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An Efficient Static VAR Compensator for Simultaneous Elimination of Voltage Flickers and Current Imbalances of Arc Furnaces

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ABSTRACT

Electric arc furnaces as unbalanced, nonlinear and time variant loads, cause unbalancing and flickers in the voltage profile and low power factor for their feeding power systems. In this paper, an efficient static var compensator in the structure of TCR-FC has been proposed for load balancing, voltage fluctuation and flicker reduction, reactive power compensation and power factor improvement. The efficiency of the proposed structure is verified through the simulation results carried out by *Matlab/Simulink* software.

Keywords: Electric Arc Furnace, Static VAR Compensator, TCR-FC, Power Quality, Load balancing, Voltage Fluctuation, Flicker, Power Factor

1. INTRODUCTION

The Electric Arc Furnaces (EAF) are widely used for production of qualified steel and it has steadily expanded during the past few decades. EAF is an unbalanced, nonlinear and time variant load that causes unbalancing and flickers in the current and voltage of its feeding power system.

Voltage fluctuations caused by the EAF are reflected as flicker to other consumers connected to the Point of Common Coupling (PCC). Several methods could be used to minimize the effects of EAF on the power system where utilizing Static VAR Compensators (SVC) for this objective is a well known and cost benefit procedure. Reactive power compensators are employed to reduce the worse effects of load disturbances on the PCC. SVCs can be in any form such as:

- Thyristor-Controlled Reactors (TCR)
- Thyristor-Switched Reactors (TSR)
- Thyristor-Switched Capacitors (TSC)
- Saturated Reactors (SR)
- Fixed Capacitors (FC)
- Thyristor-Controlled Reactors with Fixed Capacitor (TCR-FC)
- …….

where in this paper, an efficient TCR-FC structure is applied for simultaneous elimination of voltage flickers and three-phase current imbalances caused by EAFs.

2. STATIC VAR COMPENSATOR MODEL

The voltage fluctuations at PCC are caused by a change in the reactive power of the EAF load. The proposed SVC can reduce the voltage flickers and can be used for load balancing and also improvement of power factor. So with suitable control of the reactive power, the voltage will be kept almost constant and the fluctuations would be prevented. This paper utilizes SVC in the structure type of TCR-FC as shown in Fig. 1. Changing the thyristor turn-on angle, the amplitude of voltage and current of terminals of SVC will change too, where as shown for two different turn-on angles in Fig. 2.

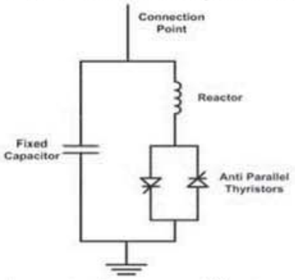

Fig. 1: *Schematic diagram of Thyristor-Controlled Reactors with Fixed Capacitor (TCR-FC)*

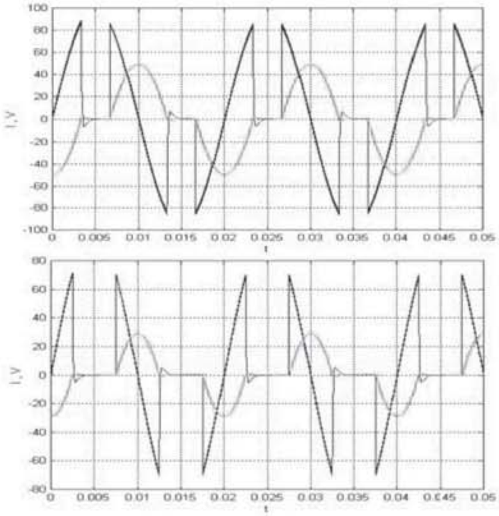

Fig. 2: *The Voltage and current waveforms of SVC for two different turn-on angles of the thyristor*

By changing the turn-on angle of thyristors, the effective value of the fundamental component of the reactor current can be expressed as follow:

$$I_l1(\alpha)=V(2\pi-2\alpha+\sin 2\alpha)/\pi\omega L \qquad (1)$$

where α is turn-on angle of the thyristor, V is effective value of supplied voltage, L is the inductance of reactor and ω is the angular frequency of the applied voltage.

I_L can be expressed as below:

$$I_l1(\alpha)=V.[(\sigma-\sin\sigma)/\pi\omega L] \qquad (2)$$

where σ as the conduction angle equals $(2\pi-2\alpha)$

The effective reactive suseptance $B_L(\sigma)$ is calculated by:

$$B_L(\sigma)=I_L1(\sigma)/V=(\sigma-\sin\sigma)/\pi\omega L \qquad (3)$$

The equivalent suseptance of SVC is given by:

$$B_{svc}=B_c-B_L(\sigma) \qquad (4)$$

The reactive power absorbed by reactor Q_L equals:

$$Q_L= \quad -V^2\times \quad B_L(\sigma)$$

(5) And the capacitive power of TCR-FC can be expended as:

$$Q_c=V^2/X_c=B_c\times V^2 \qquad (6)$$

Then the reactive power flowed through SVC to the network is equal to:

$$Q_{svc}=Q_L+Q_c \qquad (7)$$

3. MODELING CHARACTRISICTICS OF EAF

Fig. 3 shows a single line diagram of a power distribution system feeding an EAF where a SVC is also applied to the system as the proposed compensator. The value of resistance of power supplied and furnace transformer and cables (except the resistance of arc) are much lower than their reactances. But arc resistance in addition to being much higher than other resistances in the network, is time variant therefore; the EAF modeling in accordance with the variable resistance of arc is shown in Fig. 4.

