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Application of a thyristor-controlled series reactor to reduce arc furnace flicker

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Abstract. This paper presents the basic principles of a thyristor-controlled series reactor for the reduction of arc furnace flicker which negatively impacts a transmission network. The developed models of a transmission network and an arc furnace with a sinusoidal variation of arc length were used for simulations and calculations. The concept of flicker compensation using a thyristor-controlled series reactor is presented with simulation examples. These simulations showed that the integration of a thyristor-controlled series reactor can successfully reduce flicker levels in the transmission network.

Keywords: power quality, flicker, arc furnace, thyristor-controlled reactor

1 INTRODUCTION

Electricity is a commodity like any other product and it must satisfy quality standards. It is necessary to maintain a certain level of voltage quality in a network to ensure the proper operation of connected equipment. The system operator and users of the system are responsible for the voltage quality. Each network user (a consumer or producer of electricity) must limit the negative impact of their own equipment on network voltage quality (due to the injection of higher harmonics, consumption of reactive power, flicker, unsymmetrical load…) to a pre-agreed level. A violation of power quality involves a violation of basic steady-state voltage parameters and a deformation of waveforms. Arc furnaces are one of the main sources of flicker in transmission networks.

2 SIMULATION MODEL AND THE OPERATING PRINCIPLE OF A THYRISTOR-CONTROLLED SERIES REACTOR

A thyristor-controlled series reactor improves the stability of the high voltage arc of an arc furnace and reduces flicker. The compensator stabilises the arc by dynamically controlling the series reactor installed between the transformer and the arc furnace. The controlled reactor acts as a dynamic spring [1, 2]. The technology takes advantage of the rapid switching of thyristors and advanced predictive computer controls. Figure 1 shows a single line scheme of an arc furnace installation with a thyristor-controlled series reactor connected to a high voltage grid. The basic operating principle is based on diverting the current from the series reactor (L_1) to the parallel reactor (L_2). The parallel reactor has a smaller inductive resistance and is switched in and out of the electrical circuit to control the furnace current. The series reactor has a large fixed inductive resistance and is connected on the line side. When the compensator senses an overcurrent, the thyristor switch opens and current flows through path P_1. The fast insertion of reactor L_1 limits the overcurrent swing.

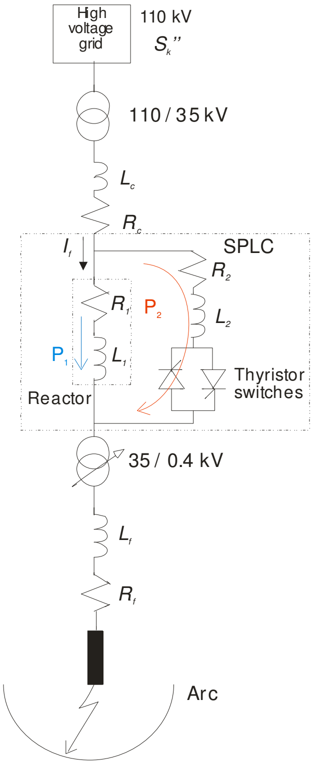

Figure 1. Single-line scheme of the plant network used in the simulations

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When the compensator senses stable arcing, the switch closes, connecting the furnace through reactor L_2 to the main substation transformer for high power operation as shown by path P_2 [1, 2, 3].

Figure 1 shows part of the plant network which is used in the simulations. The network model involves a high-voltage network equivalent, a 110/35 kV transformer substation, a 35/0.4 kV furnace transformer, reactors, thyristor switches and impedance of the cable between the substation and furnace transformer. The values of these parameters are shown in Table 1. S_k'' represents the short-circuit power at the 110 kV connection point. Short circuit voltages (u_k) for different tap positions of the furnace transformer are shown in Table 2. An equivalent model of the plant network was designed using PSCAD software [5, 6].

