STATCOM, an efficient means for flicker mitigation

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Abstract: Flicker, annoying light intensity fluctuations, is a power quality problem caused by large time-varying loads like arc furnaces. State-of-the-art technology to reduce this kind of disturbances has so far been mainly the Static Var Compensator (SVC) which however has a limited flicker mitigation capability. With the availability of forced-commutated components, a STATCOM becomes possible to be used as an efficient means to reduce voltage fluctuations causing flicker. In the paper, an arc furnace installation with a STATCOM is modeled dynamically both as a digital computer model in the program EMTDC as well as in a low-power analog real-time model. Flicker mitigation studies using an ideally optimal control algorithm for the STATCOM have been performed. In the algorithm, fluctuations in imaginary and real current are considered as well as fluctuations in the real current time derivative. The flicker reduction is demonstrated in the digital model and validated with the analog model.

Keywords: flicker, mitigation, SVC, STATCOM, arc furnace, simulation, analog model

I. INTRODUCTION

Power quality has during recent years achieved an increasing interest. The concept power quality includes the quality of the supplying voltage with respect to for instance interruptions, voltage dips, harmonics and flicker [1].

A. Flicker

Flicker is understood to be the sensation that is experienced by humans when subjected to changes in the illumination intensity. The human maximum sensitivity to *illumination* changes is in the frequency range from about 5 to 15 Hz. The fluctuating illumination is caused by amplitude modulation of the feeding alternating voltage.

Large industrial loads, such as electric arc furnaces, used for melting for example scrap with electric energy, cause voltage distortion like harmonics and voltage fluctuation in the feeding AC system. An arc furnace is probably one of the largest existing end-users of electric energy with a rated power up to the order of 100 MVA. The arc furnace is a very non-linear load and a large source for flicker [2]. To limit the effects of these disturbing loads, compensation devices have usually to be connected.

B. State-of-the-art flicker mitigation

The most used device for compensation of arc furnaces is the Static Var Compensator (SVC) [3]. A major advantage is that reactive power supplied by the SVC increases the steel production. However, due to the operation with switching at fundamental frequency, conventional SVC:s have disadvantages such as relatively long response time and the possibility to only compensate for the fundamental frequency reactive current of the load. This limits the possibilities to reduce flicker with an SVC. Further, an SVC also introduces harmonics, and therefore it has to be combined with a passive filter bank.

Flicker mitigation devices can also be connected in series with the arc furnace [4]. However, in this paper only a unit connected in parallel will be treated.

II. STUDIED SYSTEM

An arc furnace installation mostly consists of a large arc furnace used for melting scrap and a smaller ladle furnace used for the refining of the steel. The large arc furnace is creating the major part of the flicker problems. Usually the installation also contains some kind of compensating equipment to reduce the line disturbances caused by the furnace operation. The disturbances from the arc furnace are transferred to other users of electric energy via the Point of Common Connection, PCC. The voltage fluctuations causing flicker are then spread in the grid from the PCC with very low damping. Fig. 1 shows a single line diagram of the studied three-phase model [5].

The system has been simplified such that the model contains only the large arc furnace. At the top of Fig. 1, the grid with a nominal short circuit power of 3600 MVA is shown. Two transformers, T_1 and T_2, are included. T_1 (S_{N1}=2x65 MVA, x_{T1}=11/2 %) is the transformer supplying power to the arc furnace bus. The nominal voltage on the bus between T_1 and T_2 is 31,5 kV. T_2 (S_{N2}=100 MVA, x_{T2}=8 %)

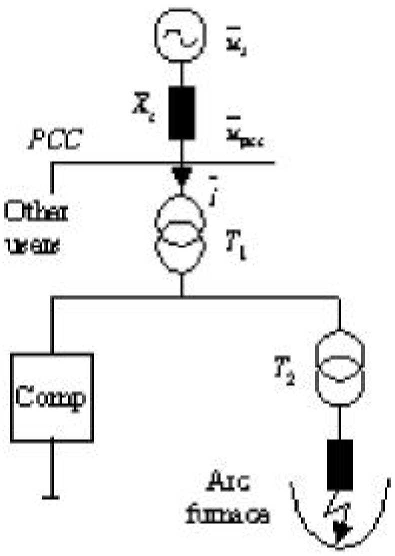

Fig. 1. A typical arc furnace installation.

is the furnace transformer. The system has been simulated in the program EMTDC [6].