Fig. 5 shows the different operation modes of the EAF where it can be changed from open circuit to short circuit. In normal operation, irregular voltage fluctuations are caused by movement of arc so that some suitable techniques of compensation are needed for restricting and preventing voltage flickers.

The values of resistance and reactance of furnace transformer are also nonsymmetrical. Values of three phase furnace circuit impedance are non equal which results in the line currents to be unbalanced. The load is three phase unsymmetrical load with delta connection.

The load admittances are given by:

$$\begin{aligned} Y_Lab&=G_Lab+jB_Lab\\ Y_Lbc&=G_Lbc+jB_Lbc\\ Y_Lca&=G_Lca+jB_Lca \end{aligned} \qquad (8)$$

Three phase suseptances that are needed for the SVC being connect in parallel with load, for balancing of current and improvement of power factor can be expressed by:

$$\begin{aligned} B_{svc}ab&=(1/\sqrt{3})(G_Lca-G_Lbc)+(1/3)(B_Lbc+B_Lca-2B_Lab)\\ B_{svc}bc&=(1/\sqrt{3})(G_Lab-G_Lca)+(1/3)(B_Lca+B_Lab-2B_Lbc) \quad (9)\\ B_{svc}ca&=(1/\sqrt{3})(G_Lbc-G_Lab)+(1/3)(B_Lab+B_Lbc-2B_Lca) \end{aligned}$$

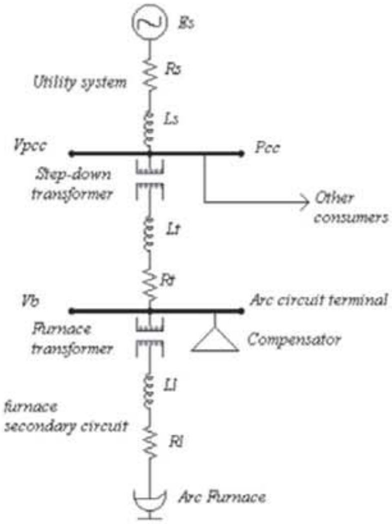

Fig. 3: *Single line diagram of a power distribution system feeding EAF load simulated with Matlab/Simulink*

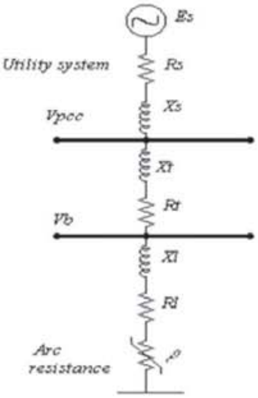

Fig. 4: *EAF load as unbalanced and variable load due to arc resistance characteristics*

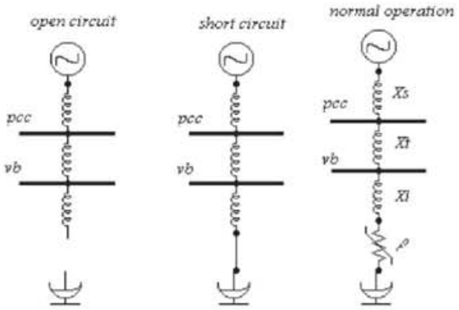

Fig. 5: *Different operation modes of the EAF resulting in time variable load*

To find the conduction angle of the thyristors in TCR-FC, we have:

$$\begin{aligned} B_{svc}ab&=-jB_Lab+j(G_Lca-G_Lbc)/\sqrt{3}\\ B_{svc}bc&=-jB_Lbc+j(G_Lab-G_Lca)/\sqrt{3}\\ B_{svc}ca&=-jB_Lca+j(G_Lbc-G_Lab)/\sqrt{3} \end{aligned} \qquad (10)$$

therefore:

$$B_L ab(\sigma)=B_{svc} ab-B_C ab$$
$$B_L bc(\sigma)=B_{svc} bc-B_C bc \qquad (11)$$
$$B_L ca(\sigma)=B_{svc} ca-B_C ca$$

As Eq. 3 is nonlinear and has a difficult solution, the curve fitting program in the toolbox of *Matlab* software has been applied to find the conduction angle from equation 11 as below:

$$F=polyfit(B_L,\sigma,n) \qquad (12)$$

where n is the order of equation F. These values are calculated and shown in Table 1 for load balancing and voltage flicker prevention procedure for the given arc impedances.

