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Modelling of three-phase electric arc furnace for estimation of voltage flicker in power transmission network

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ABSTRACT

This paper presents a dynamic model of an electric arc furnace (EAF) developed in Matlab/Simulink environment. Model is based on simulating varying resistance of the electric arc in time-domain while taking into account its stochastic behaviour. The model was applied for estimation of voltage flicker in power transmission network at the point of common coupling caused by operation of EAF. Modelling and simulation of an International Eletrotechnical Commission (IEC) flickermeter were also performed in order to calculate voltage flicker from the simulated EAF voltage. In order to verify the developed EAF model, calculations of voltage flicker were compared to measurements obtained from various operating conditions of the EAF such as boring, melting and refining. Influence of short circuit power and switching operating condition of the transmission network on flicker levels at point of common coupling was investigated.

1. Introduction

Highly nonlinear time-varying loads, such as electric arc furnaces (EAFs), are widely used in the steel-making industry. Due to the process of melting and refining metals, mainly iron in the steel production, the EAF consumes large power which causes significant power quality (PQ) disturbances, such as harmonics and voltage fluctuations on the connected power network [1]. Disturbances produced by EAFs in electrical networks can significantly affect the voltage quality supplied by electrical power companies [2]. An EAF is a non-linear and time-varying load, which gives rise to harmonics, interharmonics and voltage fluctuations (flicker). The cause of harmonics is mainly related to the non-linear *U–I* characteristic of the electric arc, while the voltage fluctuations are due to the arc length changes that occur during the melting of the scrap. The current and voltage harmonic distortion may cause several problems in electric power systems such as premature ageing of equipment, incorrect operation of devices and additional losses in both transmission and distribution networks. The flicker phenomenon causes a physiological uneasiness in vision due to electric lightning flux fluctuations, which are particularly important with incandescent lamps. Therefore, it is of crucial importance to predict the flicker levels when an EAF is connected to a network or when an existing EAF is upgraded. In cases when flicker emission limits are exceeded, mitigation techniques should be considered in order to correct such disturbances. An extensive research which enables practical application of static synchronous compensators for improving PQ in EAF and flicker compensation applications was published in Ref. [3]. Obtaining an accurate model of EAF in time domain is thus important to study the impact of such load on the connected power system. For instance, the flicker assessment of EAF loads has to be calculated to check the compliance with the regulated standards [4,5]. Therefore, it is crucial to model these nonlinear loads for the PQ studies and mitigation designs.

Many models of the *U–I* characteristics have been proposed in the literature for both steady-state or dynamic operation of EAF. In Ref. [6] a controlled voltage source model for the EAF was proposed based on the piecewise linear approximation of the *U–I* characteristic. In Refs. [7,8] nonlinear time-varying resistance models for the EAF were proposed, where the arc length is dominated by periodic sinusoidal and band-limited white noise laws for flicker compensation purpose. In Ref. [9] the conductance model of the EAF for harmonic studies was proposed based on Cassie equation representing the single-phase *U–I* characteristic during refining stage. A time-varying resistance model was proposed in Ref. [10] for studying the early stage of melting cycle where the arc voltage is described by a linear function of arc length in random

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variation. Several chaotic systems were shown in Refs. [11,12] in order to describe the EAF operating behaviour and dynamics. Stochastic approaches were proposed in Refs [13–17], either with or without modelling the linear approximation of the *U–I* characteristic, in order to predict EAF voltage and current relationship in next few cycles or reactive power consumptions for compensation improvement. One of the greatest difficulties of stochastic approaches is prediction and modelling of the EAF stochastic nature, particularly in the initial boring stage of operation. The problem is how to take into account both non-linear and stochastic behaviour of the electric arc for different operation modes of EAF, which is especially important for estimation of voltage flicker levels. Despite the importance of stochastic representation of EAF to achieve real and accurate model in PQ studies, less attention has been paid to it in the literature. Because the arc melting process is a highly non-stationary stochastic phenomenon a deterministic or stochastic model for fully describing the EAF in different operating stages is usually very difficult to obtain.

Many new EAF models such as neural network-based types have been proposed recently. In Ref. [18] an accurate neural-network-based method was proposed for modeling the highly nonlinear *U–I* characteristic of an EAF. The neural-network-based model can be effectively used to assess waveform distortions, voltage fluctuations and performances of reactive power compensation devices associated with the EAF in a power system. Simulation results obtained by using the proposed model were compared with the actual measured data and two other traditional neural network models. It was shown that the proposed method yields favourable performance and can be applied for modelling similar types of non-linear loads for power engineering studies. In Ref. [19] the authors proposed a grey predictor model for the forecast of flicker levels produced by an EAF load. Actual measured data were adopted to implement the predictor model. Test results based on the proposed model were compared with two other neural network methods. It was shown that more accurate forecast is achieved for the flicker prediction based on the proposed method. In Ref. [20] a discrete wavelet transform (DWT) and radial basis function neural network (RBFNN)-based method was proposed for modelling the dynamic *U–I* characteristics of the EAF. The proposed method can also be applied to model other highly nonlinear loads to assess the effectiveness of compensation devices or to perform relative penetration studies. To model the multiple EAF operation stages more precisely, the authors extended the previous research of Ref. [20] by enhancing the model with including convergence check in the RBFNN training phase, an extended look-up table (ELUT) to save the RBFNN parameters (i.e. weights, centers, standard deviations, RMS value of input current data segment), and the criteria for identifying the four EAF operation stages obtained by DWT [21]. However, neural network approach requires significant training so issues such as learning speed, stability, and weight convergence remain as areas of research and comparison of many training algorithms.

Although many research papers described above have been published regarding modelling the EAF this problem still represents a challenging task, especially for PQ studies where accuracy of the model is of crucial importance. Therefore, in this paper a dynamic model of an EAF is proposed taking into account the stochastic behaviour of an electric arc. Model is developed for estimation of voltage flicker levels caused by EAF operation. Parameters describing stochastic behaviour of the electric arc for different operating modes of EAF are determined by matching the simulated short term flicker severity levels with the measured ones. The developed model is applied for estimation of flicker levels in the transmission network in case of different short circuit powers and switching operating conditions. The comparison between measured and calculated flicker values showed good agreement for various EAF operating modes. The aim of proposed approach is to introduce an accurate model of EAF which can be easily derived from field measurements of a particular EAF and applied in case of the flicker levels estimation at the point of common coupling.

This paper is organized as follows. In Section 2, the model of International Eletrotechnical Commission (IEC) flickermeter for estimation of voltage flicker from simulated voltage waveforms is described. The proposed dynamic model of an EAF based on simulating varying resistance of the electric arc in time-domain is elaborated in Section 3 while taking into account its stochastic behaviour. Model is applied for estimation of voltage flicker in the power transmission network. The verification of the developed EAF model is presented in Section 4 by comparing calculation results with measurements of voltage flicker obtained from various EAF operating conditions. In Section 5, proposed EAF model is used for estimation of voltage flicker at point of common coupling for two different switching operation conditions of the transmission network. The conclusions are given in Section 6.

2. Model of IEC flickermeter

In order to determine voltage flicker from simulated voltage waveforms an IEC flickermeter presented in Ref. [22] is modelled in Matlab/M-file. Functional diagram of IEC flickermeter shown in Fig. 1 consists of five blocks: 1 – voltage-adapting circuit scales the mean root-mean square (RMS) value of the input voltage to an internal reference level; 2 – squaring demodulator extracts the voltage fluctuation; 3 – two filters: the first one filters out the DC and residual ripple components of the demodulator output, while the second filter simulates the frequency response to a sinusoidal voltage fluctuation of a lamp and of the human eye; 4 – squaring multiplier to represent the nonlinear visual perception and a first-order low-pass filter with a time constant of 300 ms to represent the built up effect in the brain (the output of this block represents the immediate flicker sensation); 5 – online statistical analysis of the instantaneous flicker level. Flicker severity level indices are calculated both in short term and long term in this block, and the results are displayed. The output of block 5 is divided into suitable subclasses (at least 64 classes) according to the instantaneous flicker level. At first the probability distribution function (PDF) is formed by accumulating the number of elements at each level of the flicker. Afterwards, the cumulative probability function (CPF) is formed by integrating flicker distribution over the flicker range.

