Reducing the Impact of Transient Phenomena of Arc Furnace on Power Network Operation

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***Abstract*—This paper deals with the analysis of the transient phenomena caused by the operation of the electric arc furnace in the 22 kV network, describes the causes of their origin and proposes the possibilities of their reduction with regard to the fulfillment of the quality of electric energy. In particular, it focuses on assessing the short-term flicker rate and the use of the STATCOM device to reduce it. The analysis and subsequent reducing of transient phenomena impact was realized by simulations using the Matlab / Simscape Power Systems tool. The obtained results were evaluated in accordance with the valid European standards and legislation of the Slovak Republic.**

Keywords*—*transient phenomena, distribution electric system, electric arc furnace, flicker, STATCOM

I. Introduction

Particular types of transient events do not only affect the operation of the electricity system but also affect their effects directly on humans. Such a transient phenomenon is a flicker that causes dynamic flashing of light sources that adversely affect the well-being of people. A strong source of such transient operations is the operation of an electric arc furnace (EAF) because the permissible flicker rate is not met earlier than the other conditions permitting operation at a given point in the network. The problem also adds to the fact that the development of power semiconductor elements has recently enabled FACTS (flexible AC transmission systems) to be applied in the system. These properties meet the assumptions of reliable compensation of transient processes caused by EAF without extensive interference in the network composition.

The problem was investigated by an example of a fictitious connection of an electric arc furnace with an apparent power of 2 MVA to the 22 kV distribution network for the V-281 power line connected to the Bardejov power station.

II. Transient Phenomena Caused by EAF Operation

The article examined the transient processes that arise during the operation of EAF, which belong to the category of electromagnetic transient events. EAF by its operation represents an irregular current load on the network causing voltage drops on the network impedances resulting in voltage fluctuations in the system. Due to [1], [2], the fluctuations mentioned are due to 2 types of current load originating in the EAF, designated as the 1st and 2nd types of changes [3].

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A. *First type of change in current load*

It occurs especially in the first 30 minutes of melting with a frequency of 0.5 to 1-times per second and represents a short-circuit current when ignition of the arc between the electrode and the batch (charge). In the EAF, its occurrence is constantly repeated until the batch is cold. Another possibility of changing this type is by accidentally contacting the batch with the electrode (e.g. by shifting the batch during the melt process).

B. *Second type of change in current load*

It represents a change in current intensity in the range of ±15 to ±50 % of the nominal value, with a frequency of occurrence of 2÷20-times per second. "These current fluctuations do not seem to be subject to unambiguous regularity because they are still changing both in their amplitude and in their multiplicity" [2], [4]. Current changes and their fluctuations have three causes:

- Changes in current intensity without significant changes in the length of the electric arc when the current passes from one half-wave to the next one. Due to the temperature, the material exposed to the arc melts and partially evaporates, with strong local overheating, the evaporation of the additives in the steel can explode [5], [6], [7]. The resulting vapors rise, and in the vicinity of the arc they are ionized by the influence of high temperatures, increasing the concentration of free carriers and allowing the arc to transfer a higher current.
- Fluctuations caused by the arc flash-over from one protruding piece of batch to the other. The jump (flash-over) occurs with a period of 0.1 to 0.4 seconds (2 to 10 jumps per second), with the jump occurring each time the protruding piece of batch is rounded by the electric arc. Changes in the amplitude of the current caused by arc flash-overs are the main cause of flicker effect [8], [9].
- Extending the arc due to its loop motion. The deflection of the arc is caused by the amplification of the magnetic field of the neighboring phase, which, for some of the above-mentioned reasons, began to flow through a larger current.

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III. Methods For Analysis of Transient Phenomena

Elimination as well as the simulation of the unbalanced load in the form of EAF itself was done through the Matlab program in the Simulink graphical environment. For simulation of power system elements, the Simscape Power Systems Simulink tool was used for the libraries of these elements. With the above mentioned libraries, models of superior grid, transformers, external and cable lines, compensation chokes, and models of symmetrical loads on the low voltage side were created.

The power network was modeled according to the 22 kV line V-281 powered by the Bardejov power station. Multimeters were added to the grid in the nodes to provide information on voltages and currents in the grid, and at the AV node it was considered to connect a fictitious arc furnace with a nominal apparent power of 2 MVA [10], [11], [12]. Inter-connections with surrounding lines were considered in a disconnected state, and the whole power-line could be considered as a radial.

