Effects of Electric Arc Furnace Loads on Synchronous Generators and Asynchronous Motors

Tolga Sürgevil[1] and Eyüp Akpınar[2]

[1,2] Dokuz Eylul University, Department of Electrical and Electronics Engineering
Kaynaklar Kampusu, 35160 Buca, Izmir, TURKEY
tolga.surgevil@deu.edu.tr, eyup.akpinar@deu.edu.tr

Abstract

This paper presents an investigation on the effects of voltage flickers caused by AC electric arc furnace (EAF) loads in electrical power systems. This investigation is based on measurements and simulations, and carried out in the industrial zone where multiple EAF loads are intensely located. The scope is focused on the effects of such continuous disturbances on synchronous generators used in the co-generator plant and asynchronous motors fed from the same bus nearby the EAFs. The measurements and PSCAD simulation results are analysed and discussed in the scope of power quality aspects. Finally, the some of the methods for flicker mitigation that can be employed in the studied system are discussed.

1. Introduction

Electric arc furnaces (EAF) used in iron and steel industry cause severe power quality issues in electrical power systems. These problems are mainly current harmonics, low power factor, and voltage fluctuations due to rapidly changing EAF currents, which give rise to voltage flicker at the point of common coupling (PCC). The effect of the voltage fluctuations on lighting is a well-known phenomenon called light flicker, which causes a sensible and annoying disturbance to human eye [1-2]. Besides, such voltage fluctuations cause torque and power oscillations in the rotating electrical machines connected to the same bus, reduction in equipment efficiency, and interference in protection systems [3]. An example of how voltage flicker disturbances may affect the stabilities of interconnected generators serving nearby EAF loads is discussed in [4].

Although the degree of susceptibility of electric apparatus to flicker levels cannot be easily determined, the limits of voltage flicker are defined in standards based on common practice [5-8]. Hence, the mitigation of voltage flicker has become an important concern to comply with these standards and several solutions have been suggested, such as static VAR compensators (SVC), flexible AC transmission systems (FACTS), and energy storage systems (ESS) [3,9]. Also, decreasing the susceptibility of the electrical apparatus to voltage flicker is another way of matching equipment immunity with the power quality index. For example, the authors of [4, 10, 11] proposed that the proper settings in the excitation systems of the synchronous generators will result in less active power oscillations and would make the generators less sensitive to voltage flicker disturbances. The study on how electrical parameters such as short circuit powers and transmission line lengths affect the voltage flicker propagation over the entire power network is also present in the literature [12].

The pulsating nature of EAF loads may create large mechanical torques in the shaft of the turbine-generator systems. This may cause a potential problem due to mechanical stress, fatigue, and wearing yielding to a possible failure of the system. From this point of view, the effects of EAF loads on stand-alone synchronous generator torque are investigated in [13-14]. According to these studies, EAF loads impose excessive torques on generator-turbine shafts, especially in scrap melting stage. The SVCs employed in EAF systems may also increase the torques on turbine-generator shafts interconnections when EAF currents are rapidly changing in scrap melting stage [14]. The proposed solutions in these papers are developing a new construction standard for generators that are subjected to pulsating loads, implementation of on-line loss-of-fatigue-life monitoring systems, smoothing out active power oscillations through energy storage devices, starting EAFs at different times. It is an obvious fact that stand-alone generator systems should not supply the EAF loads only.

Any distortion in the supply voltages causes electromagnetic torque oscillations in rotating electric machines. The high frequency components in electrical torque impose stress on small components such as turbine blades and low frequency components on main shaft section of the turbine-generator systems [15]. The effects of various power disturbances on machine transient torques and turbine-generator mechanism have been a major concern in literature [15-21]. The sub-synchronous resonance due to the interaction of torsional oscillations on several rotating parts in the turbine-generator system with electrical power system, especially in series-capacitor compensated systems, is the most well known phenomenon studied in the literature [16-17]. Steady-state switching operations also impose stress on generator units causing loss of shaft fatigue life and it was recommended that the resulting change in the average power (ΔP) should not be higher than 0.5 pu in [18,22] as a rule-of-thumb. However, when the generators are serving nearby EAF loads, the case is more complicated since EAFs generate a continuous disturbance at random nature for the generator systems. There is no specific value for limiting the magnitude of power oscillations when generators are imposed to such continuous disturbances. Actually, the effect of torsional oscillations on mechanical shaft fatigue is determined by the properties of the material of the mechanical system. In that case, fatigue characteristics and high–cycle fatigue limit (HCFL) should be determined for the materials subjected to cyclic stress [16] and should be studied with torsional oscillations caused by power system disturbances.

