EVALUATION OF SOLUTIONS FOR FLICKER MITIGATION IN THE SLOVENIAN TRANSMISSION NETWORK

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ABSTRACT

This paper presents the results of a study which aim was to provide solutions for flicker mitigation in a large part of the Slovenian transmission network. Flicker is mainly caused by two 36 MVA arc furnaces in the area. First, extensive power quality measurements have been carried out to evaluate flicker levels and its spreading. Next, a simulation model was developed in PSCAD and different solutions for flicker compensation were tested, including network changes and the use of a static-var compensator (SVC) and static compensator (STATCOM). A set of recommendations is provided as a result.

INTRODUCTION

In the Slovenian transmission network flicker is the main power quality problem. The main sources of flicker are three large arc furnaces. Flicker distortion spreads easily to medium-voltage (MV) and low-voltage (LV) levels, still exceeding the value of 1 and is the cause for several customer complaints.

This paper presents the results of a research which was aimed at finding a solution of the flicker problem in a large part of the Slovenian transmission network, where two out of three large arc-furnaces are connected. Extensive power quality measurements in the high-voltage (HV) and medium-voltage (MV) network (at 11 sites) have been carried out. Next, the Slovenian transmission network model was constructed in PSCAD, including arc-furnace non-linear models and a flicker-meter model. The simulated network was calibrated using measurement results. For flicker mitigation various solutions were evaluated:

- system solutions (changes in network topology and elements),
- installation of a series inductor and
- compensation with a SVC or STATCOM.

Compensator models were constructed base on the current state-of-the-art and solutions that are commercially available and commonly used. Based on the simulations results solutions are proposed at the end.

NETWORK DESCRIPTION

The power system under research represents a large part of the Slovenian transmission network covering an area of approx. 3500 km^2. The investigated power system includes 110 kV, 220 kV and 400 kV voltage levels. Several generating units, including hydro power plants (HPP), thermal power plants (TPP) and a nuclear power plant (NPP), are connected on HV levels. The total installed power of the power plants in the area is more than 2100 MVA. In the area there are two larger arc furnaces with a nominal power of around 36 MVA each. The furnaces are part of ironworks Štore and Ravne which are connected at different parts of the observed network. The fault levels (at 110 kV) are around 1400 MVA for Ravne and around 3700 MVA for Štore. There is also a smaller arc furnace connected in the area (nominal power of 4 MVA) but its effect on flicker is small. The simplified single-phase diagram of the observed power system is shown in Fig. 1. The points where measurement equipment was connected and also flicker levels were measured are denoted with MP followed by a number.

FLICKER MEASUREMENTS

The main sources of flicker in the Slovenian transmission network are large arc furnaces at Jesenice, Štore and Ravne ironworks. While Jesenice is geographically and electrically reasonably far from Štore and Ravne, the later two are closer together. The research project which is presented in this paper was started to evaluate possible solutions for the flicker problem in the Ravne-Štore area. The first step of the research was a one-week power quality measurements carried out according to the 50160 standard [1]. Eleven synchronized power quality recorders were used. Nine were connected at 110 kV and two were connected at the point of arc-furnaces connection to factories MV networks. The aim of measurements was to identify flicker levels in the area, to evaluate contributions of individual arc furnace to flicker and to evaluate the influence of different network operating conditions (generators operation, network configuration etc.). Within measurements arc-furnaces operation was varying, different HV connections were switched on and off and some HPP were connected to and disconnected from the network.

Measurements results

Measurement revealed that high flicker values are virtually the only problem in the observed transmission network area. In large network parts the flicker limit value of 1 (as defined by EN 50160) is exceeded. Although the standard is aimed at MV and LV networks it can be adapted also for use in HV networks. After all, it is difficult to maintain flicker bellow 1 in MV and LV networks if this value is exceeded at transmission level.

