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LIMITATION OF VOLTAGE FLUCTUATIONS IN THE CASE OF INDUSTRIAL CUSTOMERS USING ARC FURNACE

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This paper deals with the theoretical analysis of the electromagnetic disturbances generated by industrial customer having arc furnaces, the results of monitoring of disturbances generated by industrial customer to power system, and the calculation of the parameters using specialized software (ETAP). The comparison between these three ways of determination of the level of disturbance is included in present work. The paper is focused on the voltage fluctuations (flicker effect) in power network. The influence of the short-circuit power on the propagation of disturbances in power system represents a challenging issue studied within the existing context. The revising of the characteristics of STATCOM has been considered within the paper, avoiding the exceeding of admissible disturbance levels stipulated by current standards.

Keywords: power quality; monitoring; renewable; voltage fluctuation; arc furnace

1. Introduction

The changes of the structure of electricity generation in Romania, because of appearance of the energy renewable sources connected to the grid through convertors and because of conventional power plants being in reserve, determined a dramatic reduction of the short-circuit power in the buses of power system (S_{sct}) [1]. In this context, the ratio between disturbing loads and S_{sct} in the buses of power system has increased very much and this leads to redesign of compensation and limitation systems.

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The reduction of the rigidity of the buses of the power system through reduction of S_{sct} has determined the electromagnetic disturbances (harmonics, voltage fluctuations, voltage sags, voltage unbalance) to be present in power network. In this way, the end customers connected to the grid near the disturbing customers are affected by Power Quality (PQ) indices outside the admissible limits of the standards [2]. As consequence, the end users which did not generate disturbances outside the standard limits before, have to do now a revision of the stage and to do the supplementary measures, in the most of cases investment measures, in order to ensure the PQ indices inside the admissible limits of the standard.

The analysis from this paper refers to an end user – industrial customer – which generates voltage fluctuations in its technological process, using arc furnaces. In actual conditions, the operation of the end user could determine the overtaking of voltage fluctuations (Flicker effect) on 110 kV busbar and could propagate the disturbance in the network area around the bus of connection [3, 4].

In order to analyze the technical solutions for limitation of the disturbances on the busbar of connection of the customer to the grid, some technical and experimental studies have to be done. The STATCOM system has to be connected to internal 6kV busbar in order to limit the electromagnetic disturbances.

The paper is focused on the calculation of the disturbance indices using analytical method, simulation and power system analyze using the specialized software for a real case of the distribution electricity to industrial customer using arc furnace. *Two cases*: without or with STATCOM and *two scenarios*: S_{sct} = 2080 MVA and S_{sct} = 1050 MVA were taken into consideration.

In additional to these two methods, the measurement in the both cases (without / with STATCOM) was done.

Finally, the original contributions in this paper refers to the analysis of the results using these three methods allows to draw the conclusions.

2. Theoretical Analysis of Voltage fluctuations of arc furnace

The customer manufactures metal powders and it is connected to the grid through two 6kV feeders of a substation 110/6kV, having 4 transformers 110/6kV (two of 40MVA and two of 25MVA). Other end users are connected to busbars 1 and 2 - 6kV (as shown in Fig. 1).

The maximum demand active power of customer PM 1 feeder is 7.5 MW and of customer PM2 is 5 MW.

The disturbing user (arc furnace) connected to 6kV feeder PM 1 (15 tone) has a STATCOM system installed at 6 kV, which ensures improvement of power factor, reduction of voltage fluctuations and has filters for harmonic limitations of range 5^{th} and 7^{th}.

The disturbing user (arc furnace) connected to 6kV feeder PM 2 does not has any compensation system. Evaluation of the Voltage fluctuations (Flicker effect) generated by PM 1 and PM 2 has been done in 110 kV busbar of substation A which is Point of Common Coupling (PCC) [5]. The hypotheses used in the analysis were:

- Arc furnace severity factor k_{st} = 45 for both arc furnaces;
- The maximum short circuit power S_{sct} = 2080 MVA – First scenario;
- The real short circuit power S_{sct} = 1050 MVA – Second scenario.

The simplified diagram of the analyzed network is shown in Fig. 1. The disturbing user has two arc furnaces: PM 1 is an electric arc furnace (EAF) and PM 2 is a ladle refining furnace (LRF).