Finally, short term flicker severity P_{st} is calculated by using the following expression:

$$P_{st} = \sqrt{\sum_{i=1}^{n} k_i P_i}, \quad (1)$$

where k_i represents the weighting coefficient and P_i represents flicker level exceeded during a particular percent of the observation time. These P_i values were taken from the cumulative distribution curve:

$$P_i = CPF(\eta_i), \quad (2)$$

where η_i is a particular percent of the observation period. At least five points of the CPF should be used while evaluating the short-term flicker severity. All of the weighting coefficients and the corresponding time percentages can be found in Refs. [22,23]. In summary, the flickermeter model has two main parts: 1 – simulation of the response of the lamp-eye-brain chain; 2 – online statistical analysis of the flicker signal and displaying the results. The first task is accomplished by blocks 2–4, while the second task is performed in block 5. More detailed information about the IEC flickermeter can be found in Ref. [22–24].

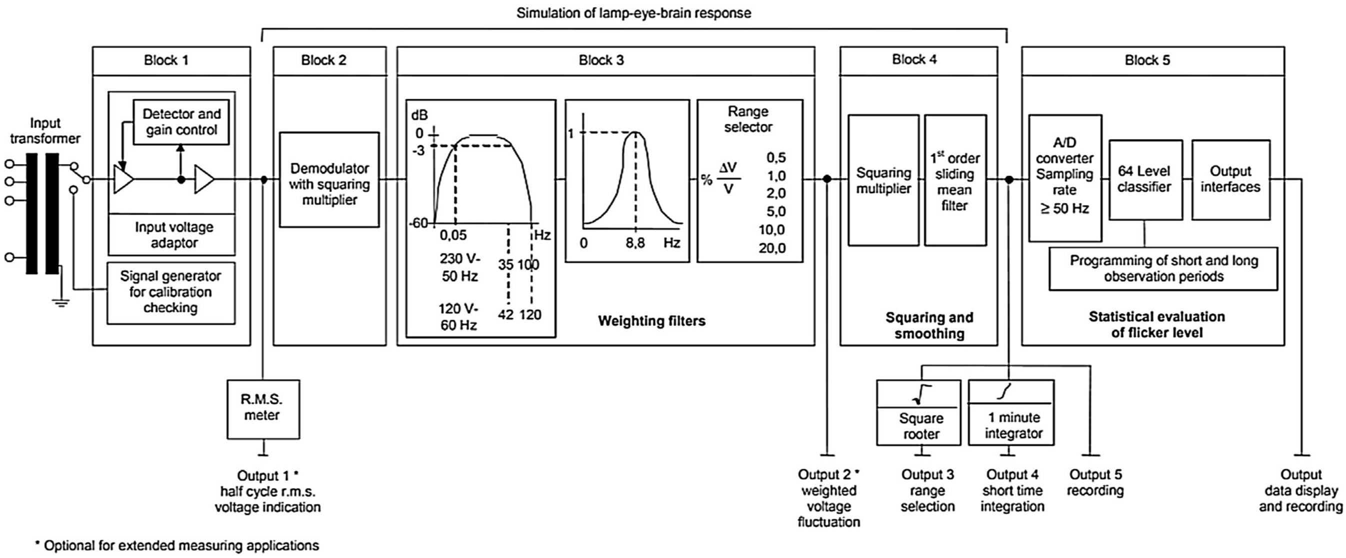

Fig. 1. Functional diagram of IEC flickermeter.

Table 1
Results of flickermeter performance testing.

Changes per minute	Voltage changes $\Delta V/V$ (%)	Calculated P_{st}	Error (%)
1	2.724	0.974	−2.6
2	2.211	0.994	−0.6
7	1.459	1.002	0.2
39	0.906	1.013	1.3
110	0.725	1.004	0.4
1620	0.402	0.987	−1.3
4800	2.40	1.032	3.2

Developed flickermeter model is verified with standard waveforms provided in Ref. [22]. Performance testing of flickermeter considers the frequencies and amplitudes of the seven regular series of rectangular voltage changes for which P_{st} should be 1 ± 0.05. Test signals for 230 V lamp in 50 Hz system and corresponding results that are obtained from flickermeter model are shown in Table 1.

Performance testing results indicated that all errors produced by developed flickermeter model were below error tolerance range of ±5% prescribed by Ref. [22].

3. Model of a substation connecting EAF to power system

The model of a substation in Matlab/Simulink connecting EAF to 110 kV transmission network is shown in Fig. 2.

The EAF with rated power of 28.8 MW is connected to a 33 kV switchyard through EAF transformer 0.7/33 kV. 33 kV switchyard is connected to 110 kV transmission network through power transformer 110/33/6.3 kV. The equivalent 110 kV transmission network is represented with a voltage source in series with sequence impedances, for two different switching states of transmission network characterized by three-phase short circuit current and X/R ratio: (1) I_{sc3} = 14.6 kA, X/R = 5.16; (2) I_{sc3} = 11.1 kA, X/R = 4.88.

Parameters of three-winding three-phase power transformer and two-winding three-phase EAF transformer are shown in Table 2.

Power transformer 110/35 kV is connected to 33 kV switchyard via 50 m long cable (copper 300/25 mm^2) and EAF transformer is connected to 33 kV switchyard via 800 m long cable (aluminium 300/25 mm^2). Power transformers are modelled with three-phase power transformer model in Matlab which takes into account the winding resistances and the leakage inductances, as well as the magnetizing characteristics of the core. Cables are represented by their resistance and reactance. Modelling of substation components including power transformers, cables and network equivalents is performed the same way as shown in numerous references described in the introduction section. For estimation of voltage flicker levels in the power transmission network a crucial component which has to be modelled in detail is EAF. The proposed model of EAF is described in Sections 3.1–3.3.

3.1. Mathematical model of EAF

Different EAF models are described in Refs. [25–28]. Most of them represent dynamic behaviour of electric arc resistance, while some of them also take into account the stochastic behaviour of the electric arc. The main problem is how to take into account both non-linear and stochastic behaviour of the electric arc for different operation modes of EAF, which is especially important for estimation of the voltage flicker levels.

In this paper EAF is modelled as a current controlled non-linear resistance using embedded Matlab function in Simulink Power System. The electric arc current and its derivative are input parameters of the function while the nonlinear time-varying resistance is the output which is connected to the power system through a controlled voltage source. The voltage source is controlled by a nonlinear resistance and the current through it.