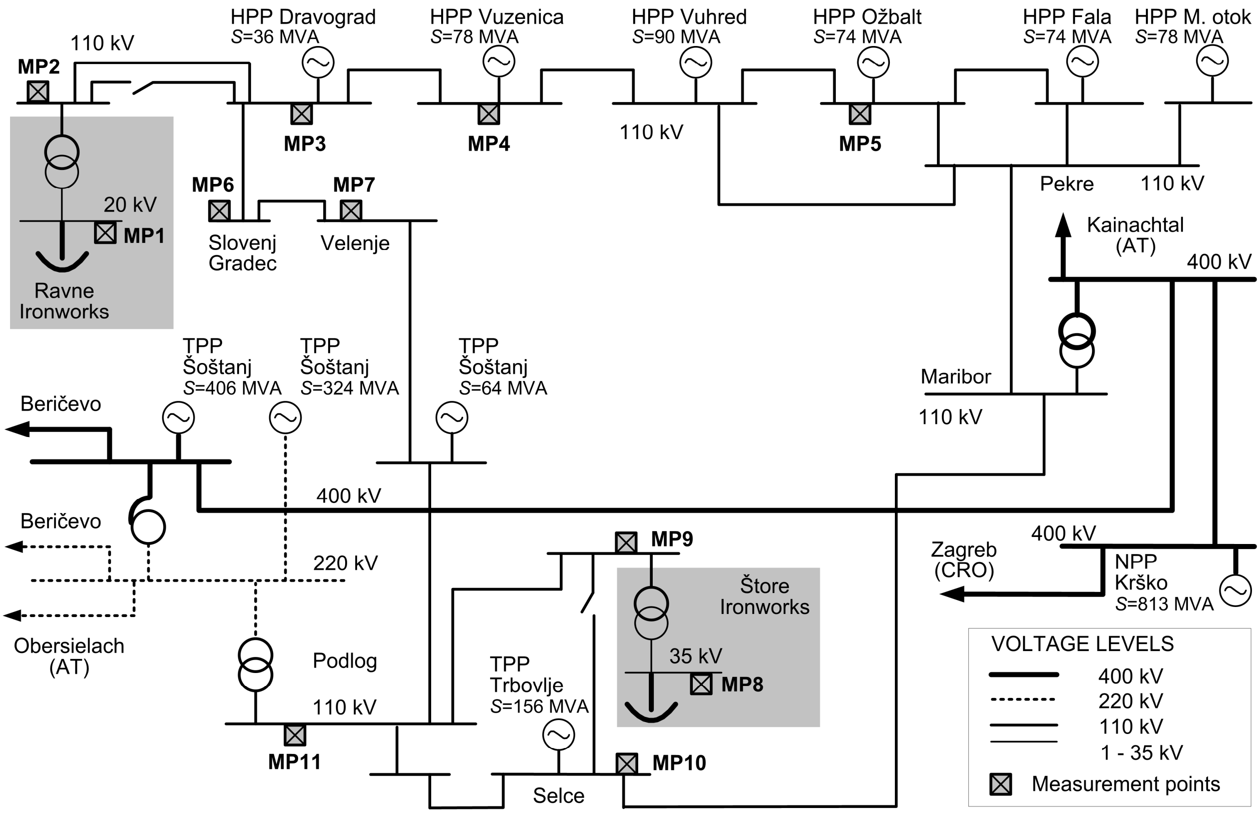

Figure 1: Simplified single-phase diagram of the observed part of the Slovenian transmission network

Measurements results which are given in Table 1 (column 'Measurements') show flicker values (at all measurement points) recorded at the same time within the measurements week. At that time the network was operating in a typical configuration and both arc furnaces were in operation. The results are given as a range of values because flicker is different in each phase. Measurements confirmed that arc furnaces at Ravne and Štore are the predominant flicker sources in the area, while the contribution of other sources (e.g. arc furnace at Vuzenica) is minor. Measurement also showed that the Podlog substation is a point of strong voltage support. As a consequence Ravne ironworks has limited influence on flicker levels at Štore location and vice versa. However, flicker in the network depends upon the contribution of both furnaces. The impact of power generators on voltage fluctuations and therefore flicker depends upon their regulation system. As Ravne and Štore ironworks are connected to the HV network with different fault levels, their contribution to flicker is different despite similar arc-furnace nominal power.

FLICKER MITIGATION

The measures for flicker mitigation can be divided in two groups. The first one includes changes in network structure and network elements, while the second comprises compensation devices, capable of compensation of the fluctuating reactive power at its source.

The flicker at the HV arc-furnace connection point can be reduced if the network impedance is decreased (stronger network) or if the impedance between the HV point and the arc furnace is increased (series inductor installation). Network changes may have a strong influence on arc furnace operation, which must be taken into account. For example, a series inductor lowers the arc-furnace voltage and therefore its maximum size is limited by the desired arc-furnace power and by the maximum available secondary voltage of the arc-furnace transformer.

On the other hand, compensators such as SVC and STATCOM can deal with the flicker problem at its source – the variable flow of reactive power. If the fluctuating part of reactive power is compensated the arc furnace draws a more constant power from the source, causing less voltage amplitude variations and therefore less flicker. A more stable voltage at the point of common coupling also enables a more efficient arc-furnace operation.

NETWORK SIMULATION MODEL

The simulation model of the investigated transmission network was implemented in PSCAD. Beside the basic network elements a non-linear arc-furnace model and IEC-based flicker-meter model were also developed. For flicker compensation SVC and STATCOM models were developed. The newly developed models are briefly described below.