The block "Comp" connected to the bus voltage is the compensating device used. In this paper, a Pulse Width Modulated (PWM) STATic COMpensator (STATCOM), comprising a voltage source converter in combination with a passive filter bank, will be used for compensation of reactive power and for flicker mitigation. Its performance regarding flicker mitigation will be compared with that of an SVC. Fig. 2 presents the main circuit of the STATCOM used, the filter is not shown. It is a so called three level or Neutral Point Clamped (NPC) converter. In this study, it is operated with a switching frequency of 1 kHz. The rating of the STATCOM is 60 MVA.

The arc furnace will be modeled first as a time-varying resistance and later by using a more physical model by incorporating the Cassie equation [7] for the electric arc given as

$$\frac{dR_{arc}}{dt} = \frac{R_{arc}}{q}\left(1 - \frac{u_{arc}^2}{U_{ARC}^2}\right). \tag{1}$$

R_{arc} is the resistance of the electric arc, q is the deionizing time constant of the arc. u_{arc} is the instantaneous arc voltage and U_{ARC} is the arc voltage for very high currents. In the model, an arc length modulation is also included. This is implemented in (1) by setting U_{ARC} as a time-varying value. The arc length modulation consists of a noise source with a realistic spectrum.

III. THE FLICKER METER

To be able to measure the level of flicker, a meter is needed. There are different standards existing describing flicker meters. The flicker meter used in this paper is the one described by the International Electrotechnical Commission, IEC [8], sometimes referred to as the PST meter. "ST" stands for short time, which in this case refers to measurements during 10 minutes. Unity output from the PST meter corresponds to a flicker level causing 50 % of the persons in a reference group to be disturbed by the flicker. In the PST meter, the measured voltage is filtered. The filter is selected to emulate the transfer function of the human eye and a 60 W 230 V bulb. Fig. 3 shows the transfer function of the filter for the illumination fluctuations. The maximum sensitivity for illumination fluctuations is found at 8.8 Hz. Slower fluctuations are not that annoying and faster fluctuations are "smoothed" by the brain. Calculating flicker according to the norm requires measurements during at least 10 minutes. This is highly impractical in digital computer simulations and can therefore not be made. Instead, the maximum of the instantaneous flicker level is used here [9]. Applying real measured data to this algorithm will give a too high PST value. If the arc furnace model used in the simulations is adjusted to create an actual measured PST level using this method, the proposed procedure can be used.

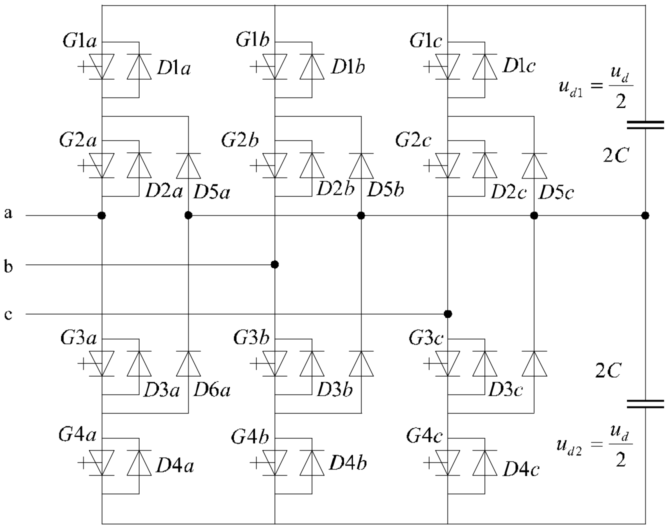

Fig. 2. Main circuit of the STATCOM (AC filters not included).

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Fig. 3. Transfer function of the flicker meter filter.

This works well since the same case will be run for comparison of the performance of different flicker mitigation means.

To evaluate the possibilities for different flicker mitigation schemes, an initial level for the PST is needed. Based on experience, knowledge of the furnace type and network short circuit power, the uncompensated flicker level in the PCC was estimated at PST=3,8.

IV. CONTROL STRATEGY

Traditionally, mainly fluctuations in reactive power of a load have been considered to cause flicker since a fluctuating voltage drop occurs across the reactance of the grid. This is basically true, but the flicker generation is more complicated [10].

For control studies, the system was transferred into the dq frame rotating synchronously with the alternating voltage. The more general concepts for real and imaginary power proposed by Akagi et. al. [11] were used to study the instantaneous electrical properties. Through this theory, the arc furnace current was split up in one real component, i_p, in phase with the instantaneous voltage and one imaginary component, i_q, perpendicular to the voltage. With a dynamic calculation, it was found [12] that the voltage fluctuations in the PCC were caused by three different components; the imaginary current, the real current and the derivative of the real current. By using a flicker mitigating unit without energy storage, it is however not possible to directly compensate for the fluctuations in the active load power. If the compensator current i_C instead is set up as