The realized measurements have shown that only PM1 generates electromagnetic disturbances during the metal melting process.

The equivalent electric diagram is shown in Fig. 2. The STATCOM system has been designed for a compensation capacity of 8 MVAr. It is considered that the greatest value of voltage drops is in the melting period of the metal, in which a short-circuit appears among the electrodes and metal mass. It is accepted with a good accuracy, the reactance from the circuit is enough to be taken into consideration [6].

In the analysis two cases were considered: First case, when renewable sources are not available (lack of wind blowing, lack of solar radiation), and then S_{sct} on the 110kV busbar was considered 2080 MVA; Second case, when renewable sources are available and the S_{sct} on the 110kV busbar was considered 1050 MVA.

The calculation was done using quantities reported to 110kV voltage, where PCC of the connection user to the grid is considered.

Data have been calculated for two values of the S_{sct}, without or with STATCOM, and these are reported in Table 1 [5].

Based on the data from Table 1 the electrical quantities of circuit were calculated and included in Table 2. The level of disturbances on the 6kV busbar where other users are connected, have been determined.

The electrical quantities from Fig. 2 are calculated for S_{sct} = 2080 MVA, without STATCOM, using the characteristics of elements from Fig. 1 and the relations from Appendix 1. In the similar way, the electrical quantities are calculated for S_{sct} = 2080 MVA, with STATCOM and S_{sct} = 1050 MVA, with and without STATCOM.

Table 1

Calculation of reactance of system's components, reported to 110 kV level

Reactance [Ω]	S_{sct} = 2080 [MVA]	S_{sct} = 1050 [MVA]
X_{system}	5.82	11.52
$X_{T110/6\ kV}$	87.12	87.12
$X'_{\text{cable 6 kV}}$	16.27	16.27
X'_{reactor}	235.28	235.28
$X'_{\text{T6/0.36 kV}}$	102.85	102.85
$X_{\text{short network}}$	214.74	214.74
X_{total}	662.08	667.78
$X_{system}+X_{T110/6\ kV}$	92.94	98.64