In this paper, an overview on electrical power quality in Aliağa region where multiple EAF loads are intensely located is given. The effects of voltage flicker caused by these EAF loads on synchronous generators supplying the same bus in this region are investigated. Their possible effects on mechanical shaft system of low and medium power range asynchronous machine and inertia load systems are also analysed using computer simulations. The measurement and PSCAD simulation results are discussed in the scope of aforementioned aspects. Finally, the some of the flicker mitigation methods that can be employed in the power system considered here are analysed through PSCAD simulations and its results are discussed.

2. Measurements in the Transformer Substation and Cogeneration Plant Supplying EAFs

The single-line diagram of Aliağa-II transformer substation is given in Fig.1. The 154-kV feeder supplies 5 EAF plants and other residential and industrial loads in the region. Also, a 320 MVA natural gas combined-cycle co-generation unit feeds electrical power to the 154-kV bus. In order to investigate the current status of the power quality in the region, two field measurements were performed in this region at two different times. The measurements are performed during 15-hours in the transformer substation at the points marked on Fig.1 in order to see the effects of EAF loads to the 154-kV bus. During measurements, the coupling between the two buses was open and BUS-1 supplied one EAF plant, while BUS-2 and the cogeneration system supplied four EAF plants. The variations of the rms line-to-line voltage, instantaneous flicker level, rms current, active power, and reactive power at 154-kV buses for 3 hours are given in Fig.2. The instantaneous voltage flicker level at 380-kV bus is observed at the level of %1, which is above the standard limits. The previous field measurements also showed that the voltage flicker at 380-kV bus is at a critical point and long-term flicker values cannot meet the standard limits [23]. Typical operation of one EAF fed from BUS-1 is shown in Fig.2a and the amplitude of flicker is highest during the boring phase of the new scrap metal in EAF. The amplitude of the flicker reaches up to %3 at this stage. The voltage flicker is more severe at BUS-2 where multi-EAFs operate at different times. The rises in the voltage flicker level at BUS-1 during the scrap melting stage of one EAF operation is indistinct at BUS-2 due to interaction of multi EAF, SVC, and filter systems.

The variations of electrical quantities in the co-generation plant were also observed at a different period of time. The single-line diagram of this plant feeding 154-kV bus is given in Fig.3. The plant consists of 2 units each of which have two 63.5 MVA gas turbines and one 32.44 MVA steam turbine generator. Generators are rated at 11 kV and connected to the 154-kV bus through step-up transformers. All generators in the plant have brushless rotating rectifier excitation system. The variation of the rms line-to-line voltage, instantaneous flicker, rms current, active power, and reactive power at 154-kV side of the gas and steam turbine generator systems for 9 hours is given in Fig.4. Measurements show that the voltage variations at the 154-kV bus reaches up to %3 instantaneously and as a result the amplitudes of the power oscillations %8.3 for steam turbine and %6 for the gas turbine, respectively. These measurement data were used for the verification of the system models built in PSCAD package program.