High voltage level U_{grid} [kV]	110
Short circuit power S_k'' [MVA]	3750
Short circuitvoltage $u_{k\_110/35}$ [%]	7.69
Reactor inductance L_1[H]	0.02
Cable inductance L_c [H]	0.0002
Furnace cable inductance L_f [H]	0.00035
Parallel inductance L_2[H]	0.001
Parallel resistance R_2[Ω]	0.015
Reactor resistance R [Ω]	0.3
Cable resistance R_c [Ω]	0.062
Furnace cable resistance R_f [Ω]	0.00035

Table 1. Values of the parameters of the model shown in Figure 1

Tap position	Voltage on low voltage level of transformer [V]	u_k [%]
7	343.1	4.19
8	363.3	3.96
9	383.2	3.75
10	4.038	3.54
11	425.1	3.33
12	444.9	3.14
13	464.6	2.94
14	481.7	2.78
15	500	2.61

Table 2. Values of u_k for different tap positions of the furnace transformer

2.1 Description of the arc furnace model

A nonlinear model of the arc furnace and flicker meter are designed in the simulation programme. The nonlinear voltage-current (V-I) characteristics of the arc furnace can be described by the following equation (1) [5, 6]:

$$U_{\text{a}} = U_{\text{a}}(I) = U_{\text{at}} + \frac{C}{D + I_{\text{a}}} \quad (1)$$

where U_a and I_a are the voltage and current of the arc, U_{at} is the minimum arc voltage to which the voltage drops when the current increases and C and D are constants which determine the difference between increasing and decreasing current paths of the V-I characteristic [5].

To simulate variation in the arc length, a stochastic or a deterministic approach can be used. The stochastic approach provides random variations of the arc length, which is closer to reality, but the mathematical treatment in this case is more complex and requires long simulation times. Under the deterministic approach, the arc length varies by a sine function at the corresponding selected frequency. This approach does not fully describe the operation of the electric arc furnace but allows a much easier simulation with shorter simulation times and without additional statistical treatment of the results. The deterministic model provides higher flicker levels at a certain operating point of the arc furnace compared to the stochastic model. For this reason, the deterministic variation of the arc length was chosen in our simulations. The following formula describes the deterministic variation of the arc length:

$$l(t) = l_0 - \frac{D_1}{2} \sin \omega t \quad (2)$$

where D_1 is determined by the amplitude of the sine curve and l_0 is constant. When the length of the arc equals l_0, the furnace model does not produce harmonics. Since human eyes are most sensitive to flicker at voltage fluctuations at around 8.8 Hz, the frequency 9 Hz for the frequency ω of arc fluctuations in (2) was selected [5, 6].

2.2 Description of the control algorithm

The control algorithm is based on the continuous monitoring of the reactive current of the furnace. The block diagram of the control algorithm is shown in Figure 2. The current between the network and the furnace is measured. The reactive, i.e.q-component, of the current is proportional to the reactive power of the furnace. Since higher order harmonics are present, the q-component of the current is not a constant value. Using a Fast Fourier Transform (FFT), the control algorithm extracts the low-frequency variations of the reactive current which are the source of flicker. The 50 Hz FFT filters harmonic components out of the reactive current component and the 9 Hz FFT removes the fundamental frequency reactive current component. The outputs of these two filters are subtracted. Block Table 1 converts the difference of these two signals into reactance X. When the value is minimal the output signal of the block table 1 is equal to 6.28 Ω which is the maximum value of both reactances. When the value is maximal, the output signal of block Table 1 equals 0.30 Ω which is the minimum value of both reactances. Next, this reactance value is converted to susceptance B.

Susceptance B represents the equivalent susceptance of both reactors, as shown in Figure 2b.