Melting process inside EAF can be divided into three parts. In the first part, the electric arc begins to reignite from extinction. In EAF model it is assumed that electric arc current and voltage reach the zero-crossing point at the same time instant. As the arc voltage increases until it reaches the reignition voltage u_{ig}, the equivalent circuit of electric arc behaves as an open circuit. During this period, a small leakage current exists which flows through the foamy slag parallel with the electric arc. It is assumed that a foamy slag has a constant resistance R_g, while the u_{ig} is assumed to be proportional to the length of the electric arc. In the second part, the electric arc is established and a transient appears in the voltage waveform at the beginning of arc melting process. This causes the arc voltage to drop suddenly from u_{ig} to a constant value u_d. This process is described with an exponential function having a time constant τ_1. The arc begins to extinguish in the third part of the melting process. The arc voltage continues to drop smoothly with a sharp change after the arc extinction and this process is described by an exponential

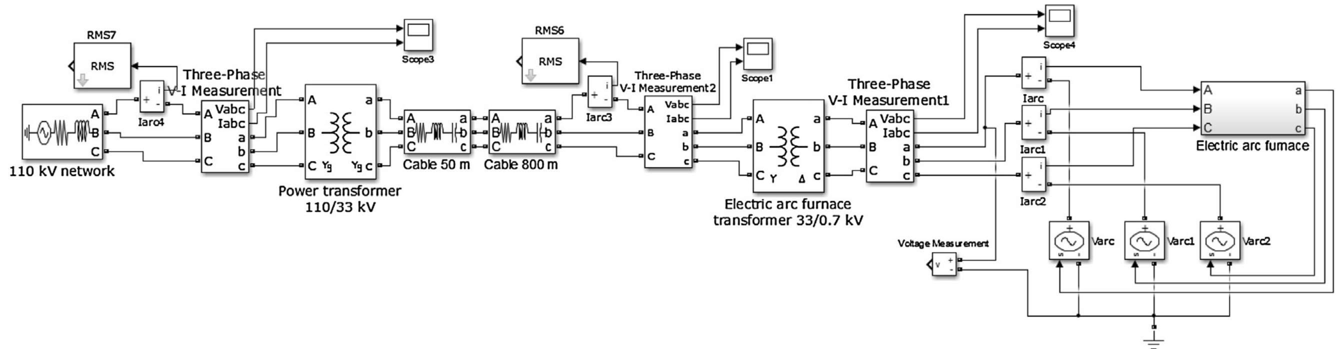

Fig. 2. Model of a substation connecting EAF to 110 kV transmission network in Matlab/Simulink.

Table 2
Parameters of three-winding three-phase power transformer and two-winding three-phase EAF transformer.

	Three-winding three-phase transformer	Two-winding three-phase EAF transformer
Rated power	63 MVA/63 MVA/21 MVA	60 MVA
Rated voltage	$U_{r1}/U_{r2}/U_{r3}$ = 110 kV ± 10 × 1.5%/33 kV/6.3 kV	U_{r1}/U_{r2} = 33 kV/(0.7 kV–0.344 kV)
Rated currents	$I_{n1}/I_{n2}/I_{n3}$ = 330.6 A/1102.2 A/1924.5 A	I_{n1}/I_{n2} = (1050 A–630 A)/(60400 A–49500 A)
Vector group	YNyn0d5	Yd
Short-circuit impedance	$u_{k,1\text{-}2}$ = 13.5%, $u_{k,1\text{-}3}$ = 7.5%	u_k = 13.3–20.6%

function with a time constant τ_2. Non-linear behaviour of electric arc resistance R_a is represented by expressions (3)–(5):

$$R_a = R_g, \quad \text{if} 0 \le I < i_{ig};\ \frac{dI}{dt} > 0\,, \tag{3}$$

$$R_a = \frac{u_d + (u_{ig} - u_d)e^{\frac{-(I - i_{ig})}{\tau_1}}}{I}, \quad \text{if} I \ge i_{ig};\ dI/dt > 0\,, \tag{4}$$

$$R_a = \frac{u_t + (u_{ig} - u_t)e^{\frac{-I}{\tau_2}}}{I + i_{ig}}, \quad \text{if} \frac{dI}{dt} < 0\,, \tag{5}$$

where:

$$I = |i(t)|; \quad u_{ig} = 1.15 u_d; \quad i_{ig} = \frac{u_{ig}}{R_g}; \quad u_t = \left[\frac{I_{max} + i_{ig}}{I_{max}}\right] u_d; \quad \tau_2 = 2 \cdot \tau_1. \tag{6}$$

Dynamic U–I characteristic of EAF obtained using the above expressions is shown in Fig. 3.

3.2. Stochastic behaviour of electric arc furnace

Dynamic EAF model for analysis of voltage flicker should take into account the random nature of electric arc. Highest flicker values can be expected in the period when the length of the electric arc is changing and this corresponds to high-current region of U–I characteristic. In order to take this effect into account the voltage of the EAF U_{eaf} is varied randomly according to sinusoidal variation:

$$U_{eaf}(t) = \alpha U_{eaf}\left(1 + m \sin\left(\omega_f t\right)\right), \tag{7}$$

where m is modulation coefficient, ω_f is flicker frequency and α is a factor that can be adjusted according to the active power of EAF. Modulation coefficient m is varied using the uniform noise generator block which generates uniformly distributed noise between upper and lower bounds, e.g. in the range 0–m_{max}. Ten minutes period of EAF operation is simulated and afterwards calculated voltage is inserted into flickermeter model in order to obtain short term flicker.

3.3. Procedure for estimation of EAF model parameters

Parameters R_g, u_{ig}, u_d, I_{max}, τ_1 and τ_2 which define dynamic U–I characteristic change with load operating conditions of EAF. In order to determine these parameters corresponding to different operating conditions and active power of EAF, a procedure shown in Fig. 4 is performed. At first, a trial and error procedure is performed where parameters of the electric arc are determined in a way to obtain a good matching between calculated and measured active power of EAF (difference less than 1%), and maximum values of current and voltage. Analysis showed that variation of parameter R_g has a significant influence on calculated active power compared to other parameters, since the power consumed by the EAF corresponds to the area under the U–I characteristic. Nevertheless, the selected arc parameters describe only single U–I characteristic for a given active power and EAF operating condition, while the voltage and current responses of real EAF have stochastic behaviour with multiple U–I characteristics. This phenomena is taken into account by applying the modulation coefficient m, which is in the first step determined with regard to measured voltage fluctuations.

However, since EAF voltage fluctuations have a stochastic behaviour over a longer period of time, the final selection of the modulation factor is performed based on difference between measured and calculated P_{st}. Modulation coefficient is changed slightly from the initial value in order to obtain the good matching between measured and calculated P_{st} (difference less than 1%). This part of the procedure is to some extent time consuming because the simulation in time domain requires a longer time period to obtain P_{st}. However, only few iterations are required because the increase of modulation coefficient increases calculated P_{st} value and therefore it is relatively simple to find an acceptable solution. After application of selected modulation coefficient, the calculated mean value of active power is slightly changed and in this case an additional factor α is applied in order to eliminate this effect. Finally, parameters of EAF model for initial boring period of operation are estimated: R_g = 0.05 Ω, u_d = 305 V, u_{ig} = 350.75 V, I_{max} = 100 kA, τ_1 = 0.01 s, τ_2 = 0.02 s, m_{max} = 0.085, α = 1.125.

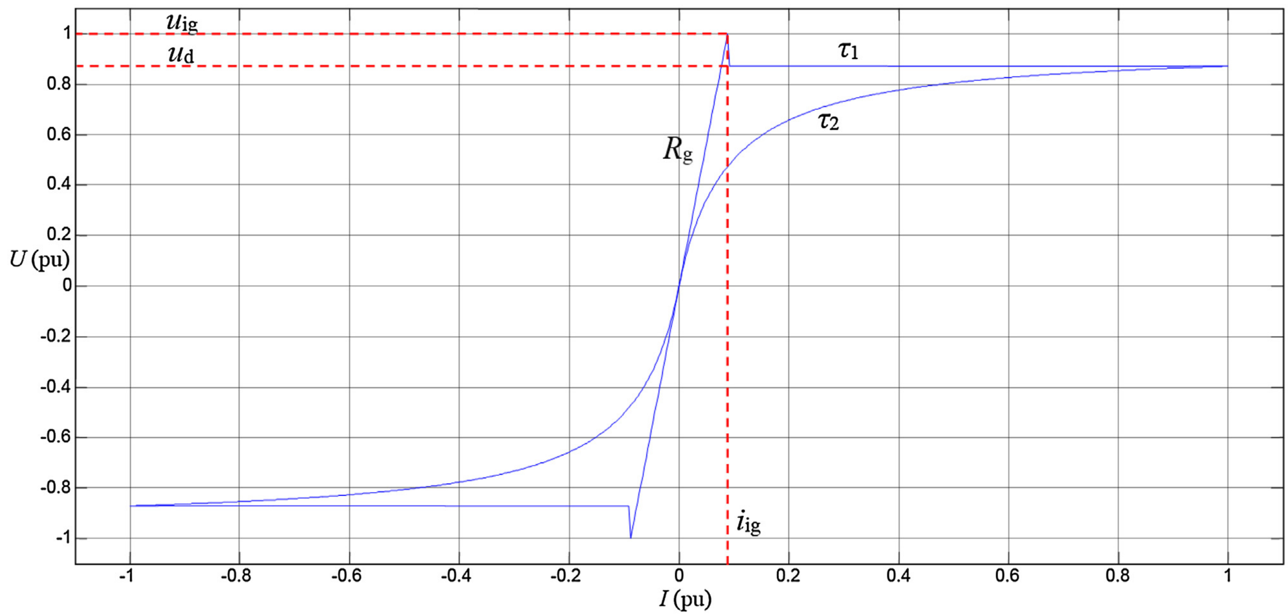

Fig. 3. Dynamic *U–I* characteristic of electric arc.