3. Modelling and Simulation Results of the Cogeneration Plant

The modelling of the generator units is performed using PSCAD simulation package program in order to investigate the behaviour of the generators under distorted supply voltages. Simulations are performed with supply voltages, which were measured at 154-kV side of transformer substation, and the generators are fed through these voltage sources and through a short transmission line. The infinite bus voltage behind the transformer and transmission line impedances is calculated from measured terminal voltage and line currents. The calculated instantaneous values were input to the controlled voltage source block in PSCAD model and the model parameters are given in Appendix. In the modeling of generator systems with governor and exciter, since the generators in the plant have brushless rotating rectifier system, the suitable AC1A exciter model with typical parameters [16] was picked up from those provided in PSCAD. The turbine-governor system consists of a non-reheat type steam turbine and mechanical hydraulic control. In simulations solver step size was chosen to be Δt=62.5 microseconds. The transient response of the system was investigated by setting the initial active and reactive powers of the generator to zero and then increasing to power value obtained from measurements via governor. In simulations, the steady-state conditions obtained from the field measurements are almost satisfied with slightly more active and reactive power oscillations. The performance of the generator system was also tested with multi-mass model block built-in PSCAD package program. The turbine mechanical system was considered to have 4 main shaft sections. The results from the generator with multi-mass model are shown in Fig.5. At start-up, the generator units are loaded from zero to 0.7 pu. Any stability problem was not observed in generator systems operating under distorted supply voltages. Once the generators reaches steady-state operation, the oscillations in the electromagnetic torque are suppressed due to large inertia of turbine-generator units. The other types of exciter systems were observed to have a very little effect on power oscillations on generator systems in simulations.

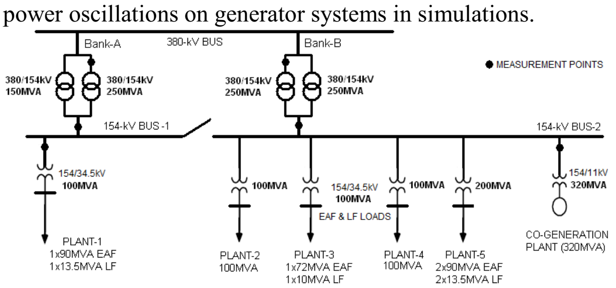

Fig.1. Single-line diagram of Aliağa-II transformer substation

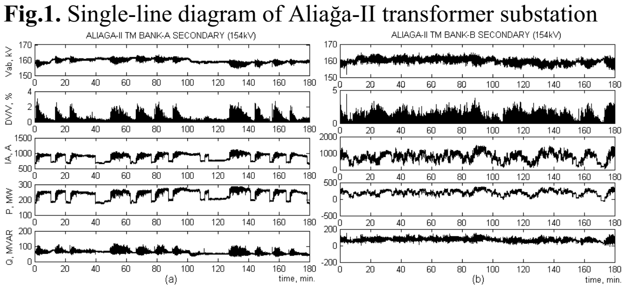

Fig.2. The variation of electrical quantities at transformer substation a) 154-kV side of 400MVA transformer bank feeding BUS-1, b) 154-kV side of 500MVA transformer bank feeding BUS-2

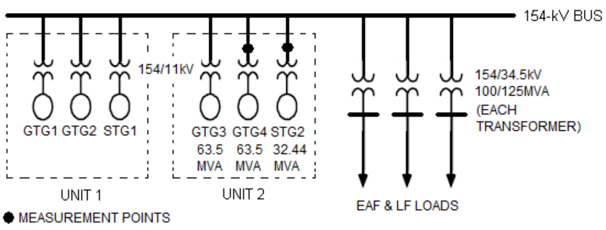

Fig.3. Single-line diagram of co-generation plant serving nearby EAF loads

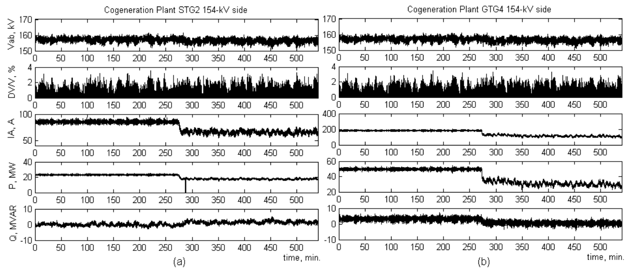

Fig.4. Results of co-generation plant measurements from the data during 9 hours a) Steam Turbine Generator (STG2) unit b) Gas Turbine Generator (GTG4) unit