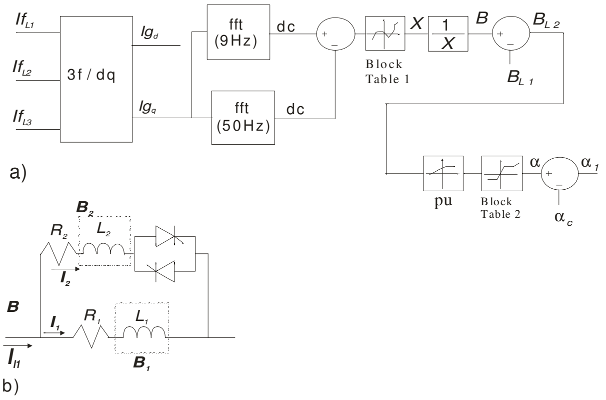

Figure 2. Block diagram of the control algorithm

The value of susceptance B_1 is constant and equals 0.159 S, while the value of susceptance $B_2$is controlled with the thyristors firing angle. Resistances R_1 and R_2 are relatively small and are not considered in the control scheme. Angle α is a nonlinear function of susceptance B_2 and is obtained from block Table 2 [5]. Because of the phase displacement between the 35 kV voltage and the current through thyristors there is also a correction angle α_c. Finally, α_1 represents the angle value for thyristors triggering. The correction angle value equals 53°. This control algorithm can be used for the selected frequency of arc length variation.

3 SIMULATION OF OPERATION

In the experimental part of this work, three simulations were performed. With the first simulation the operation of the furnace without a reactor was shown. In the second simulation a thyristor-controlled series reactor with "coarse regulation" was used. The third simulation was performed with a thyristor-controlled series reactor with full regulation. The results obtained from the simulations are compared at the end. The data obtained from simulation of the arc furnace operation without compensation are used as reference values.

3.1 Simulation without a reactor

A simulation of the furnace operation without a reactor, i.e. operation of the furnace directly connected to a high voltage grid, was carried out. Waveforms of the signals are shown in Figures 3 and 4. Numeric values of the active and reactive power and flicker levels are listed in Table 3. High- and low-frequency oscillations of voltage, current, active and reactive power are also evident from Figures 3 and 4. As no series reactor is used, the values of active and reactive power of the furnace are equal to the values of the active and reactive power of the network. The flicker level on the 110 kV voltage level equals 1.03.

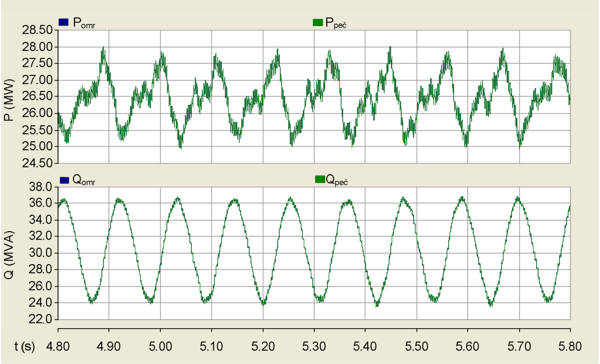

Figure 3. Waveforms of the active and reactive power of a furnace without a thyristor-controlled reactor (P_{fur}, Q_{fur}), tap position 13

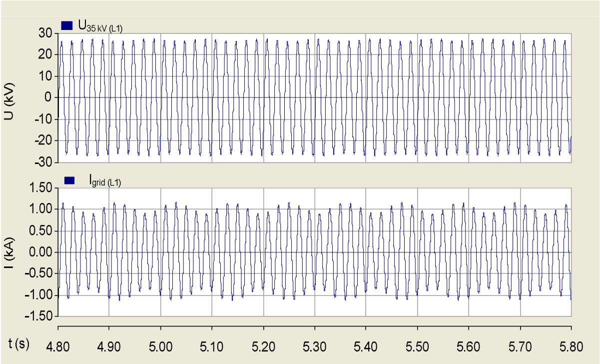

Figure 4. Waveforms of the voltage at the 35 kV level and current of the network without a thyristor-controlled reactor, tap position 13

A simulation at different tap positions of the furnace transformer was performed. The results for different tap positions of the furnace transformer are shown in Table 3. In order to compare the results, all the simulations must be performed at the same operating point of the furnace.

