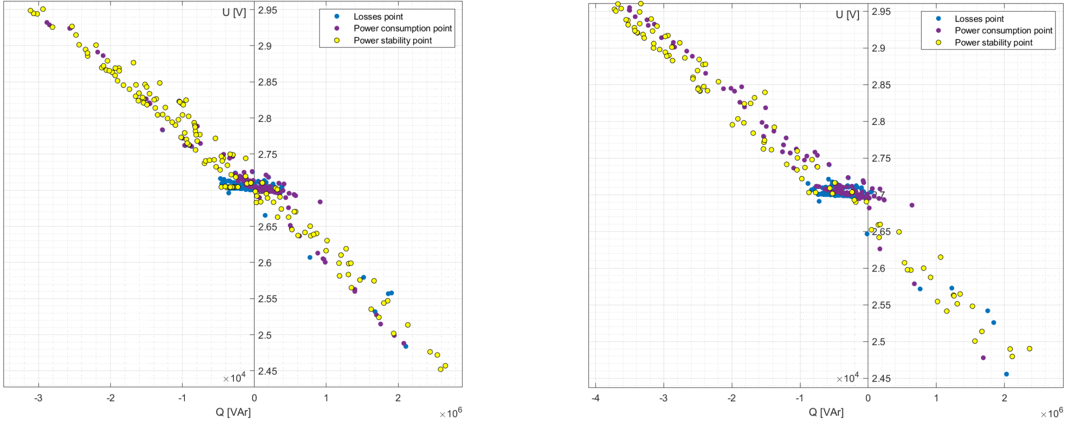

Fig. 6: a) Working points of all criteria for 0° b) Working points for all criteria 2°

7. Conclusion

Simulations have shown that they can determine the output characteristics. Compared to the real world output characteristic plots, the calculated points of the simulations were similar. Especially for the reactive power/voltage characteristic. For the active power output characteristic, the points did not form a clear curve.

In the next steps it will be necessary to select the weight of each criterion or to classify their extreme values (suitable/very unsuitable operating point). These points with their weights will then have to be consolidated into a single curve by optimization calculations. Furthermore resulting curve must be a compromise not only in considering the criteria but also in selecting the most common operating situations. It will be useful to assemble the output characteristic from parts so at the end it becomes a continuous line. Raw optimized operating points would certainly produce a hardly defined curve that could not be entered into the converter control unit.

Comparison of active and reactive power characteristics is also important. Based on the measured graphs, the effect of the voltage phase shift angle on the reactive power characteristic is rather minor. Furthermore, except at the extremes of the converter output voltage, when the angle changes, its effect on the operating points is predictable. Thus, from this conclusion, it can be said that the characteristics could be adjusted independently. An important progression will be also the follow-up integration of more converter stations into the simulations so that the general power grid structures can be evaluated. The criteria will remain the same for these cases, but the influence of the stations to each other will have to be considered.

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