4. Effects of Voltage Flicker on Smaller Size Asynchronous Machines

The analysed system consists of an asynchronous machine and an inertia load as shown in Fig.6. In general, for a system consisting of N separate sections of masses; the equations of mechanical motion are expressed as [24]

$$J_i \frac{d^2\theta_i}{dt^2} = T_i - K_{i,i-1}(\theta_i - \theta_{i-1}) - K_{i,i+1}(\theta_i - \theta_{i+1}) - D_{i,i-1}\left(\frac{d\theta_i}{dt} - \frac{d\theta_{i-1}}{dt}\right) - D_{i,i+1}\left(\frac{d\theta_i}{dt} - \frac{d\theta_{i+1}}{dt}\right) - D_{ii}\frac{d\theta_i}{dt} \tag{1}$$

$$\frac{d\theta_i}{dt} = \omega_i - \omega_{i-1} = \Delta\omega_i \tag{2}$$

where $i=1,2,...,N.$ and θ is the radial displacement, J_i is the inertia of each separate mass, K is the stiffness between the masses, and D is the damping coefficient. When the equations (1)-(2) are arranged for a two-mass-spring rotational system as shown in Fig.6 and expressed in the convenient state-space form as follows

$$x' = Ax + Bu \tag{3}$$

$$x = \begin{bmatrix}\theta_1 & \theta_2 & \Delta\omega_1 & \Delta\omega_2\end{bmatrix}^T \tag{4}$$

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \dfrac{-K_{12}}{J_1} & \dfrac{K_{12}}{J_1} & \dfrac{-D_{12}-D_{11}}{J_1} & \dfrac{D_{12}}{J_1} \\ \dfrac{K_{12}}{J_2} & \dfrac{-K_{12}}{J_2} & \dfrac{D_{12}}{J_2} & \dfrac{-D_{12}-D_{22}}{J_2} \end{bmatrix} \tag{5}$$

$$B = \begin{bmatrix}0 & J^{-1}\end{bmatrix} = \begin{bmatrix} 0 & 0 & 1/J_1 & 0 \\ 0 & 0 & 0 & 1/J_2 \end{bmatrix}^T \tag{6}$$

$$u = \begin{bmatrix}T_1 & T_2\end{bmatrix}^T = \begin{bmatrix}T_E & T_L\end{bmatrix}^T \tag{7}$$

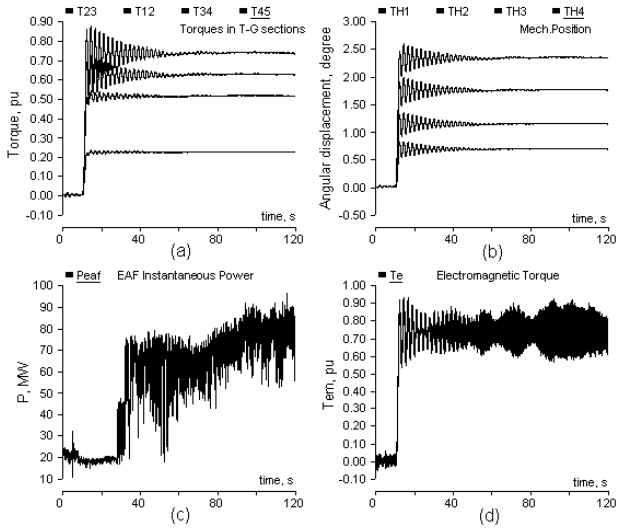

Fig.5. The electromagnetic torque oscillations during EAF operation and its effect on mechanical shaft sections. a) Torques between turbine-generator sections b) angular displacement in the shaft sections with respect to generator c) instantaneous EAF power d) generator electromagnetic torque