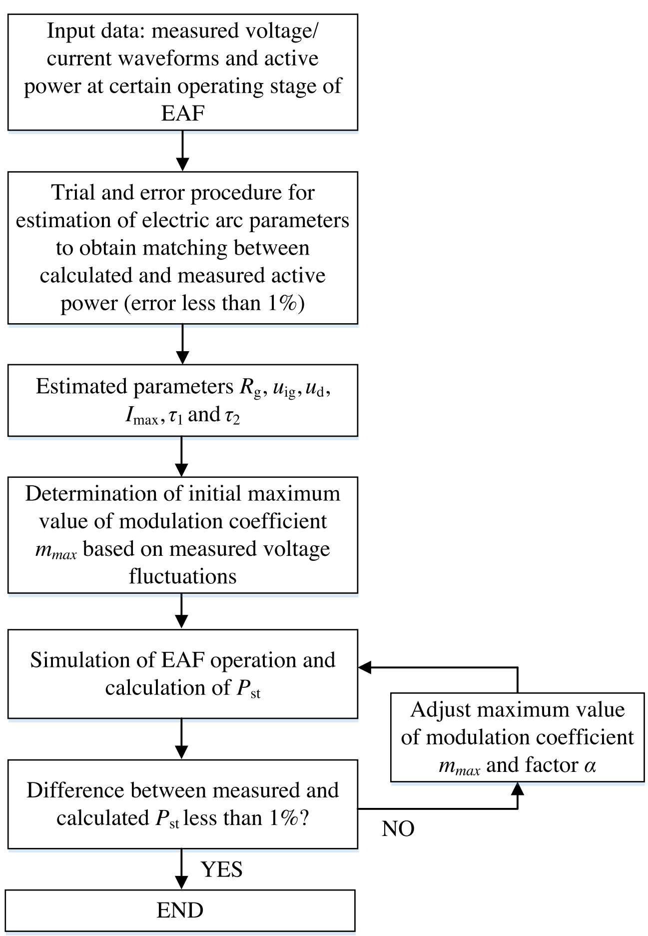

Fig. 4. Procedure for estimation of EAF model parameters.

4. Validation of an EAF model

In order to make an accurate model of EAF for voltage flicker estimation the parameters of EAF model are adjusted according to measurements obtained in 30 min time period covering different modes of EAF operation, e.g. boring, melting and refining.

Table 3
Long term flicker values P_{lt} and short term flicker values P_{st} measured at 110 kV level.

	Phase A	Phase B	Phase C
P_{st} ($\leq$0.8)	1.55	1.54	1.50
P_{lt} ($\leq$0.6)	1.16	1.17	1.15

EAF is connected to 110 kV voltage level, through 110/33 kV transformer with rated power 63 MVA. Measurement points inside 110/33 kV substation are shown in Fig. 5.

Measurements are performed with PQ analysers Power Logic ION 7650 and Dewetron DEWE 571. ION 7650 has 5 current and 4 voltage inputs while Dewetron DEWE 571 has 4 current and 4 voltage inputs. Both instruments can measure RMS values of voltage and current, flicker, dips, interruptions and other PQ parameters. They also have the ability to record voltage and current waveforms.

Among many nonlinear loads, EAF used for steel production are a one of the main causes of voltage distortion in electrical networks, which may give rise to the harmonics, interharmonics, load imbalance and flicker effect. Different conventional compensation systems have been used such as passive filters to mitigate harmonics. The EAF described in this paper has compensation devices (that are also designed as 3rd and 4th passive harmonic filters) connected to the 33 kV side of transformer. The limitation of passive filters for compensating complex problems such as non-integer harmonics and flicker has made active filters attractive. Shunt active filters using traditional control methods have successfully been used to compensate for basic PQ problems such as current harmonics, reactive power and load imbalance. PQ measurements performed at 110 kV level during the time period of seven days according to Refs. [4,5] showed that all PQ parameters are within the limits except voltage flicker values (Table 3).

This is the reason why flicker problem was investigated in this paper in detail.

Measured RMS values of voltage and current in phase A at 33 kV level of EAF transformer are shown in Figs. 6 and Fig. 7 for 30 min period.

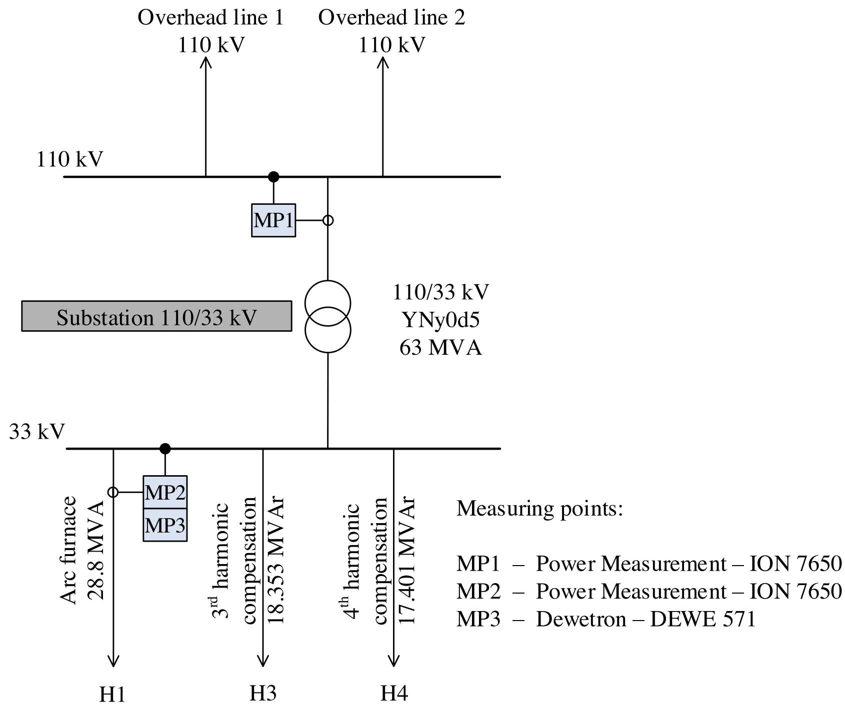

Fig. 5. Measuring points inside 110/33 kV substation.

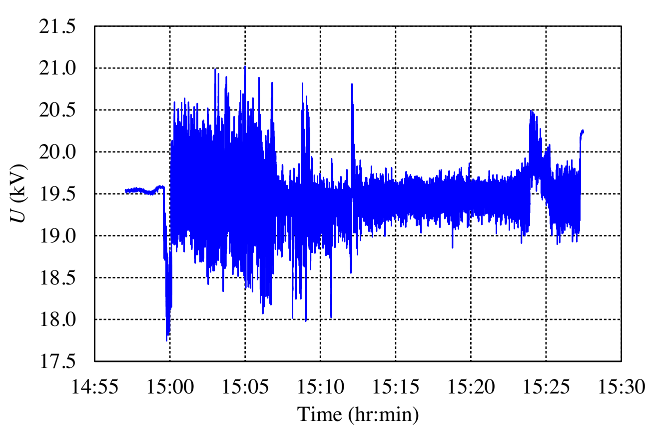

Fig. 6. Measured effective value of voltage in phase A at 33 kV level of EAF transformer.