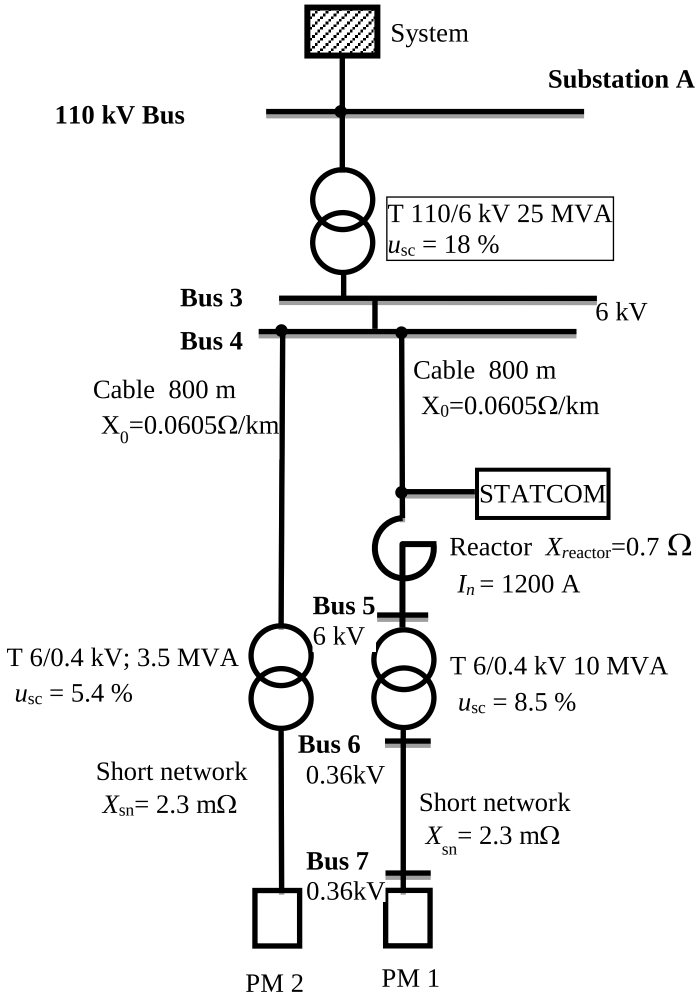


Fig. 1. The partial diagram of Substation A for calculation

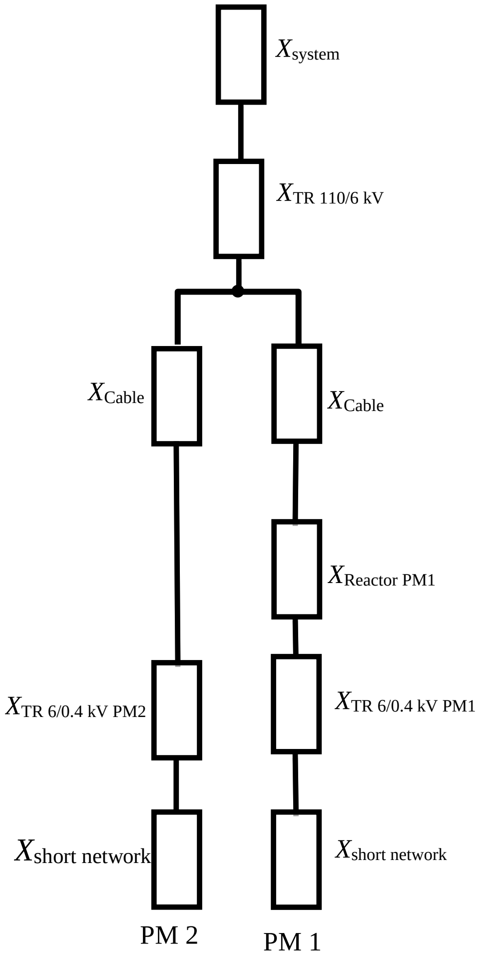


Fig. 2. The calculation diagram

Table 2

Results of calculation of quantities from circuit

Voltage level	Quantity	S_{sct} = 2080 MVA		S_{sct} = 1050 MVA	
		Without STATCOM	With STATCOM	Without STATCOM	With STATCOM
(1)	(2)	(3)	(4)	(5)	(6)
110 kV	$I_{110\text{ kV}}$ [A]	105.54	59.35	104.62	58.43
	ΔU[V] *on 110 kV busbar* (phase to ground)	614.24	345.47	1,205.20	673.10
	ΔU[%] *on 110 kV busbar* (phase to ground)	0,97	0,54	1.90	1.06
	$P_{st99\%}$	0.44	0.25	0.86	0.48
	$P_{st95\%}$	0.37	0.21	0.73	0.41
6 kV	ΔU[V] *on 6 kV busbar* (phase to phase)	926.67	521.13	974.95	544.53
	ΔU[%] *on 6 kV busbar* (phase to phase)	15.44	8.68	16.25	9.07
	$P_{st99\%}$	6.95	3.91	7.31	4.36
	$P_{st95\%}$	5.89	3.31	6.20	3.70

3. Results of of monitoring of Voltage fluctuations (Flicker effect)

The monitoring campaign was carried on by the authors in an industrial facility in Romania, in the real conditions, in the presence of technical staff of distribution system operator. The monitoring of PQ indices was done according to the standards and recommended practices in the field [3, 7, 5, 8] for a period of time of four days Nov 2016. The measurement results are validating the theoretical analysis and simulation implemented models using professional software. The evolution of flicker is illustrated in Fig. 3.

Table 3

$P_{st95\%}$ for flicker monitoring on 110kV busbar without STATCOM

Indicator	Phase A	Phase B	Phase C
$P_{st95\%\text{ measured}}$	0.81	0.78	0.72
$P_{st95\%\text{ admissible}}$	0.8	0.8	0.8

The average value of $P_{st95\%\text{ measured}}$ from the Table 3, measured on 110kV busbar is in the same range with the variation shown Fig. 3 and $P_{st95\%}$ from the Table 2 – column (5), in the same conditions: S_{sct} = 1050 MVA and without

STATCOM. That means a good compatibility of all three ways of calculation / measuring / simulation.

The same situation could be underlined for $P_{st95\%\ measured}$ on the 6kV busbar related to Table 4, Fig. 4 and $P_{st95\%}$ from the Table 2 – column (5).