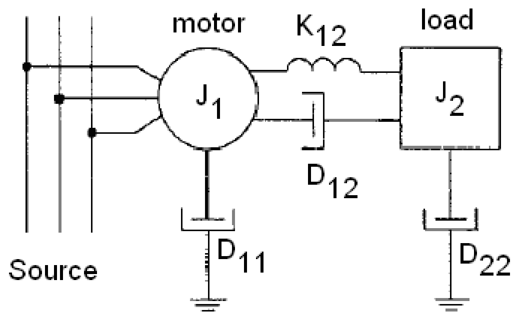

Fig.6. The scheme of simple two-mass-spring rotational system

The rotor natural frequencies can be found by applying eigenvalue problem to equation (5). The analysis of the system was done for two asynchronous machines at different power ratings and the parameters are given in Table 1. Since the analysed system contains two masses, from the eigenvalue analysis, it has two mechanical modes at two natural frequencies: for 5.4-hp machine at $\omega_1 = 1403\ rad/s$, $\omega_2 \approx 0$ and for 215hp machine at $\omega_1 = 94.3\ rad/s$, $\omega_2 \approx 0$. The resonance frequency of the system naturally decreases with increasing inertia as a result of increasing power rating. The frequency responses of the system give idea about the behaviour of the system at steady-state. However, the instantaneous electromagnetic torque of the machine varies randomly at the given voltage flicker levels. Hence, it is appropriate to analyse the system through dynamic simulation models. In PSCAD simulations, the voltage sources obtained from the measurements in Aliağa-II transformer substation were used. The asynchronous machine is connected to the 154kV bus feeding 1 EAF, through a short transmission line and step-down transformer. The effects of the voltage flickers created by the EAF are observed through simulations.

The simulation results of both asynchronous machines are shown in Fig.7. The torque oscillations are high in 5.4-hp machine, when the EAF begins to operate. In 215-hp machine, the electromagnetic torque oscillations are suppressed due to higher inertia of the system. In simulations, it was also observed that the oscillations in the machine-load mechanical shaft increase as the load inertia increases and shown in Fig.8. The mechanical oscillations are much higher when the load inertia 10 times higher than that of machine compared to the case when the load has twice the machine inertia. The effect of the voltage flickers on machine-load mechanical shaft is more dramatic with increasing load inertia. The rigidity of the shaft should be increased in such case, especially in applications where the asynchronous motors drive higher inertia loads.

Table 1. Asynchronous machine and shaft parameters

P (hp)	Electrical parameters	Mechanical parameters	Shaft parameters	
5.4	$V = 400V\ l-l, f = 50Hz, p = 4$ $r_s = 0.03513pu, L_{ls} = 0.04586pu$ $r_r = 0.03488pu, L_{lr} = 0.04586pu$ $X_m = 1.352pu$	$H = 0.0404s,\ D = 0.01841pu$ $(J = 0.0131kgm^2,$ $D = 0.002985N.m.s)$	K (N.m) 17190	J_2 (kg.m²) 0.0262
215	$V = 400V\ l-l, f = 50Hz, p = 4$ $r_s = 0.01379pu, L_{ls} = 0.04775pu$ $r_r = 0.007728pu, L_{lr} = 0.04775pu$ $X_m = 2.416pu$	$H = 0.2236s,\ D = 0.008726pu$ $(J = 2.9kgm^2,$ $D = 0.05658N.m.s)$	K (N.m) 700730	J_2 (kg.m²) 5.8

5. Analysis of the Solutions to Voltage Flicker Mitigation

With the current generating plant, the short-circuit MVA of one 154-kV bus is 4500 MVA and the detail of calculation is given in Appendix. In [3], the short-circuit voltage depression (SCVD) was introduced for estimation of the voltage flicker impact due to electric arc furnaces and for an SCVD ratio above 0.03, the condition is considered to be objectionable. When the SCVD values are considered in the power system in Aliağa, the SCVD value for the EAF having the highest MVA rating is 0.068 for one bus, 0.04 for one bus with the cogeneration plant, and 0.029 with two buses coupled to cogeneration unit. When the multiple operations with other EAF plants are considered, the SCVD value will be much higher than those values as stated in [23] as well. From this point of view, one can conclude that the operation more than one EAF in this system is questionable and additional plants should be installed in the region in order to increase the short circuit capacity of the line. At this point, the following case study is performed in order to see the effects possible countermeasures that can be taken to reduce the flicker at the Aliağa-II transformer substation.