$$\bar{i}_C = j\left(i_q + i_p \frac{R}{X} f(q) + \frac{1}{w} \frac{di_p}{dt} f(q) + K \right), \qquad (2)$$

the voltage fluctuations in the PCC would ideally be nullified. R and X are the resistance and the reactance of the grid respectively. ω is the synchronous line frequency and $f(q)$ is a correction factor due to the phase shift across transformer T1. $f(q)$ can be approximated as

$$f(q) \approx 1 + \left(\frac{R}{X} + \frac{X}{R} \right) X_{T1} I \ , \qquad (3)$$

where X_{T1} is the reactance of transformer T1. The term K is used to give zero reactive power in average from the grid. To reduce the noise sensitivity of the derivative operation, it has to be preceded by a low-pass filter. Equation (2) basically describes an overcompensation of reactive power by a flicker mitigating unit. This can be done without any large energy storage in the flicker mitigating unit.

Using low pass filters on measured values to reduce the disturbances from switching ripple also gives a phase shift that has to be taken into account. By subtracting the filter phase shift at 50 Hz from the PLL (Phase-Locked Loop) argument used in the transformation from the alpha/beta frame to dq frame, zero-error is obtained for fundamental frequency signals [13].

V. DIGITAL SIMULATIONS

Digital simulations employing the algorithm in (1) have been carried out. The STATCOM has then been represented in two ways. First with an ideal current source without any delays. Then with a model of its real main circuit with filter, semiconductors and the capacitive DC side.

The first investigation was performed with the ideal current source as a model of the STATCOM. With the arc furnace represented as a constant resistance added to a sinusiodally varied resistance per phase, the flicker mitigation performance was investigated. In table 1, the flicker for four different cases is shown. The influence and importance on flicker mitigation of each of the terms in (2) can be seen in the table.

The results in table 1 verifies the theory for flicker mitigation. With an infinitely fast compensator and a smooth load, almost no flicker remains, PST=0.03 is negligible. Next, the experience from investigations on the other STATCOM model are given.

A STATCOM model as in Fig. 2 was used to mitigate flicker caused by an arc furnace modeled using (1). To emulate a digital control system of the STATCOM, Zero-Order Hold (ZOH) blocks were used on all the measured signals. A sampling rate of twice the frequency of the PWM carrier was then implemented. Table 2 shows the obtained flicker values with this model. Both sinusoidal and random arc length modulation have been investigated.

With sinusoidal arc length modulation, using only the imaginary current alone or in combination with the real current gives only half the reduction compared with the idealized model. With the aid of the real current time derivative, the flicker level is practically reduced to zero. As a comparison, the flicker level obtained with an SVC is given. It has been controlled to compensate reactive power and current unbalances. The STATCOM is, according to Table 2, superior to the SVC with respect to flicker mitigation.

With random arc length modulation, the influence of the derivative term in the flicker mitigation algorithm is lower. Due to the filter preceding the derivative calculation, the flicker mitigation performance has degraded since the high frequency content in the arc furnace current now has increased

TABLE 1
FLICKER WITH IDEALIZED STATCOM MODEL AND RESISTIVE ARC FURNACE MODEL WITH SINUSOIDAL RESISTANCE VARIATION. DIGITAL COMPUTER MODEL.

Compensation strategy	PST
No mitigation means	3.8

Compensation of imaginary current	0.53
Real current also considered	0.33
Imag. and real current, including derivative	0.03

TABLE 2
FLICKER WITH FULL STATCOM MODEL AND DYNAMIC ARC FURNACE MODEL USING SINUSOIDAL AND RANDOM ARC LENGTH MODULATION. DIGITAL COMPUTER MODEL.

Arc length modulation	Compensation strategy	PST
Sinusoidal	Comp. of imaginary current	1.1
	Real current also considered	0.7
	Imag and real current, including derivative	0.04
	SVC	2,2
Random	Comp. of imaginary current	1.4
	Real current also considered	0.8
	Imag and real current, including derivative	0.65
	SVC	2,4

VI. ANALOG SIMULATIONS

A low-power analog hardware model, or simulator, was built and used to investigate the flicker mitigation algorithms in a real-time system. Simulations in the analog model gives confidence to the results obtained in the digital simulations since the simulation environment often is closer to a real circuit.

A. The analog model

The analog model operates in real time with an analog main circuit and a digital control system based on DSP (Digital Signal Processor) circuit boards.. The used control circuitry is based on the MOTOROLA 6500X processor.

Studies with analog models are quiet common in investigations of this type. In the study performed here, a voltage level of 10 volts is used in contrast to the usual rather high voltage around 100 V commonly used. A low voltage level however calls for special action to be taken. Special attention has to be given to reduce the influence of resistance in the circuit. There is a loss compensation unit connected to reduce the largest resistance in the circuit.