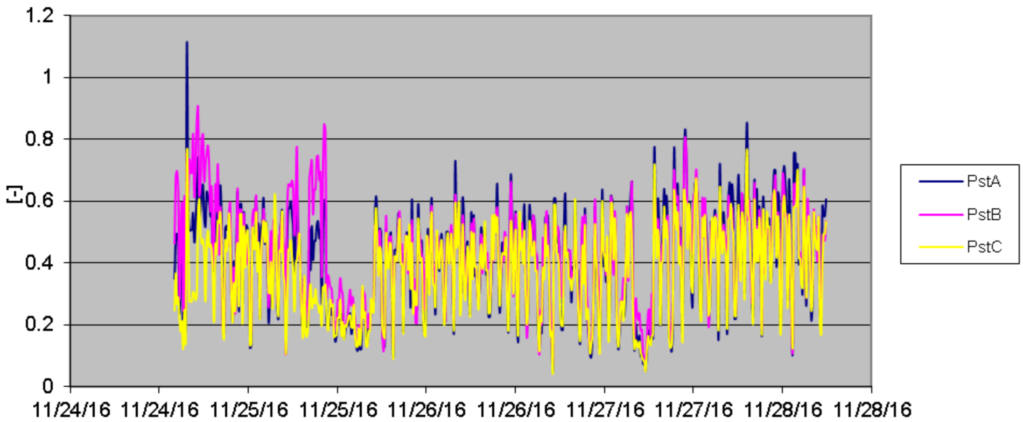


Fig. 3. Evolution of flicker level at 110 kV busbar, without STATCOM

Table 4

$P_{st95\%}$ for flicker monitoring on 6kV kV busbar without STATCOM

Indicator	Phase A	Phase B	Phase C
$P_{st95\%\ measured}$	6.37	6.3	6.31
$P_{st95\%\ admissible}$	0.9	0.9	0.9

The calculated values have been validated by experimental measurements. Fig. 3 presents the evolution of short-term Flicker indices on the 110kV busbar in the electric arc operation period, when the STATCOM system is not in operation, and the S_{sct} is considered 1050 MVA.

Fig. 4 shows the flicker level recorded on 6kV busbar in the electric arc operation period, when STATCOM system is not in operation, and the S_{sct} is considered 1050 MVA [9].

The analysis of the calculated data in comparison with recorded data highlight that the change of the short-circuit power of the system has a great influence on the level of disturbances in the PCC bus, leading to occurrences when the flicker indices exceed the admissible limits if the short-circuit power has lower values [10, 11].

The change of short-circuit in PCC has a lower influence on the level of disturbances in other buses of the electrical distribution network supplying the end user, determined by the higher value of the short-circuit voltage of the 110/6kV transformer. This solution leads to high values of the level of the disturbances on the 6kV busbar, where STATCOM system is connected.

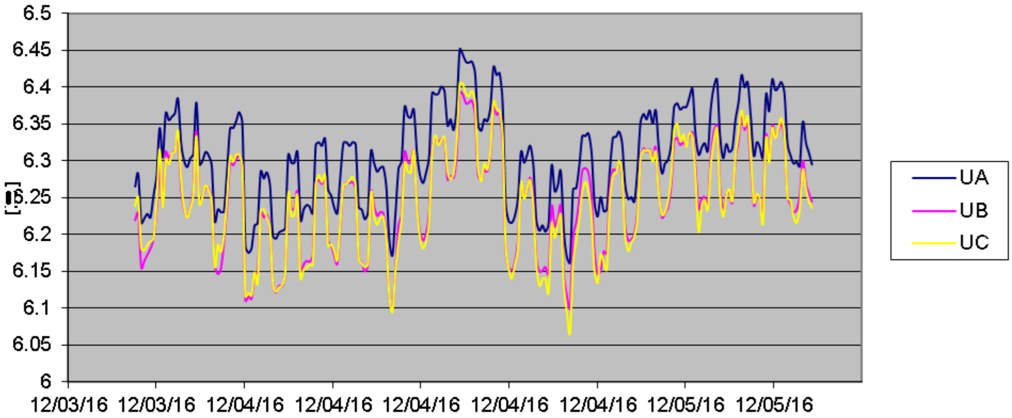


Fig. 4. Evolution of flicker level at 6 kV busbar, without STATCOM

The existence of the STATCOM means a high influence on the level of disturbances on the busbars of the electricity distribution network in the sense of reduction of the level of disturbances.