Tap position	**15**	**14**	**13**
$P_{\mathrm{st\_35kV}}$	9.51	8.91	8.36
$P_{\mathrm{st\_110kV}}$	1.21	1.15	1.10
P_{fur} [MW]	31.15	29.74	28.28
Q_{fur} [MVAr]	40.71	37.37	34.20

Table 3. Numeric values of parameters for different tap positions of a furnace transformer without a thyristor-controlled reactor (mean values of P and Q)

3.2 Simulation with "coarse regulation"

In this simulation of the furnace operation a thyristor-controlled reactor was included, but the control algorithm only worked in two conditions (on with α=90°, and off with α=180°), and hence the term "coarse regulation". In the "on" condition of the control algorithm, a maximum value of current across the thyristors is reached. In the "off" condition, the control algorithm does not trigger the thyristors. The control algorithm was switched on 5 seconds after the simulation started. During the first 5 seconds, the series compensator operates as a damping reactor. Figure 5 shows the waveforms of the active and reactive power. Significant oscillations of the active and reactive power are present. This is a consequence of the "coarse regulation". The selected tap position of the furnace transformer was 16.

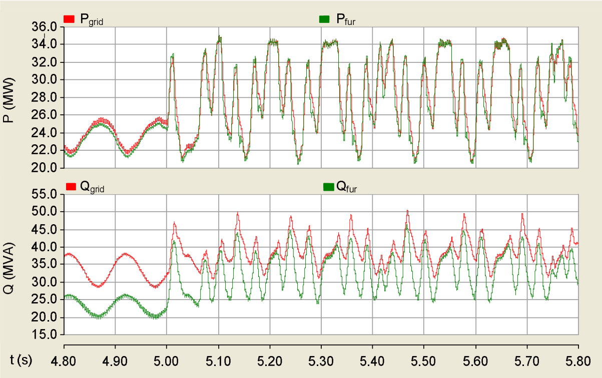

Figure 5. Waveforms of the active and reactive power of the furnace (P_{fur}, Q_{fur}) and active and reactive power of the network (P_{grid}, Q_{grid}) with "coarse regulation" before and after the start of the control algorithm; tap position 16

The control algorithm in this simulation is based on continuous monitoring of the value of an error signal. The reference value for comparison is 0. When the control algorithm of the compensator senses an error signal bigger than the reference value, the switch opens and current flows through inductance L_1. When the compensator senses an error signal less than the reference value, the switch closes and connects the furnace to the network through L_2 which is parallel to inductance L_1. As a result, there is a large and continuous oscillation of active and reactive power. The flicker at the 35 kV and 110 kV levels can be seen in Figure 6. It should be noted that the flicker meter model in PSCAD does not calculate flicker in the first 2 seconds of the simulation. In Figure 7 the amplitudes of the voltage and current on the 35 kV level before and after starting the control algorithm are shown. Table 4 shows the mean values of the furnace parameters used in this simulation and obtained flicker values.

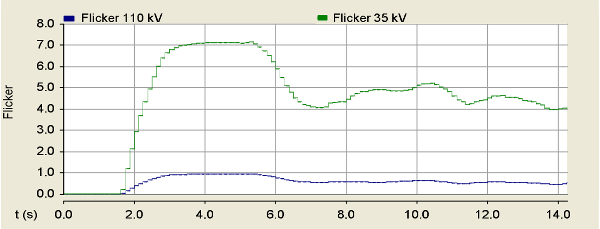

Figure 6. Flicker waveforms at the 110kV and 35kV levels with "coarse regulation" of the compensator; before and after starting the control algorithm

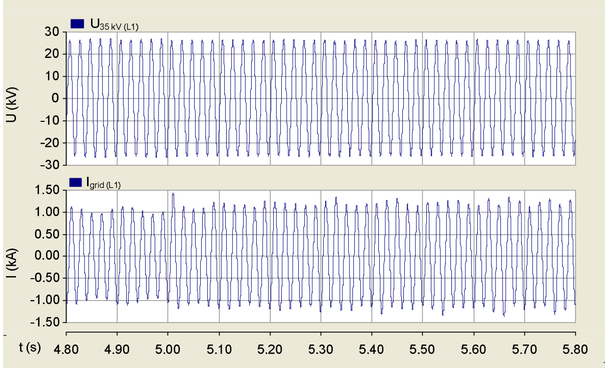

Figure 7. Waveforms of the voltage at the 35 kV level and network current with "coarse regulation", before and after starting the control algorithm; tap position 16