As mentioned before, one EAF is fed from BUS-1 at 154-kV line of the Aliağa-II transformer substation with other loads around the region. The short-circuit capacity of this bus is 2667 MVA. One of the cogeneration unit consisting of two GTG and one STG provides a short-circuit-current capacity of 9.1869pu on 100MVA and 154-kV base as the calculations are shown in Appendix. This corresponds to short-circuit MVA of 918.57 MVA, which is approximately one third of the installed short-circuit capacity of the bus. The results showing the effect of installing a new plant on the voltage flicker are given in Fig.9. The max voltage variation is reduced from %4.5 to %3.5. Simulations were performed for different lengths of the transmission line connecting the generating unit to the PCC. The transmission line length has a little effect on flicker level as shown in Fig.9b and Fig.9c.

When an additional transformer is installed at the power rating of 150 MVA to existing transformer bank, then the equivalent transformer reactance becomes $X_{t,eq}=0.0207pu$ and short circuit-capacity is increased to 3400 MVA. The results of the new transformer added to the existing bank on the voltage flicker are shown in Fig.9d. The max voltage variation is reduced from %4.5 to %3.5. The results show that increasing the short-circuit capacity by installing transformer to the existing bank would be a more feasible solution when the investment costs are considered.

5. Conclusions

The effects of voltage flicker caused by the EAF loads are investigated. Attention was focused on the generator units installed in cogeneration plant that supplies the 154-kV bus nearby Aliağa region. Computer simulations show that the generators do not have any stability problem in the presence of continuous flicker disturbance and such a problem has not been reported so far. However, the instantaneous electromagnetic torque oscillations are quite high, which imposes stress and fatigue on mechanical shaft system components and the situation may yield to a complete failure over a long-term period. Since determining the HFCL of the mechanical component requires a very detailed modelling and analysis, it is not possible to state that how the continuous flicker disturbance would cause an overall system failure. But, the current experience indicates that such disturbances a fatigue effect on mechanical components and periodical maintenance (including endoscopic examination for material deformation) is required as well as employing online fatigue monitoring systems are suggested.

The methods for flicker mitigation are also considered in this paper for proposing a solution to the current case in the region. Analysis and simulations show that the SCVD method may yield to pessimistic results, and the real situation should be analysed from the system model. The options of installing additional plants and increasing the power rating of transformer substation bank are considered. Both methods would reduce the SCVD, and installing additional plant should be considered in the planning of increasing overall generation capacity. However, as long as it is the aim to mitigate flicker level at the transformer substation, increasing the bank power rating will always be more economical solution. So, a trade-off between power generation and investment cost should be made.

Acknowledgments

This work was carried out as a part of project, “Power Quality National Projects”, sponsored by Turkish Scientific and Research Council and Turkish Electrical Power Transmission Co. (TEİAŞ) under contract 106G012.

Appendix

STG parameters:

$$H = 1.2s,\ r_a = 0.0057pu,\ T'_{do} = 5.88s, T''_{do} = 0.0339s$$

$$X_d = 2.18pu, X'_d = 0.174pu, X''_d = 0.164pu\ \ T''_{qo} = 0.182s$$

$$X_q = 2.06pu, X''_q = 0.212pu,\ X_p = 0.1499pu$$

GTG parameters:

$$H = 0.754s,\ r_a = 0.00068pu$$

$$X_d = 2.52pu, X'_d = 0.214pu, X''_d = 0.154pu$$

$$X_q = 2.3pu, X'_q = 0.26pu, X''_q = 0.19pu\ \ X_p = 0.2230pu$$

$$T'_{qo} = 2.9s, T''_{qo} = 0.04s,\ T'_{do} = 9.7s,\ \ T''_{do} = 0.05s$$

Transmission Line Impedance: R=0.1172 ohm/mi, X=0.399 ohms/mi at 20°C, 60Hz for 154kV, 2(3x795) MCM ACSR [25].