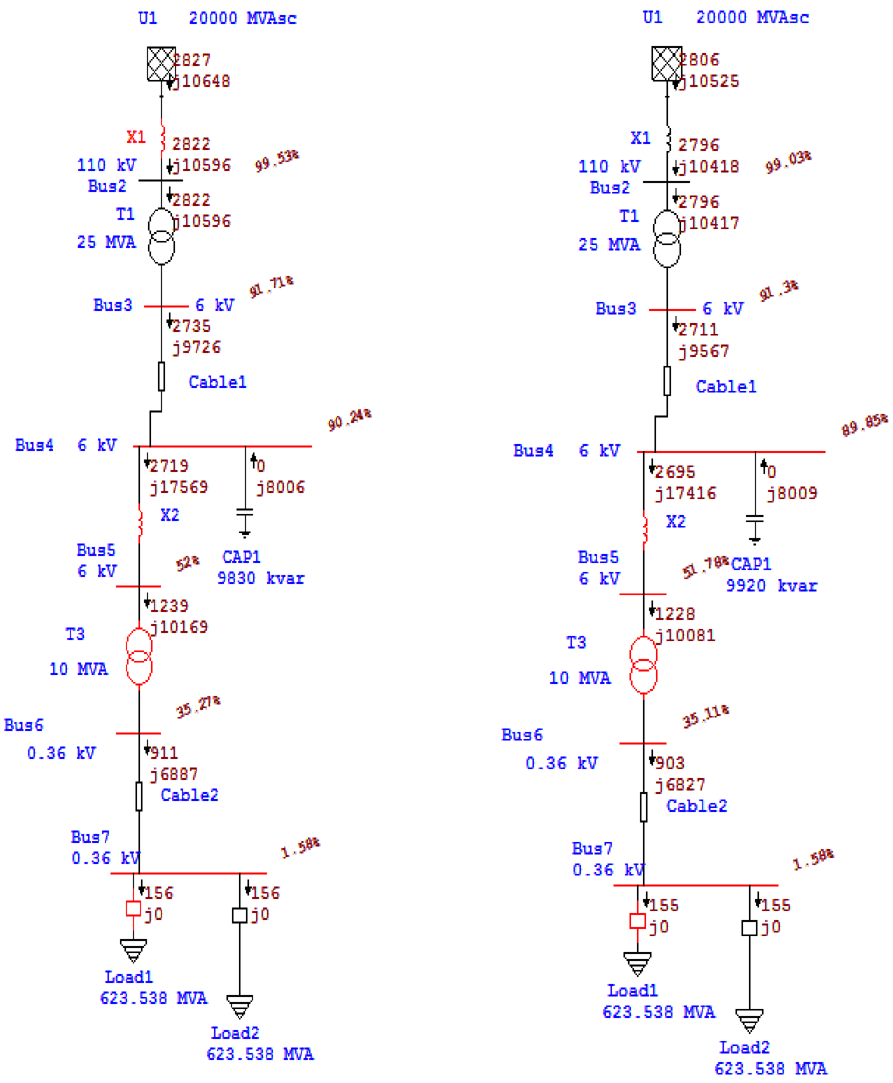
The evolution of instantaneous P_{st} during the monitoring period for each phase illustrated in Fig. 4. The maximum level of instantaneous P_{st} is 6.45, and the cumulative probability 95% - $P_{st95\%}$ is 6.34. In the calculation of the flicker indicator $P_{st99\%} = k_f \cdot \Delta V_{max}$, a factor $k_f = 45$ was used. The value of $P_{st95\%}$ has been taken into account as $P_{st95\%} = 0,8475 * P_{st99\%}$, as well. These two hypotheses have been validated by the experimental way.

4. Simulation Results

The ETAP programme (Electrical Power System Analysis & Operation Software) which has been used, is a well-known software for electric analysis in Power System.