A. *Model of electric arc furnace*

The arc furnace model consists of a "short-length-grid" and electrodes. These elements with their electrical parameters are replaced in the model by the equivalent current value that would be taken from the secondary transformer side terminals [13], [14]. In this case, the current is determined by the currents measured by the actual operation of an electric arc furnace of 50 MVA power, connected to the electrical network via a 110/33 kV furnace transformer. The currents were measured on the secondary side of the transformer, the values being read off for each half-period during a 1-minute measurement. These current values have been adapted to match the operation of a 2 MVA arc furnace connected through a 22/0.2 kV furnace transformer.

In order to derive the equivalent behavior of the arc furnace in the 22 kV network (Fig. 1, B), it was assumed that the network draws the same current I_2 in relation to the nominal as the arc furnace (Fig. 1, A) powered by the 110 kV network.

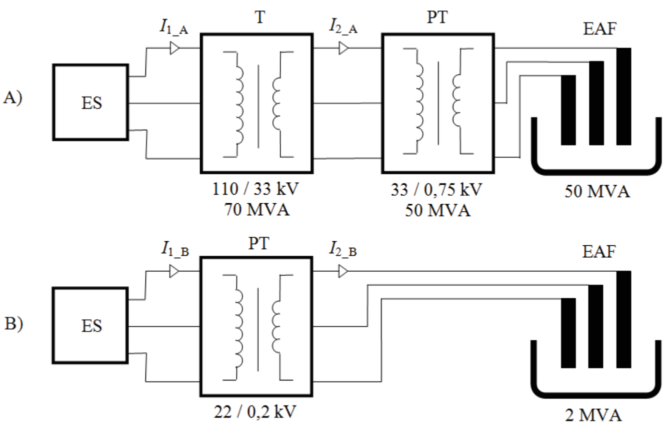

Fig. 1. Principal representation of the EAF with a furnace transformer and their main parameters

The equality of these ratios could be formulated as:

$$\frac{I_{2\_A}}{I_{2n\_A}} = \frac{I_{2\_B}}{I_{2n\_B}} \quad (1)$$

from where we get the formulation:

$$I_{2\_B} = \frac{I_{2\_A}}{I_{2n\_A}} \cdot I_{2n\_B} = \frac{I_{2n\_B}}{I_{2n\_A}} \cdot I_{2\_A} \quad (2)$$

Whereas:

$$S_{n} = \sqrt{3} \cdot U_{2n} \cdot I_{2n} \quad (3)$$

then:

$$I_{2n\_A} = \frac{S_{n\_A}}{\sqrt{3} \cdot U_{2n\_A}} ; \; I_{2n\_B} = \frac{S_{n\_B}}{\sqrt{3} \cdot U_{2n\_B}} \quad (4)$$

By putting the expression (4) into (2) we get a formulation:

$$I_{2\_B} = \frac{S_{n\_B} \cdot U_{2n\_A}}{S_{n\_A} \cdot U_{2n\_B}} \cdot I_{2\_A} = \frac{2 \cdot 10^6 \cdot 33 \cdot 10^3}{50 \cdot 10^6 \cdot 0{,}2 \cdot 10^3} \cdot I_{2\_A} = 6{,}6 \cdot I_{2\_A} \quad (5)$$

the result being the constant at which the current obtained by measuring the 50 MVA arc furnace should be multiplied to match the load of the 2 MVA furnace.

The basis for the arc furnace model is therefore the *Controlled Current Source* (Fig. 2, i_1 to i_3), which current acts against the current flowing across the network. "Controlled" means that the current value can change during the simulation run by the values input to the control input.

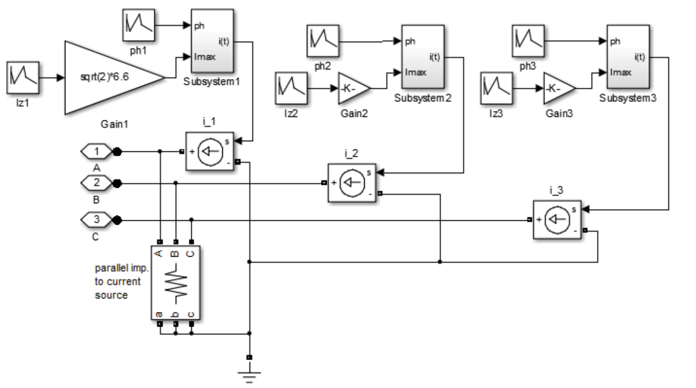

Fig. 2. Block diagram of the arc furnace model

Since the current set in this power source had to be the same as the current in the power network, the control input is defined as follows [15]:

$$i_n = I_{mn} \cdot \sin(\omega \cdot t + \varphi_n) \quad (6)$$

where n represents the designation of the phase.