6. References

[1] C. Sharmeela, G. Uma, M.R. Mohan, and K. Karthikeyan, 'Voltage flicker analysis and mitigation-case study in ac electric arc furnace using PSCAD-EMTDC', Int. Conf. on Power Sys. Tech., Singapore, 21-24 Nov. 2004, pp.707-712.

[2] C. Sankaran, 'Power Quality', CRC Press, 2002.

[3] S.R. Mendis, M.T. Bishop, and J.F. Witte, 'Investigations of voltage flicker in electric arc furnace power systems', IEEE Ind. Appl. Magazine, vol.2, no.1, 1996, pp.28-34.

[4] C. Wu, and Y. Chuang, 'Frequency domain approach to suppress power oscillations of synchronous generators caused by voltage flicker disturbances', IEEE Power Engineering Society General Meeting, Denver, USA; 6-10 June 2004, pp.1547-1552.

[5] IEEE Std 519-1992, 'IEEE recommended practices and requirements for harmonic control in electrical power systems', 2004.

[6] IEEE Std 1453-2004, 'IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems', 2005.

[7] IEEE Std 141-1993, 'IEEE Recommended Practice for Electric Power Distribution for Industrial Plants', 1994.

[8] IEC Std 61000-4-15, 'Electromagnetic Compatibility (EMC) – Part 4: Testing and Measurement Techniques – Section 15: Flickermeter – Functional and Design Specifications', 2003.

[9] L. Zhang, Y. Liu, M.R. Ingram, D.T. Bradshaw, S. Eckroad, and M.L. Crowl, 'EAF voltage flicker mitigation by FACTS/ESS', IEEE Power Systems Conf. and Exposition, New York, USA, 10-13 October 2004, pp.372-378.

[10] C.Huang, C. Wu, and Y. Chuang, 'Test results of three excitation systems for generators suffering continuous voltage flicker disturbance', Int. Conf. on Power System Technology, Singapore, 21-24 Nov. 2004, pp. 300-305.

[11] C.Wu, Y. Chuang, C. Huang, and Y. Chang, 'Tuning of excitation systems to improve dynamic performance for generators serving electric arc furnace loads', IEEE Trans. Energy Conversion, vol.22, no.2 2007, pp.350-357.

[12] B.N.Ramos, J.F.M. Garcia, and M.P. Donsion, 'Study of flicker generation and transmission in interconnected electric grids', Int. Conf. on Harmonics and Quality of Power, Rio de Janeiro, Brasil, 6-9 Oct. 2002, pp.66-70.

[13] M.W. Baldwin, 'Electric arc furnace impact on generator torque', IEEE Power Systems Conf. and Exposition, New York, USA, 10-13 October 2004, pp.776-780.

[14] B.M. Dehkordi, A. Parsapoor, and R. Hoosmand, 'Effect of different operating conditions of electric arc furnace on generator shaft', International Aegean Conf. on Electrical Machines and Power Electronics, Bodrum, Turkey, 10-12 Sept. 2007, pp.824-829.

[15] D.G. Ramey, A.C. Sismour, and G.C. Kung, 'Important parameters in considering transient torques on turbine-generator shaft systems', IEEE Trans. Power Apparatus and Systems, 1980, vol. 99, no.1, pp.311-317.

[16] P. Kundur, 'Power System Stability and Control', McGraw-Hill, Inc., 1994.

[17] D.H. Baker, G.E. Boukarim, R. D'Aquila, and R.J.Piwko, 'Subsynchronous resonance studies and mitigation methods for series capacitor applications', Inaugural IEEE PES Conf. and Exposition, Durban, South Africa, 11-15 July 2005, pp.386-392.

[18] IEEE Working Group on the Effects of Switching on Turbine-Generators, 'IEEE screening guide for planned steady-state switching operations to minimize harmful effects on steam turbine-generators', IEEE Trans. Power Apparatus and Systems, 1980, vol.99, no.4, pp.1519-1521.