Tap	16
P_{st_35kV}	4.79
P_{st_110kV}	0.56
P_{fur} [MW]	28.99
Q_{fur} [MVAr]	34.80
P_{grid} [MW]	29.24
Q_{grid} [MVAr]	39.62

Table 4. Numeric values of furnace parameters with "coarse regulation", tap position 16 (mean values of P and Q)

3.3 Simulation with full regulation

A simulation of the furnace with a thyristor-controlled reactor with full regulation was performed. The value of angle α varies between 90° and 180° [7]. Because of the phase displacement between the voltage and current through the thyristors, the maximum current through the thyristor is reached at α=90°. At α=90° the current of the furnace through the thyristor is maximal, while at α=180° the current of the furnace through the thyristor is zero. In the first 5 seconds of the simulation the control algorithm did not operate. During this time, the compensator operates as a damping reactor. After 5 seconds, the control algorithm starts calculating angle α. In Figures 8, 9 and 10 waveforms of the active and reactive power, current and flicker before and after the start of the control algorithm are shown.

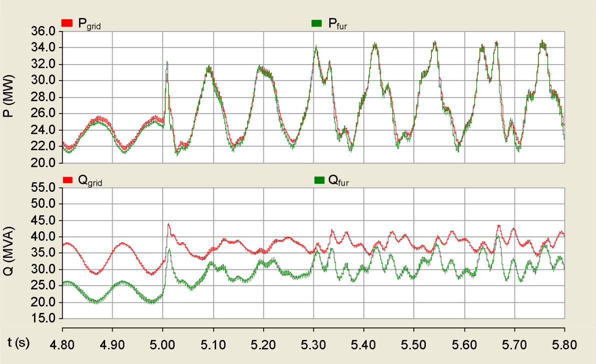

Figure 8. Waveforms of the active and reactive power of the furnace (P_{fur}, Q_{fur}) and the active and reactive power of the network (P_{grid}, Q_{grid}), before and after the start of the control algorithm, tap position 16

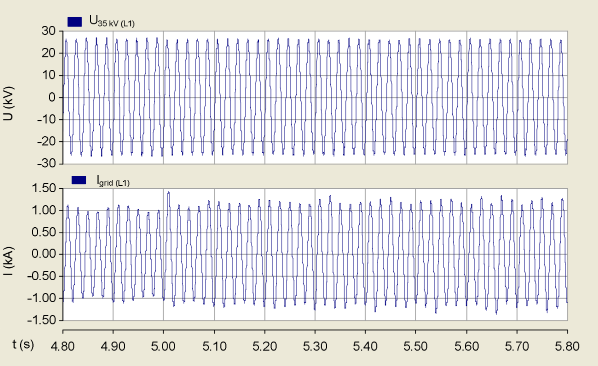

Figure 9. Waveforms of the voltage at the 35 kV level and current of grid before and after the start of the control algorithm, tap position 16

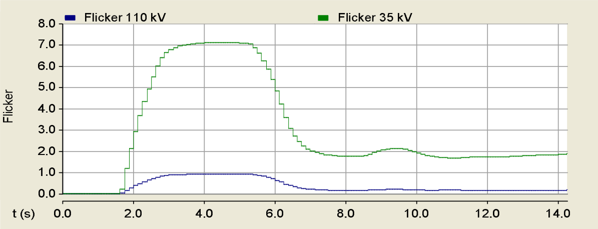

Figure 10. Flicker level at the 110 kV and 35 kV levels before and after the start of the control algorithm, tap position 16

The simulation was performed at the 16th tap position of the transformer. Numeric values of this simulation are shown in Table 5.

Tap Position	**16**
P_{st_35kV}	1.83
P_{st_110kV}	0.16
P_{fur}	27.29
Q_{fur}	30.82
P_{grid}	27.55
Q_{grid}	37.80

Table 5. Numeric values of parameters for the 16th tap position of a transformer with a thyristor-controlled reactor (mean values of P and Q)

4 ANALYSIS OF THE SIMULATION RESULTS

The fluctuations of reactive power from the grid in Figure 8 are lower after the start of the control algorithm, whereas the fluctuations of active power are higher. Since the compensator periodically bypasses inductance L_1, connecting the furnace to the network also through inductance L_2 as a result, there is increased reactive energy consumption.