The analysis of the data obtained by calculation (Table 1) and obtained by using of ETAP program shows that the change of the S_{sct} in the 110kV buses of the network (PCC of user, connected to the grid):

- has a high influence on the level of electromagnetic disturbances in these buses (110kV buses), being the possibility to exceed the admissible limits;
- has a low influence on the level of electromagnetic disturbances on the 6kV busbar of the user.



a) b)

Fig. 5. Load flow and voltages on the busbars from the network during the shortcircuit in the arc furnace with STATCOM:

S_{sct} = 2080 MVA; b) S_{sct} = 1050 MVA.

Fig. 5 shows the load flow and voltages on the busbars from the network during the short-circuit in the arc furnace with STATCOM, respectively, using the ETAP software.

The connection of STATCOM system on the medium voltage busbar of the user has an important consequence on the level of disturbances in the whole area around the PCC bus, allowing the possibility to respect the admissible levels of the standard. Considering the change of value for calculation of S_{sct}, the user has to revise and redesign the STATCOM, in order to respect the standard admissible conditions. When the S_{sct} is double (2080MVA versus 1050MVA), $P_{st95\%}$ is decreased 50% about.

Table 5 includes the results of calculation quantities using ETAP software - the voltage levels on the 110kV and 6kV busbars, and PQ indices for flicker.

The results obtained using the ETAP software confirm the experimental results from the study. By considering the electric resistances of the circuit elements, the lower short-circuit currents were obtained and, as a consequence, lower voltage drops. As in the case of the short circuit power of 2080 MVA and of the case in which the power circuit has dropped to 1050 MVA, the STATCOM system ensures the limitation of the level of disturbances at the levels stipulated by standards. In the specific condition of actual scheme, STATCOM system could not ensure the admissible PQ levels for the users connected to 6kV busbars.

Table 5

Results of calculation of quantities from circuit – centralization from the use of ETAP

Voltage level	Quantity	S_{sct} = 2080 MVA		S_{sct} = 1050 MVA	
		Without STATCOM	With STATCOM	Without STATCOM	With STATCOM
(1)	(2)	(3)	(4)	(5)	(6)
110 kV	$I_{sc110\ kV}$ [A]	96	58	94	57
	ΔU[V] *on 110 kV busbar* (phase to ground)	502	299	1035	616
	ΔU[%] *on 110 kV busbar* (phase to ground)	0.79	0.47	1.63	0.97
	$P_{st99\%}$	0.36	0.21	0.73	0.44
	$P_{st95\%}$	0.30	0.18	0.62	0.37
6 kV	ΔU[V] *on 6 kV busbar* (phase to phase)	835	497	879	522
	ΔU[%] *on 6 kV busbar* (phase to phase)	13.91	8.29	14.65	8.70
	$P_{st99\%}$	6.26	3.73	6.59	3.92
	$P_{st95\%}$	5.31	3.16	5.59	3.32

6. Conclusions

Special attention is required for steel and aluminum processing plants, disturbances generated by their technological processes being transmitted over transmission network and affecting the power quality for other customers. The customer responsible for the disturbances has to install reactive power compensation systems (SVC or STATCOM) for reducing the effects of flicker.

In the power network, the short-circuit power has a very important influence on the propagation of the disturbances in the power system. If the short-circuit power in the system is lower, the influence of the disturbance on the other customers connected to the grid is higher. This case of decreasing of the short-circuit power is met in Romanian Power System when many renewable sources are connected to the grid using static convertors and conventional generation sources are in reserve [1].

Development of the studies related to the propagation of the disturbances in the Power System in condition in which the short-circuit power is in the decreasing trend, as long as the number and capacity of the renewable sources are increased. The determination of the vulnerability area of Power System buses represents in this direction an important issue of the work.

The comparison of $P_{st95\%}$ among Calculation / Measurements / Simulation in PCC, at S_{sct} = 1050 MVA, shows the values are comparable in both cases:

- First case: without STATCOM (0.73; 0.77; 0.62 respectively) and
- Second case: with STATCOM (0.41; 0.45; 0.37 respectively).

The calculations which were done, have been confirmed by experimental determinations and offer to the disturbing users the data for finding out the appropriate solutions, most of them being important investments, in order to ensure to all users connected to the grid a standard PQ conditions. Of course, among the solutions taken into account could be:

- the change of rated voltage of the connection arc furnaces to the power grid to 20kV network or
- separate circuit including transformer 110/6 kV, 6 kV busbars without any other users connected to these 6kV busbar or
- Redesigning of the STATCOM, available for S_{sct} minim.