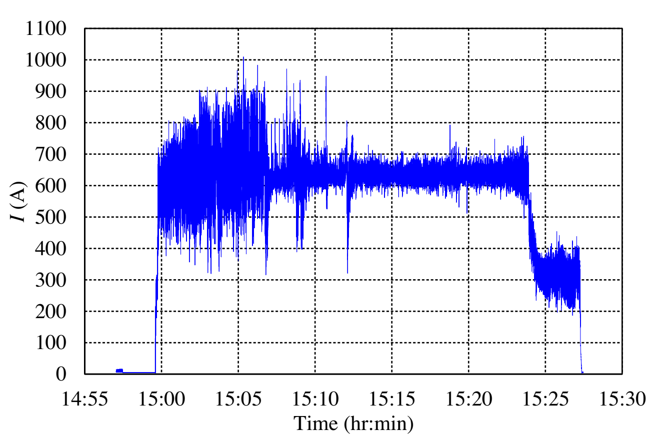

Fig. 7. Measured effective value of current in phase A at 33 kV level of EAF transformer.

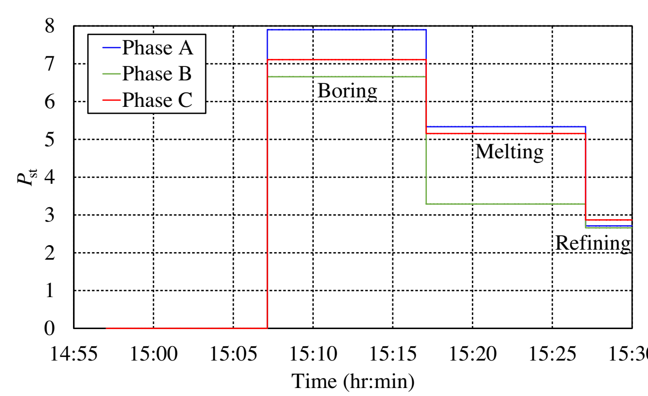

Fig. 8. Measured short-term flicker at 33 kV level of EAF transformer.

Table 4
Comparison between calculated and measured short term flicker at 33 kV level of EAF transformer.

Operation mode	Boring	Melting	Refining
Modulation coefficient m_{max}	0.085	0.058	0.029
P_{st} (measurements)	7.85	5.35	2.65
P_{st} (calculations)	7.8240	5.3261	2.6750
Error ΔP_{st} (%)	−0.33	−0.45	0.94

It can be seen that voltage values oscillate around 19.5 kV, while current values oscillate around 620 A. Values of short term flicker P_{st} are shown in Fig. 8. In the first 10 min period P_{st} equals to zero because the value of short-term flicker is determined based on cumulative measurements in 10 min interval.

Modulation coefficient of the sinusoidal variation is determined in order to obtain a match between calculated and maximum measured values of P_{st}. Comparison between calculation results and measurements are shown in Table 4 for different modulation coefficients selected according to EAF operation mode.

It can be seen that the highest values of P_{st} are produced in the initial boring phase of EAF operation. Percentage error when determining the short term voltage flicker is below 1%, so the developed arc model and determined modulation coefficients can be used to represent EAF in voltage flicker studies.

5. Estimation of voltage flicker in power transmission network at point of common coupling

Previously described EAF model is used for estimation of voltage flicker at 110 kV level for two different switching operation conditions of the transmission network:

- case A): I_{sc3} = 11.1 kA, X/R = 4.88;
- case B): I_{sc3} = 14.6 kA, X/R = 5.16.

Figs. 9 and 10 show calculated voltage and current waveforms for case A) during the boring period of EAF operation.

Figs. 11 and 12 show calculated RMS values of voltage and current at waveforms for case A) during the boring period of EAF operation.

Simulations are performed also for melting and refining periods of EAF operation. Calculated P_{st} values are shown in Tables 5 and 6.

P_{st} values are higher in case A) where the network with lower short circuit power is considered. The calculation results shown in Tables 5 and 6 refer to 10 min period of time domain

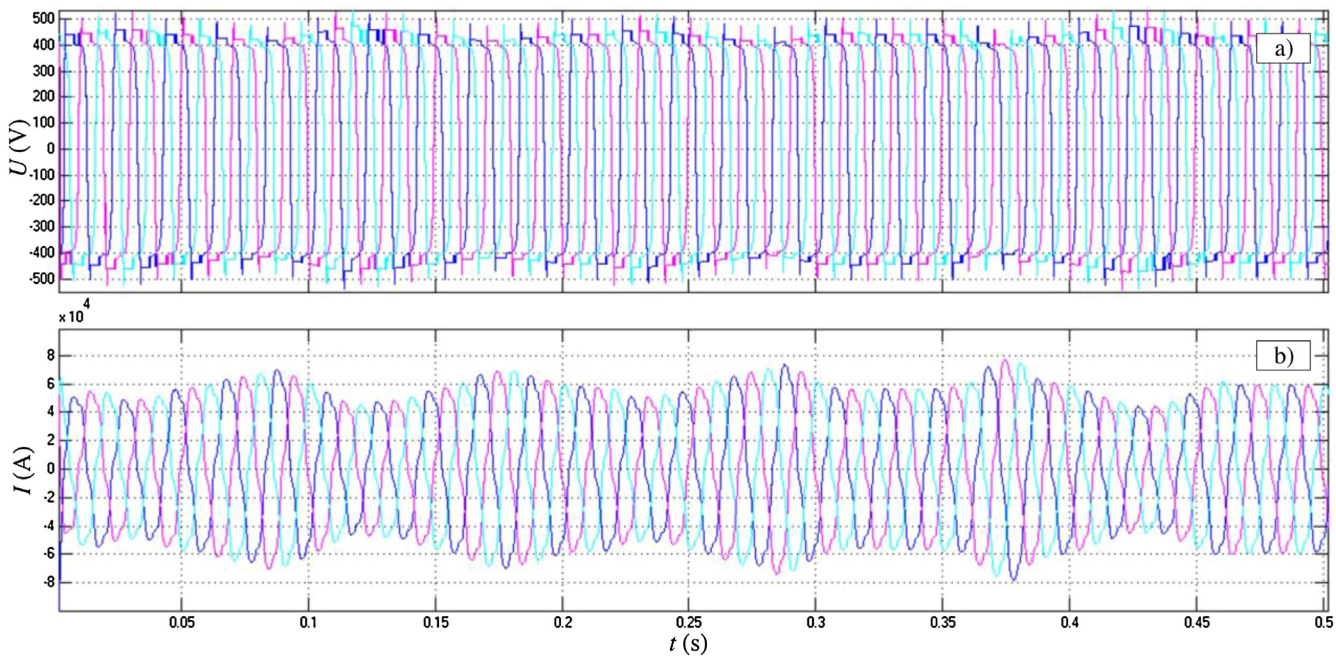

Fig. 9. a) Voltage waveform at 0.7 kV level of EAF transformer; b) current waveform at 0.7 kV level of EAF transformer.