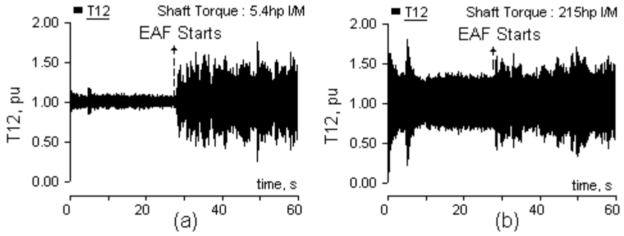

Fig.7. The effects of the voltage flickers due to EAF operation on machine-load shaft torque (a) 5.4hp (b) 215hp machine.

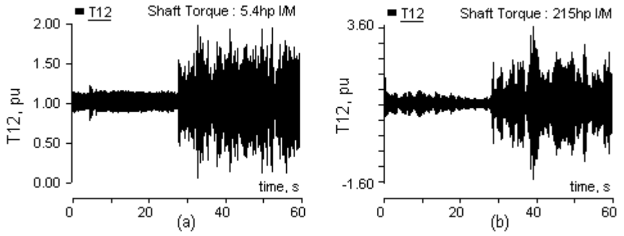

Fig.8. The torque in machine-load mechanical shaft as the inertia of the load increases 10 times higher (a) 5.4-hp machine-load system (b) 215-hp machine-load system

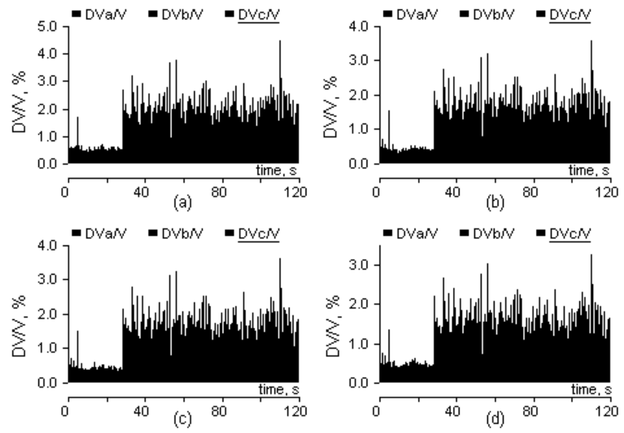

Fig.9. Voltage flicker variations at the Bank-A 154-kV terminal (a) for existing case (b) after installing an additional 160-MVA generating unit to PCC through a 2km transmission line (c) 160MVA, 20km transmission line d) after installing an additional 150MVA transformer unit to the existing bank.

[19] T.P.Tsao, and J.I. Tsai, 'Torsional interactions between an electrical arc furnace load and a turbine-generator set', Int. Conf. on Electric Utility Deregulation, Restructuring and Power Technologies, Hong Kong, 5-8 April 2004, pp.627-632.

[20] J.I. Tsai, J.T. Wang, and C.H. Lin, 'Effect of small power disturbances on turbine-generator mechanism torsional torque and fatigue', IEEE Int. Conf. on Systems & Signals, 2005, pp.119-124.

[21] Y.S. Lee, and K.C. Hsu, 'Shaft torsional oscillation of induction machine including saturation and hysteresis of magnetizing branch with an inertia load', Int. Conf. on Energy Management and Power Delivery, Singapore, 21-23 Nov. 1995, pp.134-139.

[22] IEEE Std C50.13-2005: 'IEEE standard for cylindrical-rotor 50 Hz and 60 Hz synchronous generators rated 10MVA and above', 2006.

[23] Ö. Salor et all: 'Electrical power quality of iron and steel industry in Turkey', IEEE Industry Application Conf., New Orleans, USA, 23-27 September 2007, pp.404-423.

[24] J. Machowski, J.W. Bialek, and J.R. Bumby, 'Power System Dynamics and Stability', John Wiley & Sons, 1997.

[25] J.J. Grainger, and W.D. Stevenson, 'Power System Analysis', McGraw-Hill, Inc., 1994.