The analysis and methodology applied in this paper for the EAF consumer, can be extended to other distorting end-users connected to the mains supply, like welding-based industries, steel industry end-users etc.

The proposed solutions lead not only to improvement of Power Quality but also to increase energy efficiency of the users, having a suitable voltage level.

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Appendix 1

The components of diagram (Fig. 2) are determined below:

System reactance

$$X_{\text{system}} = \frac{U_b^2}{S_{sc110\text{kV}}} = \frac{110^2}{2080} = 5.82\ \Omega\,. \tag{1}$$

Reactance of 110/6 kV transformer, reported to 110 kV voltage

$$X_{\text{T110/6}} = \frac{u_{sc}}{100} \cdot \frac{110^2}{S_T} = \frac{18}{100} \cdot \frac{110^2}{25} = 87.12\ \Omega \tag{2}$$

6 kV cable reactance, reported to 110 kV voltage

$$X'_{\text{cablu 6kV}} = (X_0 \cdot l) \cdot \frac{U_b^2}{U_{\text{cablu}}^2} = (0.8 \cdot 0.0605) \cdot \frac{110^2}{6^2} = 16.27\ \Omega\ . \quad (3)$$

Reactor reactance, reported to 110 kV voltage

$$X'_{\text{bobina}} = (X_{\text{bobina}}) \cdot \frac{U_b^2}{U_{\text{bobina}}^2} = 0.7 \cdot \frac{110^2}{6^2} = 235.28\ \Omega\ . \quad (4)$$

Reactance of 6/0.4 kV transformer, reported to 110 kV voltage

$$X'_{\text{T6/0.4kV}} = \frac{u_{sc}}{100} \cdot \frac{110^2}{S_T} = \frac{8.5}{100} \cdot \frac{110^2}{10} = 102.85\ \Omega\ . \quad (5)$$

Short network reactance, reported to 110 kV voltage

$$X'_{\text{shortnetwork}} = (X_{\text{shortnetwork}}) \cdot \frac{U_b^2}{U_{\text{shortnetwork}}^2} = 0.0023 \cdot \frac{110^2}{0.36^2} = 214.74\ \Omega\ . \quad (5)$$

Total reactance of the circuit, reported to 110 kV voltage

$$X_{\text{total}} = 5.82 + 87.12 + 16.27 + 235.28 + 102.85 + 214.74 = 662.08\ \Omega \quad (6)$$

Reactive Power demanded from power network during burning of arc furnace

$$Q = \frac{U_b^2}{X_{\text{total}}} = 18.28\ \text{MVA}\ . \quad (7)$$

Calculation without STATCOM - The current demanded from 110kV network:

$$I_{110\text{kV}} = \frac{1.1 \cdot Q}{\sqrt{3} \cdot U} = 105.54\ \text{A}\ . \quad (8)$$

Voltage drop (phase to ground) on 110kV busbar in [V] and [%]

$$\Delta U = I_{110\text{kV}} \cdot X_{\text{system}} = 105.54 \cdot 5.82 = 614.24\ \text{V}, \quad (9)$$

$$\Delta U[\%] = \frac{614.24}{110000} \cdot \sqrt{3} \cdot 100 = 0.97\%, \quad (10)$$

Flicker level at 110 kV busbar means

$$P_{st99} = k_{st} \cdot \Delta U = 45 \cdot 0.0097 = 0.44\ ;$$
$$P_{st95} = 0{,}8475 \cdot 0{,}44 = 0.37\ . \quad (11)$$

Voltage drop (phase to phase) on 6kV busbar resulting

$$\Delta U = \sqrt{3} \cdot X'_{sc6\text{kV}} \cdot I_{110\text{kV}} = \sqrt{3} \cdot (5.82 + 87.12) \cdot 105.54 \frac{6}{110} = 926.67\ \text{V}\ ;$$
$$\Delta U[\%] = \frac{926.67}{6000} \cdot 100 = 15.44\% \quad (12)$$

Flicker level at 6 kV busbar means

$$P_{st99} = k_{st} \cdot \Delta U = 45 \cdot 0.1544 = 6.95\ ;$$
$$P_{st50} = 0{,}8475 \cdot 6.95 = 5.89\ . \quad (13)$$