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Implementation of a controller for a static VAr compensator in large industrial networks

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Abstract. This paper deals with the development of a control algorithm for reactive-power compensation, flicker compensation and voltage regulation in large, industrial networks. The concept of compensation with a static-var compensator (SVC) and control-algorithm verification with realistic simulation examples using an actual industrial-network model are presented. In this paper a new control algorithm for control SVC devices is proposed. With this controller the SVC devices can operate in three modes: reactive-power compensation, flicker-level compensation or voltage regulation. The advantages of the proposed controller compared to other known regulators are the better flicker-level compensation and cheaper installation, because it requires only one measurement location. The data obtained with the simulations showed that the proposed controller can be successfully used for the control SVC devices for the reduction of flicker levels, the compensation of reactive power and for the regulation of voltage levels in large industrial networks.

Key words

SVC, controller, flicker reduction, reactive-power regulation,

1. Introduction

The use of electric arc furnaces (EAFs), because of their productivity, precision, flexibility and some advanced applications for steelmaking, has grown dramatically in the past few decades. The time-varying nature and non-linear voltage-current characteristic of arc furnaces used for steel production are the main cause of voltage fluctuations in electrical networks, which may give rise to the effect known as flicker [1]-[3].

It is necessary to maintain a certain level of voltage quality in a network in order to ensure the proper operation of the 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 the network's voltage quality (resulting from the injection of higher harmonics, the consumption of reactive power, flicker, unsymmetrical load, etc.) to a pre-agreed level. The key role in providing the appropriate parameters to ensure the quality of electric power is played by flexible AC transmission systems (FACTS) devices. The static VAr compensator is a compensation device that is based on power electronics. [3]-[6].

A widely used method to reduce flicker reduction is to employ static VAr compensators (SVCs) [6]-[10]. The SVC is installed on the primary side of arc-furnace transformers and reduces the variation of the reactive power drawn from the source by injecting a reactive power opposite to that of the EAF. However, the ability of a SVC to compensate for flicker is limited by delays in the reactive-power measurements and thyristor ignition [7]-[10].

2. Model of Static VAr Compensator

Fig. 1 shows the main circuit of a Thyristor-Controlled Reactor Fixed Capacitor (TCRFC) type of static VAr compensator. It is composed of a set paralleled filter capacitor (FC) and a thyristor-controlled reactor (TCR), and provides the capability for a reactive adjustment in both the capacitive and inductive sections. The set of filters then filter the harmonics generated by the TCR itself or other system loads. This type of SVC is used for elimination and reduces the flicker and current unbalanced in the system caused by operating an EAF.

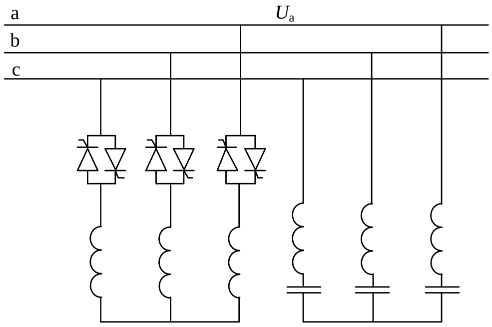

Fig.1 Scheme of TCRFC

3. Compensation Principle and Control-System Design

It is widely known that the voltage fluctuations at the point of connection are mainly caused by a rapid change in the reactive power of the EAF. The TCR can quickly alter the inductive current of a device in a continuous way by changing the firing angle of the thyristor, connected in series with the reactor, and thus adjust the reactive power as the system demands. Using a suitable controller for the control of the reactive power of the SVC, the voltage fluctuations can be decreased to an acceptable level. The control algorithm is essential for a proper and efficient operation of the TCR. Fig. 2 shows a simplified, equivalent scheme of the TCR.

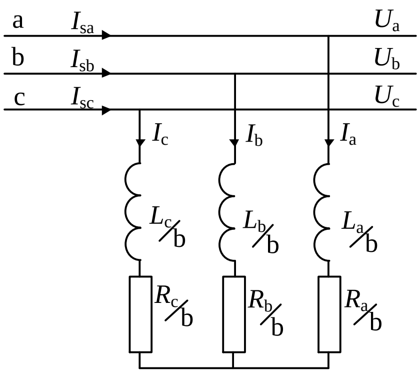

Fig. 2 The simplified equivalent scheme of the TCR

The symbols used are as follows: I_s system current (current drawn from the network), U voltage at 35-kV BUS, and I current through the reactors. When the SVC operates (dynamic conditions) the reactance of the TRC is variable, which can be modelled by a changeable factor b that can take values between 0 and 1. Adding the resistance in series with the reactor is done in order to represent the losses of the TCR. To achieve generality of the system, a per-unit system is adopted, as in the following set of equations:

$$i_1 = \frac{i_a}{i_{ba}}, i_2 = \frac{i_b}{i_{ba}}, i_3 = \frac{i_c}{i_{ba}}, \quad (1)$$

$$u_1 = \frac{U_a}{u_{ba}}, u_2 = \frac{U_b}{u_{ba}}, u_3 = \frac{U_c}{u_{ba}} \quad (2)$$

$$R_1 = \frac{R_a}{Z_{ba}}, R_2 = \frac{R_b}{Z_{ba}}, R_3 = \frac{R_c}{Z_{ba}}, \quad (3)$$

$$L_1 = \frac{\omega_b L_a}{Z_{ba}}, L_2 = \frac{\omega_b L_b}{Z_{ba}}, L_3 = \frac{\omega_b L_c}{Z_{ba}}, Z_{ba} = \frac{u_{ba}}{i_{ba}} \quad (4)$$

4. Controller design

From Fig. 2 it is clear that changing the value of the factor b influences the value of I. Reducing the fluctuations or achieving some desired values of I can be achieved by a suitable value of the factor b. For a value of 0 for parameter b the current of the TCR is equal to 0, while for a value of 1 for parameter b the current of the TCR is equal to 1 p.u.

Fig. 3 shows the control scheme for the basic idea of the design P regulator of the TCR in the d-q rotating coordinate system, which is synchronized to the 35-kV voltage level. The proportional-integral (PI) controllers in this scheme are only used to set up the reference for the major P regulator. When the regulator operates, only one of these two PI regulators is used for the set-up reference, depending on which regulator does the regulating (voltage regulation, reactive-power (flicker) compensation). Q and U_{RMS} represent the instantaneous values of the reactive power and the voltage at a low voltage level for a 110/35-kV transformer.

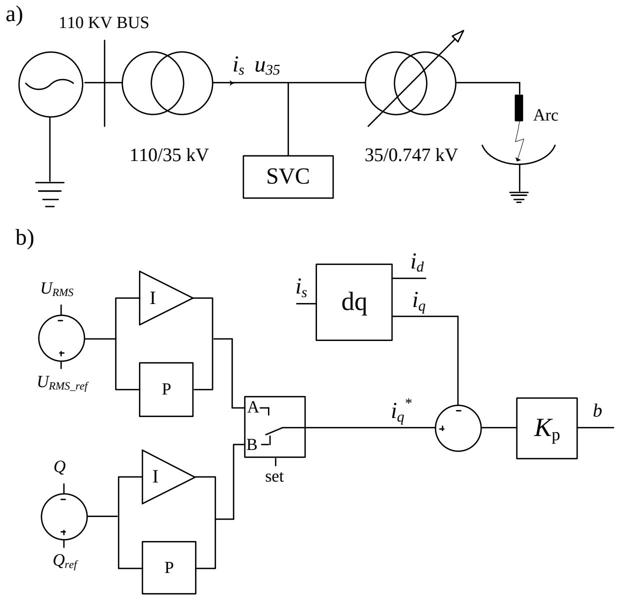

Fig. 3 Basic idea for design control algorithm, a) system configuration; b) control scheme

5. The system configuration

The SVC control system proposed in this paper has been applied in a realistic model of a steel factory in Jesenice. In Fig. 8 a simplified, single-line scheme of the steel plant's network under investigation is shown. In this system, the EAF is modelled as described in [2].

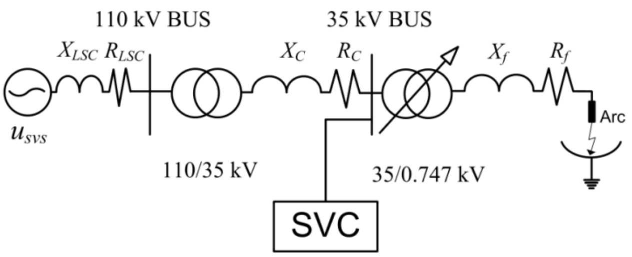

Fig. 3 Single-line scheme of the plant network

The network model involves a high-voltage network equivalent with its short-circuit reactance (X_{LSC}) and resistance (R_{LSC}), a 110/35-kV transformer substation, the resistance (R_C) and reactance (X_C) of the cable line between the substation and the furnace transformer, the 35/0.4-kV furnace transformer and reactance (X_f) and the resistance (R_f) of the cable line between the furnace transformer and the furnace electrodes. The values of these parameters are shown in Table I and correspond to the actual parameters of the steel plant. The short-circuit power (S''_{sc}) at the 110-kV bus equals 3750 MVA. The SVC device on the 35-kV voltage level of the steel plant's network is connected. The parameters of the SVC are shown in Table II.