In order to see all of the advantages of a thyristor-controlled reactor application, a comparison with some other flicker reduction process must be made. For this reason, in the first 5 seconds the compensator was operating with disabled thyristors. During this time, the compensator operates as a damping reactor. The numeric values for both types of operation are listed in Table 6 where also the values for operation without the series compensator are given. A significant reduction of flicker levels can be noticed after the start of the control algorithm operation. Because of the inductance the reactive power losses are larger than those without the reactor. Active power losses also exist, but they are much smaller.

Table 6 shows that the operating point of the furnace with a thyristor-controlled reactor, i.e. $P = 27.29$ MW and $Q = 30.82$ MVAr, is close to the values of the operating point of the furnace without a thyristor-controlled reactor at the 13th tap position.

Tap Position	**16**	**16**	**13**
Period	First 5 seconds	After 5 seconds	Without a compensator
P_{st_35kV}	7.11	1.83	8.36
P_{st_110kV}	0.92	0.16	1.10
P_{fur} [MW]	23.31	27.29	28.28
Q_{fur} [MVAr]	23.16	30.82	34.20
P_{grid} [MW]	23.80	27.55	28.28
Q_{grid} [MVAr]	33.37	37.80	34.20

Table 6. Numeric values of furnace parameters in the first 5 seconds, after 5 seconds of simulation with a compensator and without a compensator (mean values of P and Q)

Regulation	Without compensator	Coarse regulation	With a compensator
Tap Position	13	16	16
P_{st_35kV}	8.36	4.79	1.83
P_{st_110kV}	1.10	0.56	0.16
P_{fur} [MW]	28.28	28.99	27.29
Q_{fur} [MVAr]	34.20	34.80	30.82

Table 7. Numeric values of furnace parameters without compensator, with coarse regulation and with full regulation

According to the active power of the furnace it can be seen that the operating point of the furnace with “coarse regulation” is close to the operating point of the furnace without a thyristor-controlled reactor at the 13th tap position, as shown in Table 7.

The data from Table 7are graphically presented in Figure11. For a similar level of active furnace power the flicker level is smaller when using the thyristor-controlled reactor. The flicker level with the thyristor-controlled reactor is approximately 7 times smaller than the flicker level without a thyristor-controlled reactor. It may be concluded that using a thyristor-controlled reactor at the source of flicker significantly reduces flicker levels in the high voltage network.

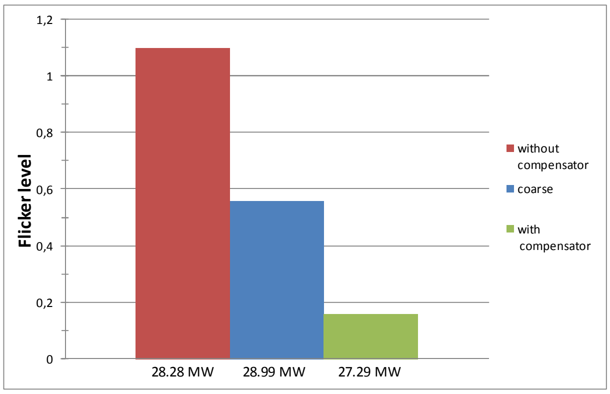

Figure 11. Graphic representation of the flicker level for approximately the same active furnace power

5 CONCLUSION

The paper shows that using a thyristor-controlled series reactor is an effective method for reducing flicker levels in a network. The comparison of a thyristor-controlled reactor with compensation using passive inductors showed that the thyristor-controlled reactor has advantages. It reduces the fluctuations of reactive power and enables the furnace's stable operation. The limitations onthe furnace's maximum power are also smaller than the limitations with passive compensation (for the same tap position). While the use of a thyristor-controlled reactor is more expensive, it is also a more efficient solution for flicker problems.

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