Modeling an arc furnace in a real-time system has usually been done in the way that recorded data has been played back from a recording unit through analog power amplifiers [14]. This works well for analysis of recorded data but is less suitable for studies involving new equipment used for e.g. reactive power compensation or flicker mitigation. In reality, there will be a feedback impact on the arc furnace due to the operation of for instance a STATCOM controlled to mitigate flicker. This connection is not possible to implement if the method with recorded data is used. In the analog model study performed here, the arc furnace has been modeled as in the digital simulation, that is with differential equations for the current and voltage of the arc. With this method, the action of the STATCOM directly influences the arc furnace model since its behavior is based on measured properties in the system.

B. Flicker mitigation.

Two methods of arc length modulation were used; sinusoidal and random. Compensation of the imaginary current was implemented in the analog model. Also the influence on flicker from compensation concerning the real current was investigated. In Table 3, the flicker values obtained in the analog model are given. The trend in the results from the analog model is the same as in the results from the digital simulations. By compensating the imaginary current, a substantial part of the flicker is reduced. If also the real current is considered through overcompensation of the imaginary current, the flicker levels are further reduced.

TABLE 3
FLICKER IN THE ANALOG MODEL USING SINUSOIDAL AND RANDOM ARC LENGTH MODULATION

Arc length modulation	Compensation method	PST
Sinusoidal	Imaginary current	1.5
	Imaginary and real currents	1.1
Random	Imaginary current	1.7
	Imaginary and real currents	1.3

Due to the difference in the nature of the two models, there is still a difference in the flicker results. In the analog model, the resistive part of the grid model is relatively higher than in the digital model since the grid impedance has been realized physically at a low voltage level. This gives a higher contribution to flicker from fluctuations in real current which is seen as a higher flicker level in the analog model when just compensating for the imaginary current. Table 4 gives a comparative overview of the flicker mitigation results with the two models.

Other probable reasons to the differing results are losses in the STATCOM and delays that have not been properly modeled in the digital system. The varying STATCOM

TABLE 4
COMPARISON BETWEEN FLICKER MITIGATION IN THE DIGITAL COMPUTER MODEL AND THE ANALOG MODEL

Arc length modulation	Compensation method	PST Digital model	PST Analog model

Sinusoidal	Imaginary current	1.1	1.5
	Imaginary and real currents	0.7	1.1
Random	Imaginary current	1.4	1.7
	Imaginary and real currents	0.8	1.3

current also gives an additional real current fluctuation corresponding to the losses. This current component is not accounted for when the STATCOM current setpoints are calculated. Due to this, the incorporation of the arc furnace real current in the flicker mitigation algorithm gives a lower flicker improvement in the analog model.

VII. CONCLUSIONS

The paper describes mitigation of flicker from incandescent lamps, by means of a STATCOM. Not only fluctuations in imaginary current give rise to flicker. Also the fluctuations in the real current and its derivative will cause flicker due to a resistive voltage drop in the grid.

The time-fluctuating voltage phase shift across the transformer feeding the arc furnace bus has to be considered during selection of definition directions for transformations between fixed and rotating frames. This has been analyzed and a useful algorithm incorporating the phase shift has been proposed for flicker mitigation.

By incorporating a circuit for calculation of the time derivative, the flicker mitigation performance of the algorithm was strongly improved. This was shown with a computer simulation of a simplified circuit. With a more complete and realistic model, however, the improvement was not that high since the derivative calculation had to be preceded by a low pass filter to avoid noisy signals. The signal delays caused by the filter are the main reasons for the detrimental effect on the flicker mitigation.

In the investigations performed here, the flicker, as indicated by the PST (flicker) value of the PCC (Point of Common Connection) voltage, was initially set to 3,8. With a STATCOM and a control algorithm incorporating all the earlier mentioned factors, a PST equal to 0,65 could be reached in the digital simulations. This corresponds to a PST decrease of more than 80 percent or a reduction factor larger than 5. Implementation of the suggested algorithm requires good knowledge of the grid impedance to work well. In case the grid changes, some of the control system parameters have to be updated.

An analog low-power model operating in real-time was built to compare the results obtained in the digital simulations. Two of the flicker mitigation algorithms were implemented in the analog model, namely compensation of imaginary load current and over-compensation of imaginary current involving also the real current of the load. The qualitative results in both the digital and analog simulation environments were equal. The absolute flicker levels were however lower in the digital simulations. Among the reasons to the differences are the higher resistive content of the impedances in the analog model, losses in the STATCOM model and delays that were not modeled in the digital simulations.

VIII. ACKNOWLEDGMENTS

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X. BIOGRAPHIES

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