As the main objective of the study is flicker, it was established that a satisfactory representation of consumer load dynamics can be achieved with correct modelling of the two 36 MVA arc furnaces. All other connected consumers were modelled as linear loads.

Arc-furnace and flicker-meter

The non-linear behaviour of an arc furnace is caused by the non-linear *U-I* characteristics [2], [3] of the electric arc that can be described with the following equation:

$$U_a(I_a) = k(t)\left(U_{at0} + \frac{C}{D + I_a}\right) \quad (1)$$

where U_a is the voltage across the arc, I_a is the current of the arc, U_{at0} is the voltage across the arc at reference arc-length and C and D are constants which determine the *U-I* characteristics. With *k(t)* the time dependence of the arc length is simulated. A deterministic approach was used for the description of the arc length variation (sinusoidal length variation). According to [2] the sinusoidal arc-length variation represents the worst-case approximation of furnace operation.

To evaluate different compensation approaches a flicker-meter was developed according to the EN 61000-4-15 standard [4]. The deterministic approach to arc length variation simplifies the structure of the flicker-meter while there is no need for statistical data evaluation. The functioning of the flicker-meter model was validated with sinusoidal and square wave signals of different frequencies and amplitudes with the output ranging from 0.95 to 1.05 [5]. The model provided correct flicker values in the frequency range between 2.5 and 22 Hz for a sinusoidal signal and between 4.5 and 20 Hz for a square wave signal.

SVC and STATCOM

SVC and STATCOM enable control of reactive power [6]. The SVC (Fig. 2) is composed of fixed capacitors (FC) and a controllable device, i.e. the thyristor-controlled reactor (TCR). The main building block of a STATCOM is a voltage-source converter (VSC) and enables supply of inductive and capacitive reactive power. Fixed capacitors are connected in parallel with STATCOM and provide constant reactive power (Fig. 3). Fixed capacitors are tuned for different harmonic frequencies. Both compensators are connected in parallel with the arc furnace at the MV level. The modelled SVC is composed of a six-pulse TCR (rated power 45 MVAr) and FCs tuned at 100 Hz, 141 Hz and 190 Hz (total rated power 45 MVAr). Therefore the SVC has a reactive power control range of 0 – 45 MVAr. STATCOM is a conventional three-phase VSC composed of IGBT's with a dc-capacitor on the dc-bus. The converter is shunt connected to the network through a coupling reactance. Firing pulses are generated by means of pulse-width modulation (PWM). The STATCOM is rated at 22.5 MVA and FCs are tuned at 5100 Hz, 100 Hz and 141 Hz (total rated power 22.5 MVAr). The STATCOM has therefore the same control range as the SVC, namely 0 – 45 MVAr. Both compensators were rated to compensate the total ironworks reactive power.

SIMULATION RESULTS

The complete network model and the arc-furnace models were first calibrated according to network conditions and measurements results at the defined date and time during measurements. The arc furnace at Ravne operated roughly at P = 26 MW and Q = 22 MVAr, while the arc furnace at Štore operated at P = 22 MW and Q = 19 MVAr. The obtained flicker levels are shown in Table 1 in column 'Simulation'. The simulation results agree quite well with measurements. Next, several solutions for flicker mitigation were analyzed.

Within system solutions several viable means for increasing the fault level at the location Ravne were analyzed. Various alternatives were considered with the aim to decrease the line impedance between substation Podlog and Ravne including the construction of a new 110 kV or 220 kV line. Also the construction of TPP at Ravne (running on natural gas, nominal power 100 MVA) was considered. However, simulations showed that a maximum 25 – 30 % flicker reduction can be achieved at Ravne (at 110 kV).

