VOLTAGE FLICKER SEVERITY IMPROVEMENT IN A POWER DISTRIBUTION SYSTEM INCLUDING ELECTRIC ARC FURNACES

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ABSTRACT

Modelling of the three phase electric arc furnace and its voltage flicker mitigation is the purpose of this paper. The arc furnace model is implemented referring to an actual electric plant installed in Mobarakeh, Isfahan, Iran. For modelling of the electric arc furnace, at first, the arc is modeled using current-voltage characteristics of a real arc, i.e., the arc current samples as inputs and their corresponding voltages as outputs in the equivalent circuit of the furnace and its supply system. Then, the arc random characteristic has been taken into account by modulating the ac voltage by a band limited white noise. Electric arc furnace compensation with static VAr compensator, Thyristor controlled reactor combined with a fixed capacitor bank (TCR/FC), is discussed for closed loop control of the compensator. Instantaneous flicker sensation curves, before and after accomplishing compensation, are measured based on IEC standard. In closed loop control, two different approaches are considered; the former is based on voltage regulation at the point of common coupling (PCC) and the later is based on enhancement of power factor at PCC. A new method for controlling TCR/FC compensator is proposed. This method is based on applying a predictive method with closed loop control of the TCR/FC. In this method, by using the previous samples of the load reactive power, the future values of the load reactive power are predicted in order to consider the time delay in compensator control.

I. INTRODUCTION

Electric arc furnaces (EAFs) are the largest concentrated loads in the power systems. The most important problems about EAF operation is voltage flicker propagation, harmonic injection and severe unbalances between phases. Because of the random motion of the electric arc, just as arc length varies during melting process, severe oscillation in supply circuit is being occurred. When this variation is bounded in 1-30Hz, flicker can occur. In addition, because of the interaction of time delay in arc creation and the arc severe nonlinear v-i characteristic, harmonics and inter-harmonics can be created. Nonlinear, time-variant and random nature of EAFs operation beside high electric energy consumption of these loads, are caused researchers to pay special attention to analyze these loads.

In 1998, J. Jatskevich et al. worked on adaptive VAr compensator (AVC) which was installed to reduce flicker. The model also includes a simulation of the UIE/IEC flicker meter to determine the effectiveness of the AVC in an objective manner [1]. In 2000, A. Garcia-Cerrada et al. worked on performance of the Thyristor-controlled reactors in comparison with shunt-connected PWM voltage source inverter (PWM-VSI) for compensation of flicker caused by electric arc furnaces. An improved measuring procedure was suggested to enhance TCR performance that it achieves faster compensation more than traditional methods [2]. In 2003, A. Hernandez et al. evaluated flicker magnitudes of rapidly varying loads by means of a new frequency domain method and analytical expressions of the instantaneous flicker sensation were obtained in terms of interharmonic voltages [3] and in 2005, S. Prins et al. presented a solution for how to obtain an optimum flicker reduction at a comparatively low capacity compensator power rating by an anti-windup extension of the controller [4].

In this paper by using the measured arc voltage and currents-to describe the arc electrical behavior-and by applying software, a practical model of EAF based on random variables is proposed. Then, voltage flicker, springs from its operation, is compensated using static VAr compensator. A proposed method for TCR/FC control is also suggested. This method is based on applying a predictive method beside the TCR/FC closed-loop control. Although, this new approach is not completely able to compensate the flicker intensity, it can suppress flicker level much better than conventional methods.

II. ELECTRIC ARC FURNACE MODELLING

In this investigation, we try to propose a method to model EAFs that contains random behavior of the arc and has minimum error compared with actual arc model. This means that for a special EAF, by sampling arc current in each stage of EAF operation such as scrap, melting and refining, we obtain the arc model. Thus, after sampling ac current in each stage of furnace operation, applying a program, arc is modeled as a current controlled voltage source. Corresponding to the input current that is the arc current, arc voltage is obtained by interpolating based on previous samples. According to random behavior of the arc and the fact that in this paper we want to lay stress on this property, in order to model arc random nature, a band limited white noise based on existing frequency band in flicker, is generated and obtained voltage is modulated by the white noise [5]. The preference of this model to the others is that this model is based on actual samples obtained from EAF. Therefore, this model has a behavior close to the actual arc. Simulation result for arc model, with including flicker noise, is shown in Fig. 1. The whole power system diagram is also shown in Fig. 2.