Table I Values of the parameters of the model shown in Fig. 1

Component	Parameter	Value
HV network equivalent	S''_{sc}	3200 MVA
	u_n	110 kV
Tr 110/35	S_{tr1}	100 MVA
	u_{ntr1}	110/ 35 kV
	u_{ktr1}	11 %
Tr 35/0.747	S_{tr2}	80 MVA
	u_{ntr2}	35/0.7473 kV
	u_{ktr2}	6.135 %
short-circuit reactance	X_{LSC}	3.93 Ω
short-circuit resistance	R_{LSC}	0.44 Ω
cable resistance	R_C	$1.48 \cdot 10^{-4}$ Ω
cable reactance	X_C	$32.35 \cdot 10^{-4}$ Ω
fur. cable resistance	R_f	$3.51 \cdot 10^{-4}$ Ω
fur. cable reactance	X_f	0.28 Ω

Table II Parameters of SVC

Component	Parameter	Value
reactor	L_{SVC}	0.102 H
resistor	R_{SVC}	32.04 Ω
filter 2. harmonic	FC_{2H}	35 MVAr
filter 3. harmonic	FC_{3H}	35 MVAr
filter 4. harmonic	FC_{4H}	35 MVAr

The parameters of the P and PI controllers used in the simulations are given in Table II. The value of K is selected in such a way that the maximum flicker compensation achieved, while the parameters of the PI controller are chosen in such a way as to achieve the first-order response of the system.

Table III Parameters of regulators

Regulator	Parameter	Value
P	K_p	1.25
PI	K_p	0.1
	T_i	1 s

6. The simulation results

First, the simulation of the realistic model of the steel factory without the SVC, i.e., the operation of the furnace directly connected to a high-voltage grid, was carried out. The waveforms of the simulated signals' active and reactive powers are shown in Fig. 5. The negative impacts (fluctuations in the active and reactive powers) of the EAF on the electric power system can be clearly seen from the figure. Oscillations of the active and reactive powers, as well as the quantity of the reactive power that is withdrawn from the power system, are at an unacceptably high level. The numerical values of these signals and the flicker levels are listed in Table IV.

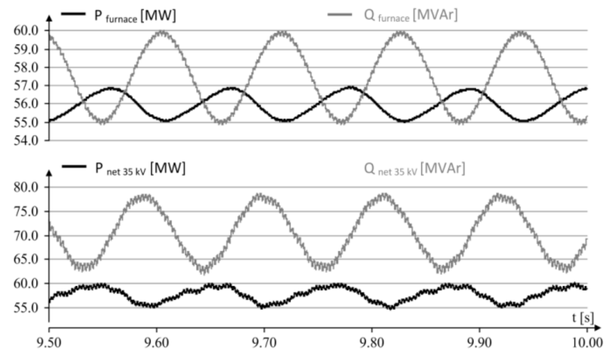

Fig. 4 Simulated signals of active and reactive power without SVC

Table IV

Without SVC				
U_{35} = 1 p.u.	P [MW]	Q [MVAr]	cosφ	Flicker
Network	57.67	81.11	0.587	1.54
Furnace	56.01	57.49	0.697	
Lost [%]	2.88	18.71		

Fig. 6 shows the rms voltage fluctuations in p.u. at the 35-kV voltage level without the connected SVC. The figure clearly shows the oscillations of the RMS voltage values that cause the appearance of flicker in the electric power system.

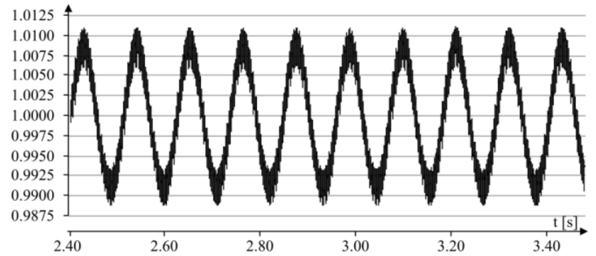

Fig. 5 Fluctuations of rms voltage at 35-kV voltage level

Afterwards, the simulation of the realistic model of the steel factory with the SVC connected at the 35-kV voltage level was made. First, the case when the SVC operates in reactive-power compensation mode was simulated. Waveforms of the simulated signals of the active and reactive power can be seen in Fig. 7, while Fig. 8 shows the rms voltage fluctuations in p.u. at the 35-kV voltage level with the connected SVC. In Table V the numerical values of these signals and the flicker level for full load are listed. For the period t<6 s the furnace operates with full load. Based on Fig. 7, it can be concluded that the negative effects of the EAF on the power system using the SVC can be reduced to one acceptable level, i.e., they are minimized. If we compare Fig. 5 and 7, it is clear that the oscillations and the quantity of reactive power that the EAF withdraws from the network are considerably less in the case when the SVC is connected. As a result of minor fluctuations in the reactive power, there are fewer fluctuations of the rms voltage value and consequently a lower level of flicker generated in the power system. The voltage waveforms at the 35-kV voltage level with a connected SVC in p.u. are shown in Fig. 8.