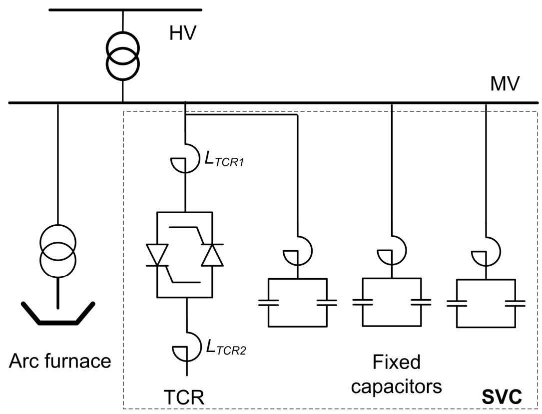

Figure 2: Basic SVC circuit

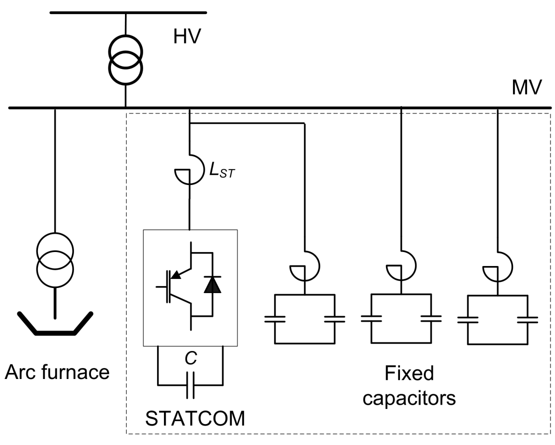

Figure 3: Basic STATCOM circuit

Substation	Voltage level	Flicker P_{lt} Measurements	Flicker P_{lt} Simulation	Flicker P_{lt} Case 1	Flicker P_{lt} Case 2	Flicker P_{lt} Case 3
Ravne ironworks (MP1)	20 kV	8.5 – 10.5	10.7	8.6	2.5	2.4
Ravne ironworks (MP2)	110 kV	2.1 – 2.5	2.4	1.8	1.0	0.8
HPP Dravograd (MP3)	110 kV	1.5 – 1.8	1.6	1.2	0.8	0.7
Vuzenica (MP4)	110 kV	1.0 – 1.3	1.3	1.0	0.7	0.6
Ožbalt (MP5)	110 kV	0.6 – 0.7	0.8	0.6	0.5	0.4
Slovenj Gradec (MP6)	110 kV	1.0 – 1.3	1.3	1.0	0.8	0.7
Velenje (MP7)	110 kV	0.8 – 1.1	1.1	0.8	0.9	0.7
Štore ironworks (MP8)	35 kV	6.6 – 7.5	7.5	6.1	7.5	6.1
Štore ironworks (MP9)	110 kV	1.0 – 1.3	1.2	0.9	1.0	0.7
Selce (MP10)	110 kV	0.9 – 1.1	1.2	0.9	1.0	0.7
Podlog (MP11)	110 kV	0.8 – 1.1	1.1	0.8	0.8	0.6

Table 1: Measurement and simulation results at selected measurement points

Beside that, a new 110 kV power line causes a flicker increase at Podlog of approximately 30 %. A better solution would be the construction of a 220 kV line, which does not cause flicker increase at 110 kV substations. On the other hand, the construction of such line is hardly feasible. There are also limited options to increase the fault level at Štore which already has a reasonably high fault level of 3700 MVA.

The next tested option was the installation of a series inductor. The maximum size of the inductor was determined so that the current steel production could be maintained. Therefore the highest secondary voltage of the arc-furnace transformer was used. This allowed installing a series inductor of 8 MVA at Ravne (at 20 kV level) and 8.5 MVA at Štore (at 35 kV level). In both cases the flicker at the 110 kV level reduces for approx. 25 %. The results with inductors installed at both arc furnaces are shown in Table 1, column 'Case 1'. Such approach would successfully lower the flicker at Štore below 1, but at Ravne the levels are still very high.

The effect of SVC and STATCOM on flicker compensation was evaluated next. Simulations showed that the six-pulse SVC and the PWM STATCOM enable to lower flicker roughly by half (SVC) and by four times (STATCOM). A 12-pulse SVC would give better results than a 6-pulse device, but at a significantly higher price. Results in Table 1, column 'Case2', give flicker levels for the case with a STATCOM installed at Ravne and without any changes at Štore. As simulations showed, installation of a STATCOM at Ravne ironworks is probably the only solution which allows sufficient reduction of flicker in that area. At Štore a series inductor could do the job. A better and dearer solution is a SVC which also enables dynamic control of reactive power. The results in Table 1, column 'Case3', show flicker levels for the case with a STATCOM at Ravne and the series inductor at Štore. It is clear that price plays an important role when selecting mitigation options. Costs for a series inductor are almost negligible when compared to SVC cost and a STATCOM price is probably at least twice the price of a 6-pulse SVC.

CONCLUSIONS

Various solutions for flicker mitigation in a large part of the Slovenian transmission network were tested by means of simulation. The flicker is mainly caused by two 36 MVA arc furnaces. System solutions have proven to be ineffective and also difficult to realize. At one arc-furnace site (Štore) the installation of a series inductor would allow lowering the flicker to an acceptable level and still enable to maintain the arc-furnace nominal power. However, at the other site (Ravne) with substantially lower network fault level, the installation of a STATCOM is probably the only effective solution. Based on the findings in the study, actions have already started to implement the proposed solutions at Ravne ironworks.

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