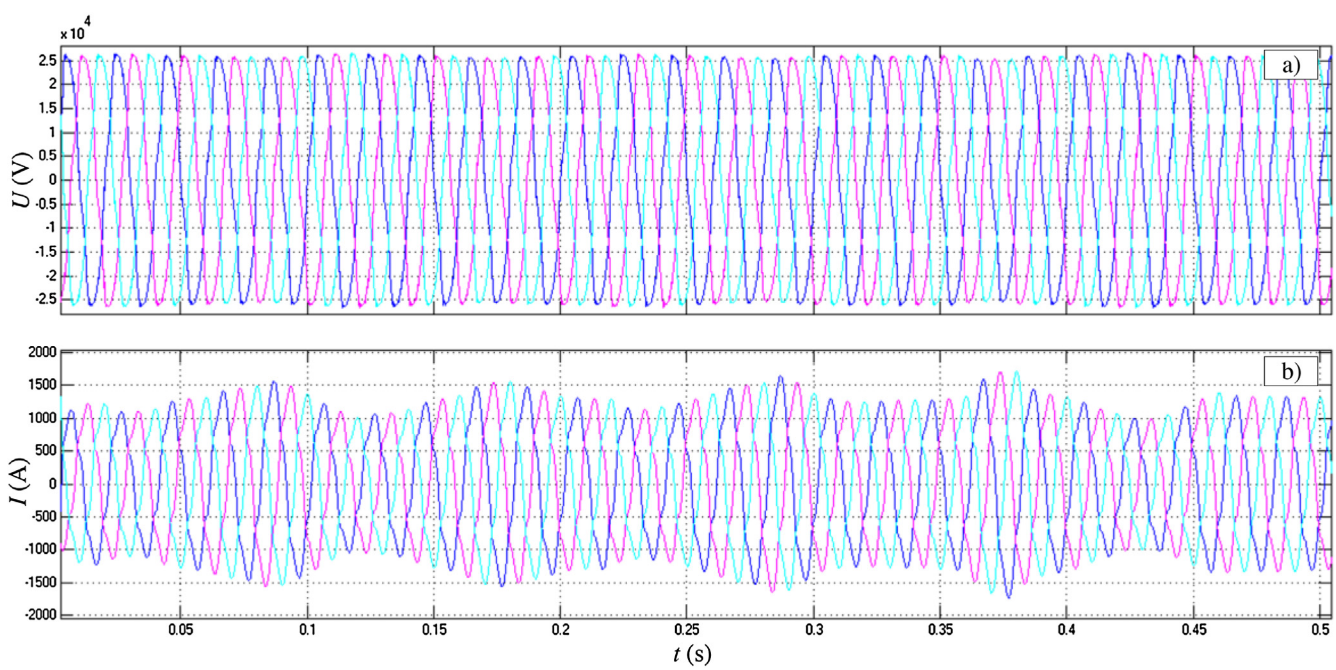

Fig. 10. a) Voltage waveform at 33 kV level of EAF transformer; b) current waveform at 33 kV level of EAF transformer.

simulation which corresponds to a single P_{st} value for each period of EAF operation. Fig. 13 shows simultaneous measurements of P_{st} on 110 kV and 33 kV levels and active power of EAF during 24 h period. The P_{st} values change significantly on both 110 kV and 33 kV level depending on power and operation mode of EAF.

It can be seen that the ratio between P_{st} at 33 kV and 110 kV level varies in the range 4.5–6.5 depending on operation mode of EAF. This ratio obtained from simulations is slightly lower, which means that the calculated flicker attenuation is slightly lower than the measured one. This is expected since the voltage and current

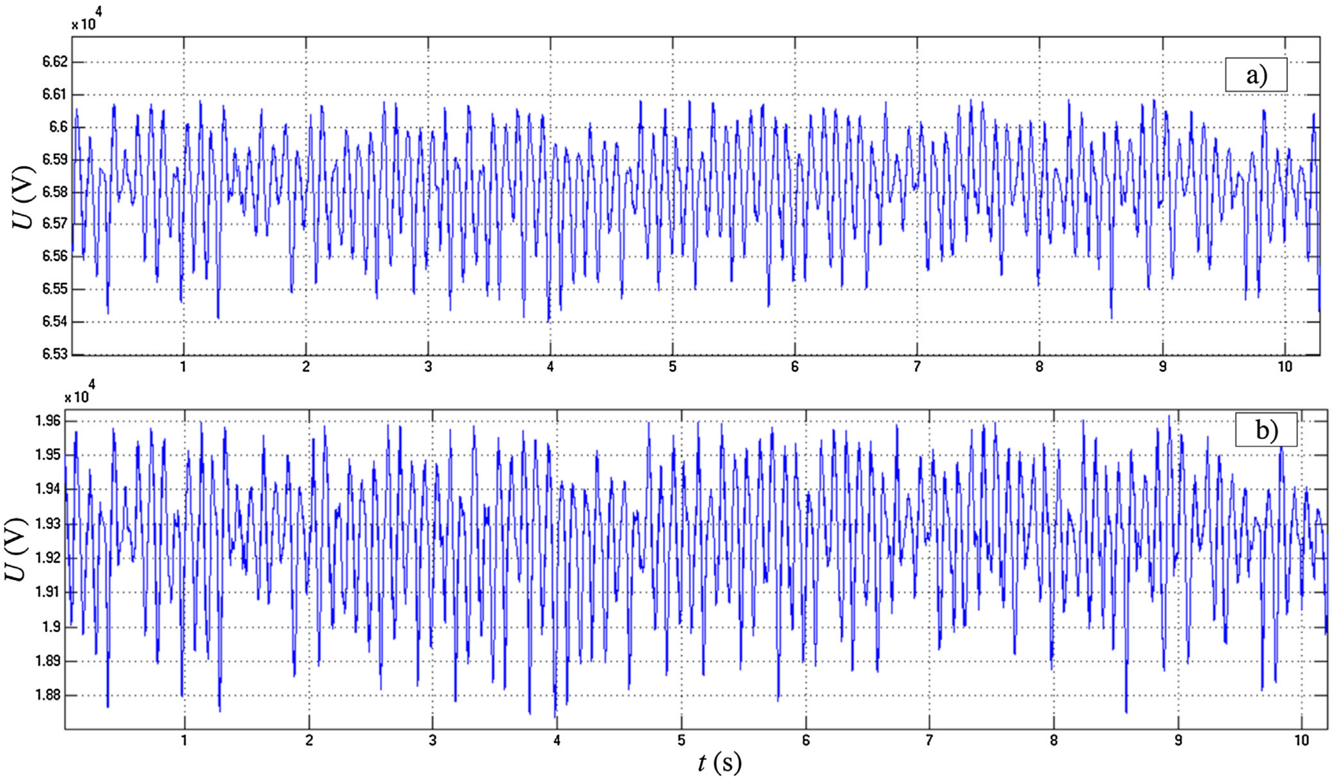

Fig. 11. a) RMS value of voltage in phase A at 110 kV level; b) RMS value of voltage in phase A at 33 kV level.