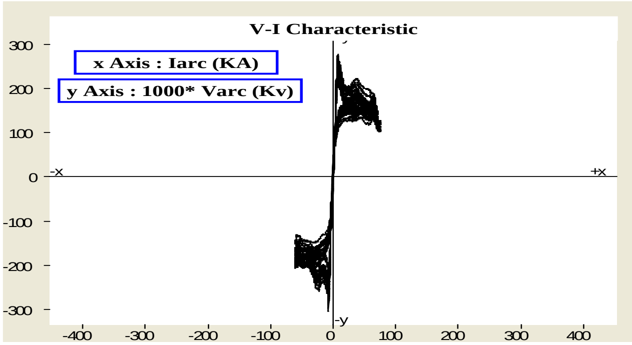


Fig. 1. V-I characteristic of the electric arc, considering flicker

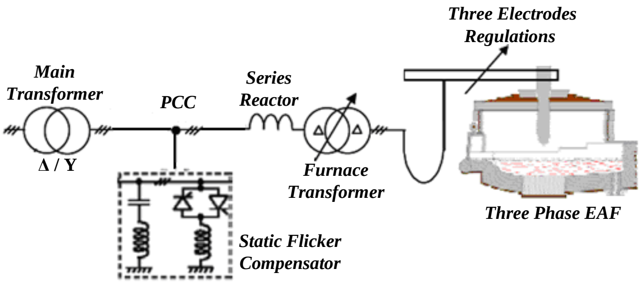


Fig. 2. The equivalent circuit of the EAF with TCR/FC compensator

III. Closed loop control of the TCR/FC compensator using voltage regulator approach

In closed loop control of the TCR/FC compensator, a voltage error that is the difference between actual voltage and exerting reference voltage to the compensator, is measured. This error is applied for increasing or decreasing the susceptance of the compensator [5]. Fig. 3 shows the compensator system block diagram using voltage regulation approach.

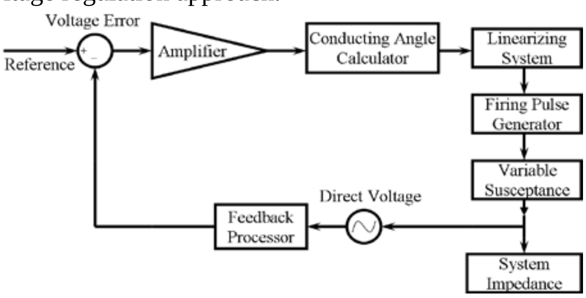


Fig. 3. Compensator based on closed loop control system using voltage regulation approach block diagram [5]

In Fig. 3, set of linearizing blocks, firing pulse generator and variable susceptance are the same as in open loop system and parallel to their operation, determined exerting firing angle applied to the TCR Thyristors. The firing angle difference ($\Delta\alpha$) with respect to the open loop firing angle ($\alpha_{Open-Loop}$) is calculated based on the ideas followed in Fig. 4. At first, for a fundamental reactive power demand, $\alpha_{Open-Loop}$ is estimated. Then, according to the Fig. 4, $\Delta\alpha$ is evaluated. Finally, closed loop firing angle (α_{TOT}) is calculated.

Fig. 4. $\Delta\alpha$ Calculation in voltage regulation approach

IV. Closed loop control of the TCR/FC compensator using power factor enhancement approach

In this method by calculating the firing angle variation that can make the whole power factor closer to the desired power factor, and exert it on the firing angle obtained from the open loop control system, enhances the whole power factor.

In this section, at first, the actual power factor at PCC is obtained and then it is compared with the desired power factor. At the next step, by varying the TCR firing angle, we cause actual power factor to be close to the desired one. With acceptable approximation, it can be seen that measured power factor at PCC, is arisen from phase difference between fundamental component of arc voltage and current, fundamental component of filter voltage and current and TCR voltage and current. In this approximation, the harmonic effects in calculation of the phase difference between voltage and current of the arc and filters are neglected. But this simplification is not applied to TCR. We suppose that the total phase difference between TCR voltage and current by considering the harmonic effects is β. Phase difference between arc voltage and current fundamental components depends on system nature and we cannot vary it. But we can vary the phase difference between TCR voltage and current by changing the switching strategies. Therefore, by setting the TCR switching pattern, we can make actual power factor close to the desired one. For this purpose, we will obtain β in two states. At the first state, β is obtained from the actual measured power factor and at the second state, β is obtained from the desired reference power factor, respectively. The difference in these two states is calculated and exerted on TCR firing angle. In fact, by applying this approach, β reaches to the desired β. Consequently, power factor enhancement is expected. Assuming that the phase difference between arc voltage and current fundamental component is ϕ_1^+ and the one for the filter is δ_1^+, then, Equation (1) can be written approximately as follows:

$$PF \approx Cos(\beta + \phi_1^+ + \delta_1^+) \qquad (1)$$

Consequently β angle can be obtained from Equation (2):

$$\beta \approx Cos^{-1}(PF) - \phi_1^+ - \delta_1^+ \qquad (2)$$

It can be proved that β is approximately equal to 90°, if voltage of each phase of the TCR is considered to have sinusoidal form. By applying Fourier series to the current waveform, according to Equation (3) only cosine terms are appeared. Consequently the phase difference is approximately equal to 90°.

$$i(t) = \sum_{n=1,3,5,...}^{\infty} a_n Cosn\omega t \qquad (3)$$

In continuation, for each phase, β is calculated separately for two different conditions. One is actual measured power factor and another one is desired reference power factor. By using the difference of the β in these two states and passing $\Delta\beta$ through a PI controller, $\Delta\alpha$ value can be obtained for each phase of the TCR. The firing angle difference ($\Delta\alpha$) is calculated based on the ideas followed in Fig. 5.

It can be seen in Fig. 6 that power factor is improved after exerting $\Delta\alpha$, i.e., closed loop control based on controlling power factor.

V. Applying a predictive method in closed loop control of TCR/FC compensator

The ability of the static VAr compensator (SVC) to mitigate the flicker intensity depends on their reaction speed. The speed of these compensators is limited by delay in measurements and thyristors firing angle circuits [6]. In this paper by applying a predictive method to compensate the delay time, enhancement of the compensator performance is achieved. In this method by using the previous values of the load reactive power, its future values are predicted. To reduce the negative effects of the time delay, we try to estimate the load reactive power in future times. Predicted values are used to compensate the delay time as a reference for static compensator. Reactive power estimation is accomplished using previous values of the reactive power [6].

A. Improving compensator performance with estimating load reactive power in future times [6]

To reduce the negative effects of the time delay, we try to estimate the load reactive power in future times. Predicted values are used to compensate the delay time as a reference for static compensator. Reactive power estimation is accomplished using previous sample values of the reactive power. The Laplace transform of the lead time T prediction function can be written as,

$$e^{ST} \cong \sum_{n=0}^{M} k_n e^{-nST_1} \qquad (4)$$

The optimum coefficients are found by minimizing the following error function [6],

$$F = \int_{\omega_1 T}^{\omega_2 T} \left| e^{j\omega T} - \sum_{n=0}^{M} k_n e^{-jn\omega T_1} \right|^2 d\omega T \, . \qquad (5)$$

In which ω_1 and ω_2 values depend on compensation frequency range. They are chosen in a manner that the frequency of the signal that we want to shift it to the left in time domain, should locate between them. Therefore, the following set of equations needs to be solved to find the optimum coefficients [6].

$$\frac{\partial F}{\partial k_0} = 0, \frac{\partial F}{\partial k_1} = 0, ..., \frac{\partial F}{\partial k_M} = 0. \qquad (6)$$