These formulations are in the scheme in Fig. 2 represented by the formed blocks Subsystems1, 2, 3, and their internal connection is shown in Fig. 3. The inputs to these blocks represent the values of the values I_{mn} and φ_n.

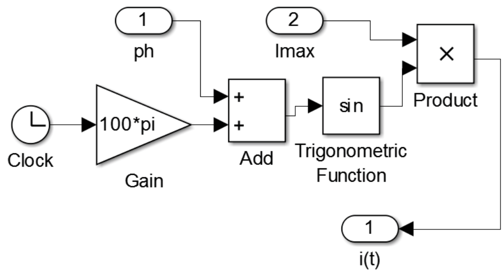

Fig. 3. Block diagram for creating sine wave signal

The *Repeating Sequence Interpolated* block was chosen as a signal source with values of I_{mn} and φ_n, and its action is illustrated in Fig. 4.

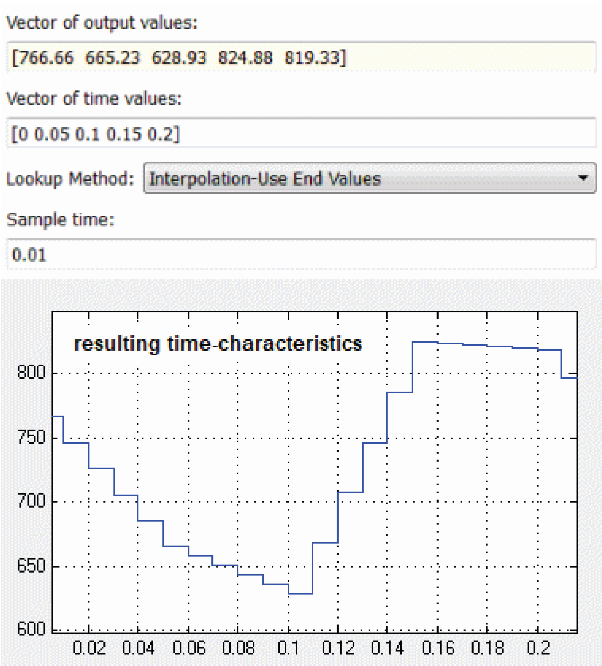

Fig. 4. Action example of *Repeating Sequence Interpolated* block

The signal from this block therefore changes its value each time after the sampling period, with the requested value being acquired at the desired time for a single sampling period. Gradual partial changes between the two required values are linear. The frequency of these current changes was set for the arc furnace, given the theoretical knowledge presented in subchapter II. *B*, and has a value of 20 Hz. Therefore, the change in the drawn current from the arc furnace occurs continuously, with the maximum current change being achieved with the period of 0.05 second.

B. Model of flickermeter

The flickermeter model is not created in a Simscape Power Systems environment but is created between sample examples that contain Matlab libraries. The flickermeter model conforms to IEC 6100-4-15 and its characteristics are described in [1]. The model allows to user to select the frequency of the network which will be analyzed. In some blocks, however, it still has a preset frequency of 60 Hz, which needs to be overwritten by user.

The aforementioned model allows instantaneous flicker sensation (IFS) to be measured in only one phase, which is not sufficient to evaluate the asymmetric load in the form of an arc furnace. For this reason, the model was further modified so that it could evaluate the flashing rate at all three phases at the specified point of the system.

The instantaneous flashing values are not listed in the standard, so the values obtained by the flickermeter have to be further evaluated to the value of the short-term P_{st} flicker. The short-term flicker rate was determined according to [1], [10].

C. Model of STATCOM

The Simscape Power Systems environment library contains several blocks of FACTS, but they are all designed for simulations using a phasor computing method, the use of which for the problem under consideration did not meet the requirements. As a model, like the flickermeter model, the selected use of the STATCOM device was modeled in this example. This is a discrete STATCOM model with a nominal voltage of 25 kV and a power regulation within ±3 MVAr in a 60 Hz frequency range [16], [17]. For its use in the power network examined, it was necessary to change the frequency setting of the regulators to 50 Hz by opening the subblocks it contains. A more detailed description of the model is described in [18], [19].

D. Simulation of the network

The flash-blinking simulations (instant and short-term) were analyzed in the network simulations for various arrangement to reduce it. The simulation time was in all cases 60 seconds. This time was chosen because the 10-minute simulations needed to determine the short-term flicker magnitude according to STN EN 50160 were virtually unrealistic in terms of computing time of the utilized computers. The flickermeter was always connected to the connection node V-281 EAF assuming that if the electricity quality at that node was met, it was also met for the rest of the network. For computational difficulty, the flickermeter was only placed on the node mentioned, and the other nodes only measured the voltage. Data obtained by measurement was exported to files and processed using MS Excel.