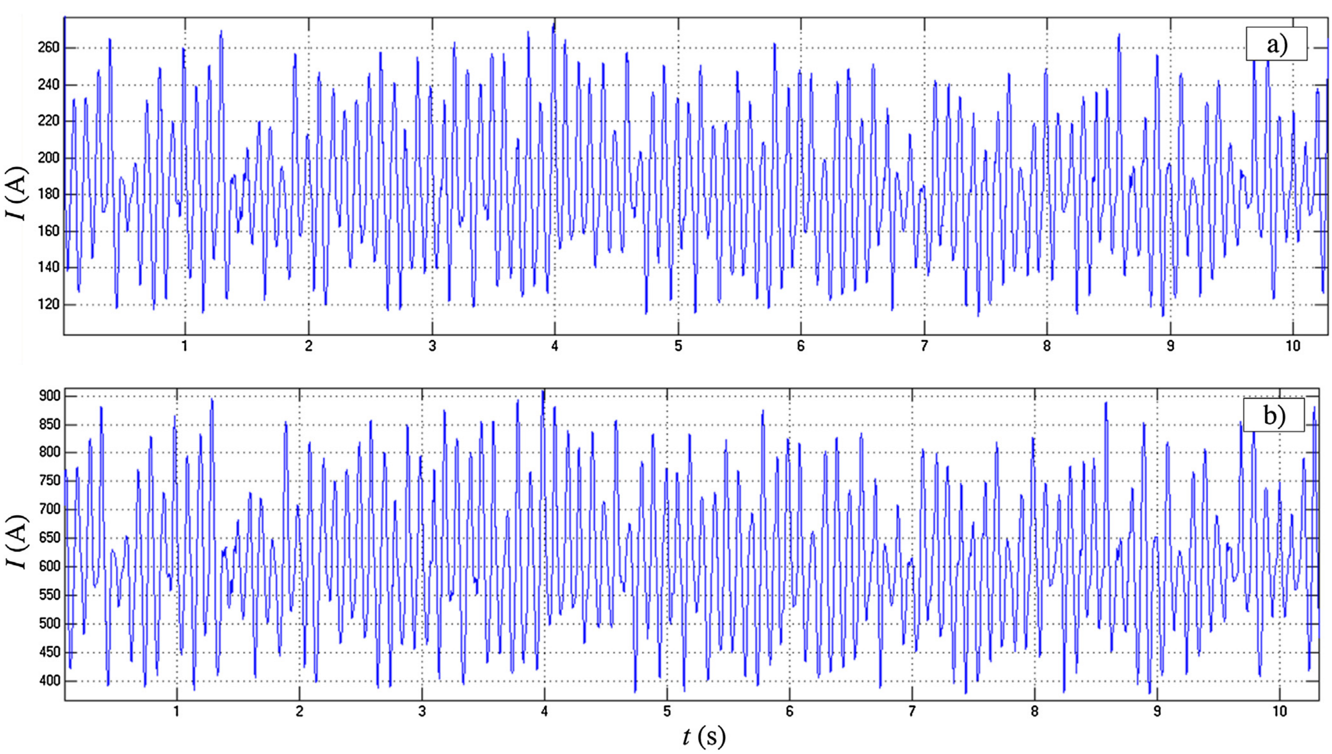

Fig. 12. a) RMS value of current in phase A at 110 kV level; b) RMS value of current in phase A at 33 kV level.

Table 5
Calculated P_{st} for case A): I_{sc3} = 11.1 kA, X/R = 4.88.

Voltage level	0.7 kV	33 kV	110 kV
P_{st} (boring)	9.8646	7.8240	1.8945
P_{st} (melting)	6.6849	5.3261	1.2924
P_{st} (refining)	3.3621	2.6750	0.6508

Table 6
Calculated P_{st} for case B): I_{sc3} = 14.6 kA, X/R = 5.16.

Voltage level	0.7 kV	33 kV	110 kV
P_{st} (boring)	9.8219	7.6528	1.4332
P_{st} (melting)	6.6646	5.2107	0.9777
P_{st} (refining)	3.3565	2.6190	0.4925

waveforms are measured on secondary side of instrument transformers and the measuring circuit introduces a certain attenuation, which is not taken into account in simulations. Also, the switching operating condition of transmission network can change during measurements so the equivalent network in the model should be adjusted in order to take this into account. Simultaneous measurements of P_{st} at 33 kV and 110 kV level have confirmed that

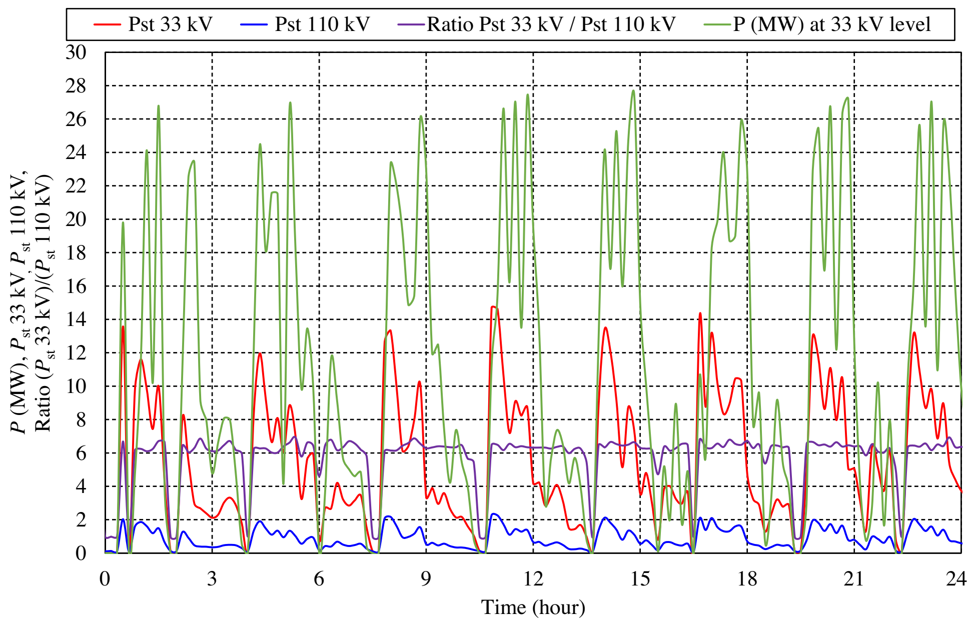

Fig. 13. Measurements of EAF active power and P_{st} at 33 kV and 110 kV levels during 24 h period.

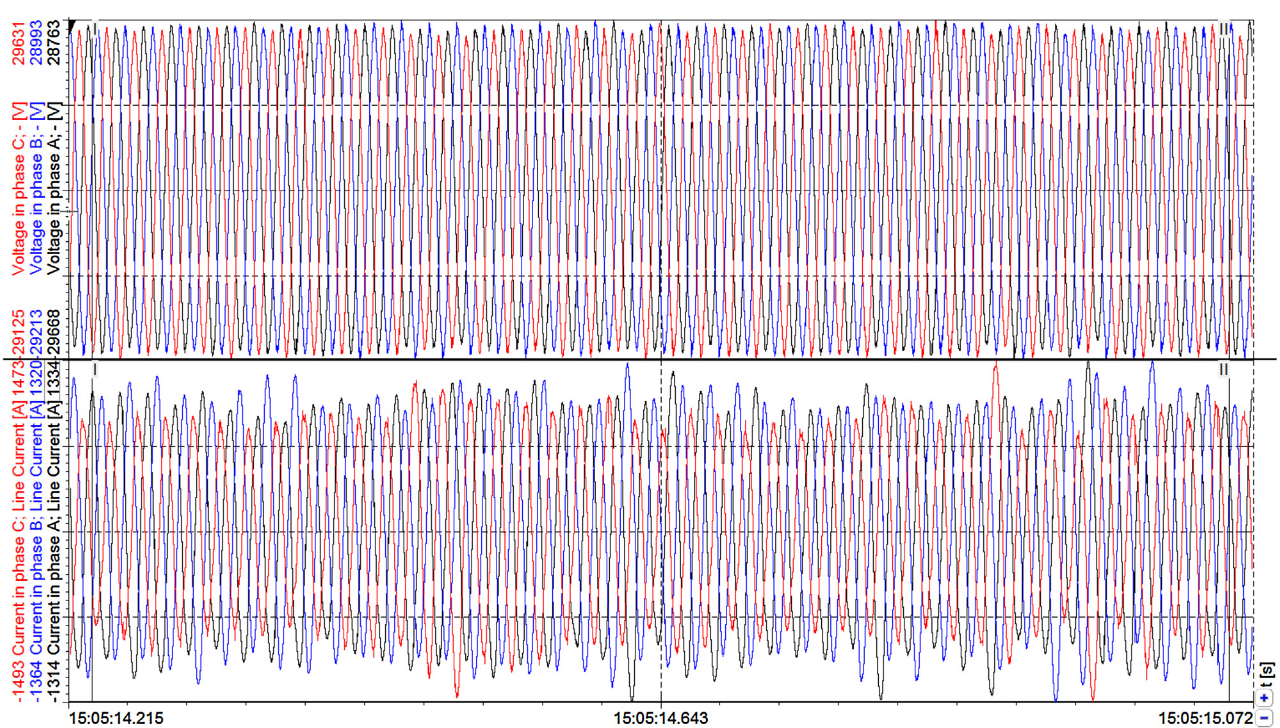

Fig. 14. Measured voltage and current waveforms at 33 kV level of EAF transformer.

developed model can be used for estimation of voltage flicker at 110 kV level.