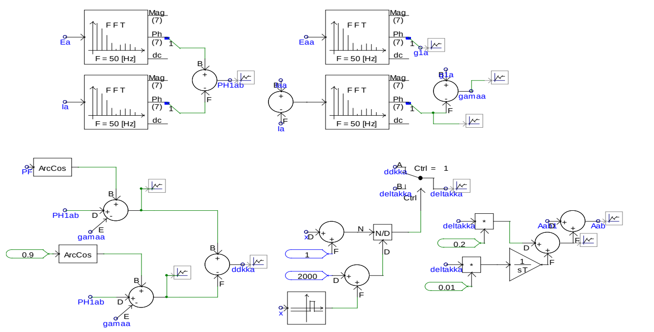


Fig. 5. $\Delta\alpha$ Calculation in power factor enhancement approach

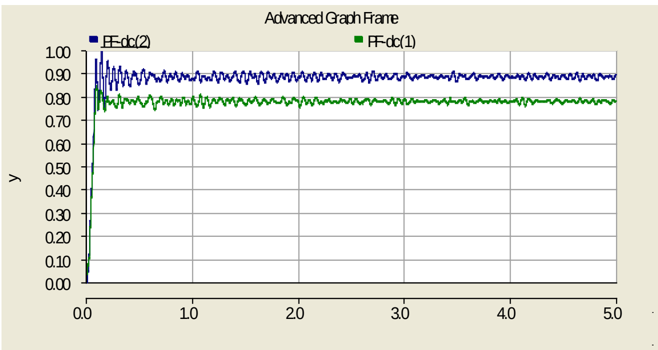
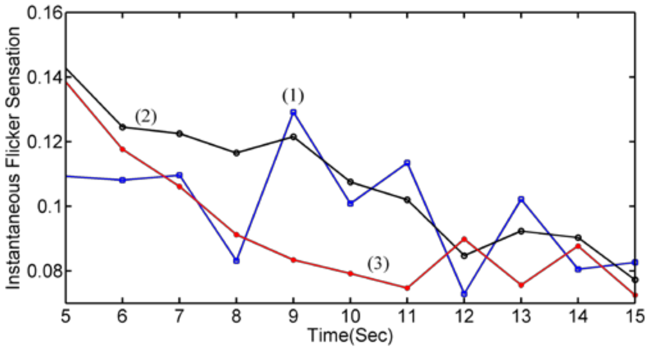


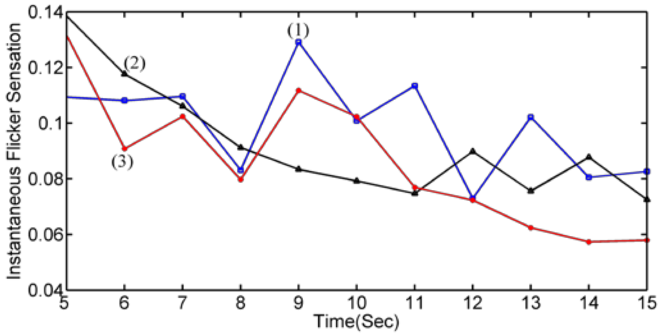
Fig. 6. Comparison the power factor average value before (lower curve) and after (upper curve) exerting $\Delta\alpha$

VI. Applying IEC flickermeter

After exerting predictive method on closed loop control method, using voltage regulation approach, voltage flicker intensity at PCC was evaluated. Fig. 7 shows a comparison between the results of three strategies. In Fig. 7a, 1 is dedicated to before compensation, 2 is the obtained curve after closed loop compensation using voltage regulation approach and the last one, 3, is the obtained curve after exerting predictive method on closed loop compensation using voltage regulation approach and In Fig. 7b, 1 is dedicated to before compensation, 2 is the obtained curve after exerting predictive method on closed loop compensation using voltage regulation approach and the last one, 3, is the obtained curve after exerting predictive method on closed loop compensation using power factor enhancement approach. We find that flicker intensity is decreased perceptibly by using predictive method. These analyses are carried out based on the IEC flickermeter 61000 which is shown in Fig. 8 and the detailed evaluation of one case is brought in the appendix I and II for further clarifications. Furthermore, the Pst values related to Fig. 7, are demonstrated in the appendix III from t=1sec to t=5sec.



(a)



(b)

Fig. 7. A comparison between obtained curves in three strategies

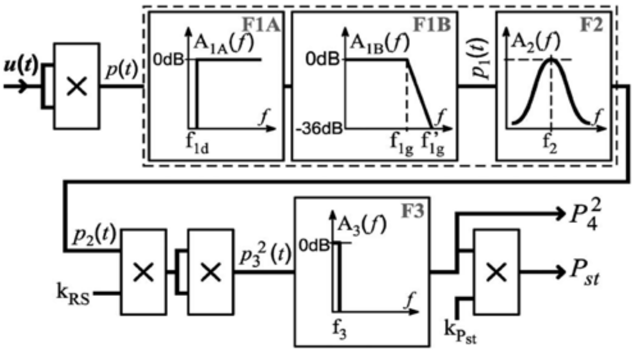


Fig. 8. IEC Flickermeter block diagram [7]

VII. Conclusion

Arc model in this paper is gotten from sampling arc currents and their corresponding voltages and then modulating arc voltage by a band limited white noise. This model can cover an actual arc characteristic. With due to the different methods in measurement of fundamental component of reactive power in polluted and unbalanced systems, it is shown that the one of the best method for reactive power measurement in these systems is instantaneous measurement. In this paper, a proposed method for TCR/FC control is suggested. This method is based on applying a predictive method with closed loop control of the compensator that can amortize the flicker intensity desirably. This closed loop control is accomplished based on both PCC voltage regulation and power factor corrections.

References

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