IV. Results of Simulations

The first simulation with compensation was performed exclusively by means of a compensation induction choke, while the EAF was connected to the AV network node. Due to the non-compliance with the permitted short-term flicker rate (Tab. 1), STATCOM was compensated, and at a continuously exceeded P_{st} value, the next possibility of eliminating flicker effect was to consider the increase in the short-circuit power at the power station.

TABLE I. Comparison of P_{ST} Values in Particular Modification of the Network Operation

Connection point / compensation method	P_{st}		
	phase A	phase B	phase C
Node AV / Inductor (TL)	9,217	19,187	23,554
Node AV / Inductor + STATCOM (S)	4,372	9,384	12,611
Node AV / Inductor + 3·S_{k3}''	9,080	19,051	23,417
Node AV / TL + S + 3·S_{k3}''	4,340	9,289	12,512
Node AV / TL (3·L) + S + 3·S_{k3}''	3,878	5,088	5,946
Substation (22 kV) / TL + S (1)	1,204	1,427	1,332
Substation (22 kV) / TL + S (2)	5,123	11,301	14,772
Substation (22 kV) / TL + S + 3·S_{k3}''	1,179	1,381	1,278
Substation (22 kV) / TL (3·L) + S + 3·S_{k3}''	1,177	1,360	1,238
Substation (110 kV) / TL + S	1,122	1,289	1,160
Substation (110 kV) / TL	1,115	1,289	1,150
Substation (110 kV) / TL – measuring at 22 kV	1,105	1,273	1,136
Substation (110 kV) / TL + 3·S_{k3}''	1,098	1,260	1,121
Substation (110 kV) / TL + 3·S_{k3}'' - mer. 22 kV	1,088	1,245	1,109

(1) - measured at the mains connection side

(2) - measured at the terminal end of the EAF

TL - connected compensation choke (inductor)

S - connected STATCOM device

3·S_{k3}'' - 3-times increasing of short-circuit power at the power station

TL (3·L) - utilizing of inductor with 3-times higher the inductance value

By comparing the short-circuit power of electric substations in eastern Slovakia it can be said that if we were to assume the installation of a 400/110 kV transformer at the given Bardejov power station, its short-circuit power would increase approximately three times, so we considered $S_{k3}'' = 3.891$ GVA. Even this measure did not produce the required P_{st} value reduction, consequently the inductance of the compensating choke (inductor) was increased to three times the original value.

However, the short-term flicker rate was 5-times of the allowable value, so as a further solution, an EAF connection with the power station was considered using its own HV terminal output. This solution has dramatically reduced the blinking rate in the network, and it should be noted that the flicker rate has fallen down due to the increase in the short-circuit power at the flicker measurement point at the start of the output and the attenuating effect of the EAF-powered line itself. At the end of the EAF power line, however, the flicker rate increased due to a smaller proportion of symmetrical load. However, this problem would be solved in the EAF auxiliary installations by connecting them from the V-281 AV line node. Nor did such a solution combined with all the previous ones ensure compliance with the legislation on permissible value. The most recent solution was to connect the EAF to the power station using a 110 kV stand-alone power output terminal.

V. Conclusion

From the results obtained in chapter IV, it follows that by connecting the arc furnace to the AV network node using a compensating choke as an element eliminating transients (inductor), there was a significant (24-times) exceeding of the allowed short-term flicker. This relatively high P_{st} value was caused by selecting a measured sample of currents when operating the furnace, where the measurement with the highest current peaks was chosen and the large difference between the maximum and the minimum drawn current. The short-term flicker rate was therefore evaluated for the most unfavorable case of EAF operation at the start of the scrap-metal meltdown.

Neither of the solutions examined has been able to eliminate/reduce the short-term flicker caused by transient phenomena to the level of allowance in STN EN 50160. The considered 2 MVA arc furnace would therefore not be able to operate on the V-281 line under investigation without failure to maintain the quality of the voltage.

For this reason, it should be added that the long-term flicker rate, measured in real measurements, would be lower than the obtained result. This is due to the fact that the long-term flicker rate is evaluated from twelve 10-minute measurements and must be maintained at 95 % of the time of one week. However, most of the events causing large fluctuations in the currents are taken only in the first 15 minutes of each melt. In the simulations, the flicker rate was only investigated for one of the worst minute of operation.

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