Fig. 14 shows measured voltage and current waveforms at 33 kV level of EAF transformer during a short period of initial boring phase of operation.

A direct comparison with simulated waveforms (Fig. 9) for a certain smaller time window is not feasible since a proposed model takes into account the stochastic behaviour of EAF by varying a modulation coefficient using the uniform noise generator block which generates uniformly distributed noise between upper and lower bounds, e.g. in the range 0–m_{max}. It can be seen that simulated and measured waveforms coincide in terms of span of current and voltage amplitudes. Nevertheless, the aim of the proposed approach is to develop an EAF model which accurately describes stochastic behaviour over a longer time period with regard to P_{st} value (Table 6).

6. Conclusion

This paper presents a dynamic model of electric arc furnace (EAF) suitable for estimation of voltage flicker in power transmission network at the point of common coupling. Presented model was developed in Matlab/Simulink environment and it takes into account non-linear and stochastic behaviour of the electric arc. The model was verified by comparing simulation results with measurements obtained from different operation modes of EAF with rated power 28.8 MW, which is connected to 33 kV level via EAF transformer 0.7/33 kV and to transmission network via power transformer 110/33 kV. In order to calculate voltage flicker from the simulated EAF voltage, an IEC flickermeter was developed and its performance testing was successfully demonstrated.

The comparison between measured and calculated flicker values at 33 kV and 110 kV levels shows good agreement for all cases of various EAF operating modes such as boring, melting and refining. Influence of short circuit power and switching operating condition of the transmission network on flicker levels at point of common coupling was investigated. Flicker values were higher in case of transmission network with lower short circuit power. Performed analysis has confirmed that proposed model could be used for estimation of voltage flicker in power transmission network.

The future work will be focused on developing the model of transmission and distribution network in order to determine the voltage flicker propagation through transmission and distribution network and estimate voltage flicker at low voltage level.

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References

[1] G.T. Heydt, Electric Power Quality, 2nd edition, Stars in a Circle Publications, New York, 1994.
[2] J. Sousa, M.T. Correia de Barros, M. Covas, A. Simões, Harmonics and flicker analysis in arc furnace power systems, in: International Conference on Power System Transients (IPST), Budapest, Hungary, 1999.
[3] CIGRE Working Group B4.19: "Static synchronous compensator (STATCOM) for arc furnace and flicker compensation", technical brochure no. 237, 2003.
[4] IEC TR 61000-3-7: Electromagnetic compatibility (EMC) – Part 3–7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems, 2008.
[5] EN 50160: Voltage characteristics of electricity supplied by public distribution systems, 2010.
[6] S. Varadan, E.B. Markram, A.A. Girgis, A new time domain voltage source model for an arc furnace using EMTP, IEEE Trans. Power Delivery 11 (January (5)) (1996) 1685–1691.
[7] G.C. Montanari, M. Loggini, A. Cavallini, L. Pitti, D. Zaninelli, Arc-furnace model for the study of flicker compensation in electrical networks, IEEE Trans. Power Delivery 9 (4) (1994) 2026–2036.
[8] H. Sharma, M. McGranaghan, J. Smith, An efficient module for flicker assessment of electric arc furnaces, Proceedings of the IEEE Power and Energy Society General Meeting, July 2008 (2008).
[9] M.A.P. Alonso, M.P. Donsion, An improved time domain arc furnace model for harmonic analysis, IEEE Trans. Power Delivery 19 (January (1)) (2004) 367–373.
[10] R. Horton, T.A. Haskew, R.F. Burch, A time-domain AC electric arc furnace model for flicker planning studies, IEEE Trans. Power Delivery 24 (July (3)) (2009) 1450–1457.
[11] E. O'Neill-Carrillo, G.T. Heydt, E.J. Kostelich, Nonlinear deterministic modeling of highly varying loads, IEEE Trans. Power Delivery 14 (April (2)) (1999) 537–542.
[12] G. Carpinelli, F. Iacovone, A. Russo, Chaos-based modeling of DC arc furnaces for power quality issues, IEEE Trans. Power Delivery 19 (October (4)) (2004) 1869–1876.
[13] M.T. Esfahani, B. Vahidi, A new stochastic model of electric arc furnace based on hidden Markov model: a study of its effects on the power system, IEEE Trans. Power Delivery 27 (October (3)) (2012) 1893–1901.
[14] F. Chen, K.B. Athreya, V.V. Sastry, Function space valued Markov model for electric arc furnace, IEEE Trans. Power Syst. 19 (May (2)) (2004) 826–833.
[15] H. Samet, M.E.H. Golshan, Employing stochastic models for prediction of arc furnace reactive power to improve compensator performance, IET Gener. Transm. Distrib. 2 (January (4)) (2008) 505–515.
[16] S.M. Mousavi Agah, S.H. Hosseinian, H. Askarian Abyaneh, N. Moaddabi, Parameter identification of arc furnace based on stochastic nature of arc length using two-step optimization technique, IEEE Trans. Power Delivery 25 (4) (2010) 2859–2867.
[17] E.A. Cano-Plata, A.J. Ustariz-Farfan, O.J. Soto-Marin, Electric arc furnace model in distribution systems, IEEE Trans. Ind. Appl. 51 (September/October (5)) (2015) 4313–4320.
[18] G.W. Chang, C.I. Chen, Y.J. Liu, A neural-network-based method of modeling electric arc furnace load for power engineering study, IEEE Transactions on Power Systems vol. 25 (February (1)) (2010) 138–146.
[19] G.W. Chang, H.J. Lu, H.J. Su, Application of grey predictor model for forecasting flicker severity associated with electric arc furnace load, in: 2012 IEEE 15th International Conference on Harmonics and Quality of Power, Hong Kong, 2012, pp. 216–219.
[20] G.W. Chang, M.F. Shih, Y.Y. Chen, Y.J. Liang, A hybrid wavelet transform and neural-network-based approach for modelling dynamic voltage-current characteristics of electric arc furnace, IEEE Trans. Power Delivery 29 (April (2)) (2014) 815–824.
[21] G. Chang, S. Lin, Y. Chen, H. Lu, H. Chen, Y. Chang, An advanced EAF model for voltage fluctuation propagation study, IEEE Trans. Power Delivery PP (99) (2016), http://dx.doi.org/10.1109/TPWRD.2016.2585740,2016, pp. 1–1.
[22] IEC 61000-4-15: Electromagnetic compatibility (EMC) – Part 4–15: Testing and measurement techniques – Flickermeter – Functional and design specifications, 2010.
[23] J.W. Smith S.M. Halpin, Voltage flicker measurement, Part I: Digital implementation of the IEC flickermeter Harmon, Transients Tech Notes, (1998) pp. 19–32.
[24] J. Jatskevich, O. Wasynczuk, L. Conrad, A method of evaluating flicker and flicker-reduction strategies in power systems, IEEE Trans. Power Delivery 13 (July) (1998) 1481–1487.
[25] O. Ozgun, A. Abur, Flicker study using a novel arc furnace model, IEEE Trans. Power Delivery 17 (4) (2002) 1158–1163.
[26] O. Ozgun, A. Abur, Development of an arc furnace model for power quality studies, Edmonton, Canada, in: Power Engineering Society Summer Meeting, vol. 1, 1999, pp. 507–511.
[27] M.A. Golkar, S. Meschi, MATLAB modeling of arc furnace for flicker study, in: IEEE International Conference on Industrial Technology, Chengdu, China, 2008, pp. 1–6.
[28] D.C. Bhonsle, R.B. Kelkar, Simulation of electric arc furnace characteristics for voltage flicker study using MATLAB, in: International Conference on Recent Advancements in Electrical, Electronics and Control Engineering, Sivakasi, India, 2011.