At the moment t=6 s the load of the furnace is changed, but it does not have a major impact on the proper operation of the regulator. The controller continues to minimize the negative effects generated by the furnace.

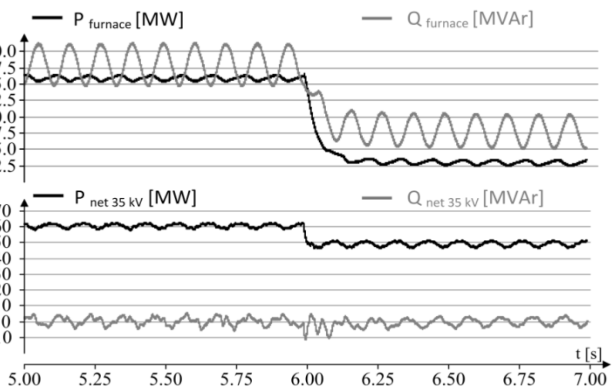

Fig. 6 Simulated signals of active and reactive power with connected SVC

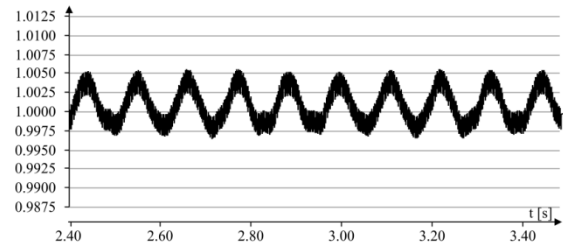

Fig. 7 Fluctuations of rms voltage at 35-kV voltage level with connected SVC

Table V Simulated values with connected SVC for period t<6 s

With SVC				
U_{35} = 1 p.u.	P [MW]	Q [MVAr]	cosφ	Flicker
Network	61.02	≈0.00	0.996	0.498
Furnace	55.95	58.04	0.694	
Lost [%]	8.30	18.71		

Changes in the values of the angle ignition thyristors are shown in Fig. 9.

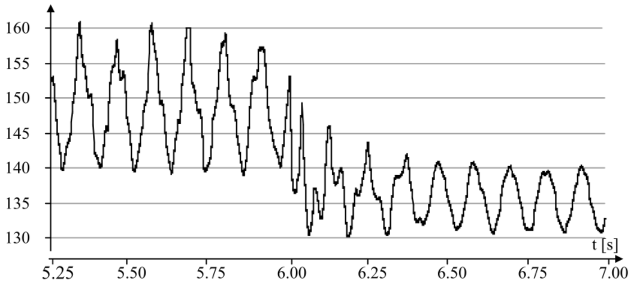

Fig. 8 Angle of tyristors ignition

Finally, the case when the SVC operates in voltage-regulation mode was simulated. For the period t<6 s the furnace operates with full nominal load. Fig. 10 shows the rms voltage fluctuation in this case. At the moment t=6 s the load of the furnace is changed and, as a consequence of the reduced load, there is an increase in the voltage. Fig. 10 shows that the regulator, after a short period, sets the value of the voltage to the desired value. In this case to 1 p.u.

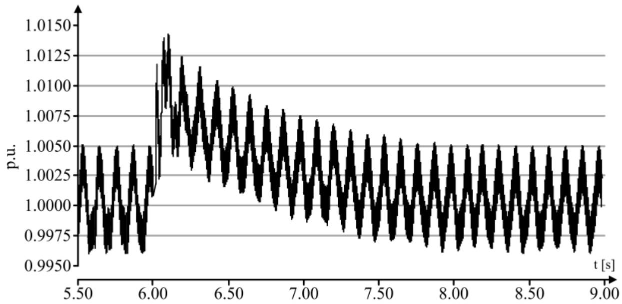

Fig. 9 Fluctuations of rms voltage at 35-kV voltage level with the connected SVC, voltage regulation

7. Conclusion

In this article the development and implementation of a regulator in the feedback-loop strategy for an industrial SVC is presented. The feedback loop ensures good characteristics in both the dynamic and steady states of the SVC operation. Based on the transfer function of the model, the controller has been designed in the DQ frame and also a complete stability analysis of the system was made. Using simulations on a real model of the industrial network the proposed regulator was validated. The simulated results are shown for the proposed model of the controller and can be successfully used to compensate for the reactive power, a reduction of the flicker level or voltage regulation. The main advantage of this proposed regulator is that its implementation requires only one place for the online measurement. One place for the measuring means a lower price for the installation and exploitation of the system, which in combination with the good dynamics and static characteristics of the working makes it very convenient to use. The control algorithm proposed in this paper can also be applied to other types of FACTS, such as a STATCOM or a thyristor-controlled series compensator.

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