The reactive power needed to be injected to the system to make the furnace voltage be almost fixed at supply voltage value, is shown in Fig. 6. The reactive power that should be injected between two buses (Q_s) to equal their voltages can be obtained as follows:

$$|E|^{1/2}=|V+(R_s.P_L+X_s.Q_s)/V|^{1/2}+|(X_s.P_L-R_s.Q_s)/V|^{1/2} \qquad (13)$$

where after some algebraic computation we have:

$$aQ_s^2+bQ_s+c=0$$

while:

$$a=R_s^2+X_s^2,\quad b=2V^2.X_s,\quad c=(V^2+R_s.P_L)^2+X_s^2.P_L^2-(E^2V^2)$$

Then, B_{Cs} as the capacitive suseptances corresponding with the calculated Q_s is equal to:

$$B_{Cs}=Q_s/(V_{LL})^2 \qquad (14)$$

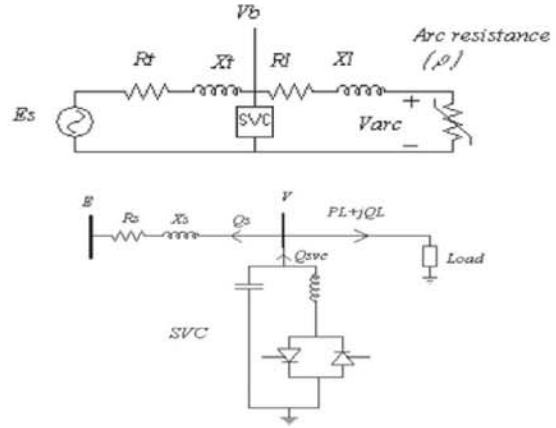

Fig. 6:Reactive power compensation of the proposed SVC

4. STUDY CASE AND SIMULATION RESULTS

For proving the efficiency of the proposed TCR-FC structure of SVC in load balancing and voltage flicker reduction of the power distribution system feeding EAFs, the distribution system in Fig. 4 has been simulated with *Matlab/Simulink* software with a time variable arc resistance, where the impedance variations of the simulated EAF load is shown in Fig. 7. Due to unbalances and time varying arc resistance, the current and voltage waveforms of the distribution system are disturbanced as expected where their single-phase and three-phase waveforms are shown in Figures 8 and 9, respectively.

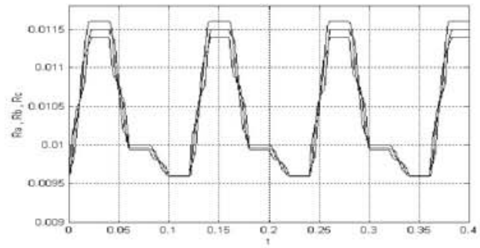

Fig. 7: Impedance variations of the simulated three-phase EAF load with time

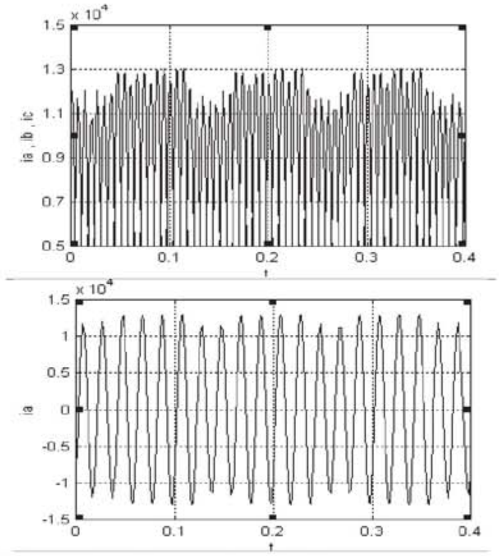

Fig. 8: Three-phase and single-phase currents of arc circuit of EAF load without SVC

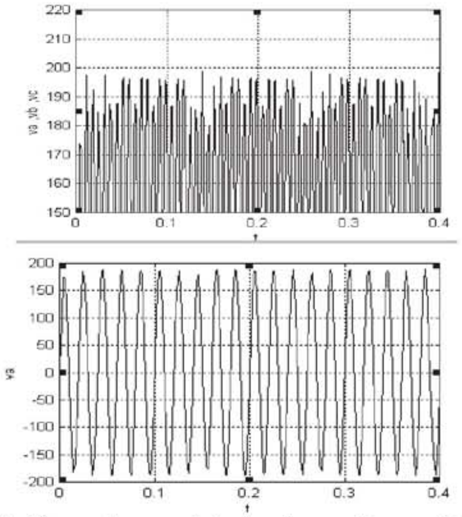

Fig. 9: Three-phase and single-phase voltages of electric furnace load without SVC

Studying the reactive power consumption of the EAF load also indicates its high value which results in low power factor of the system. The waveforms of the reactive power consumption and power factor variations for the three phase of the distribution system feeding the EAF load are shown in Figures 10 and 11, respectively.

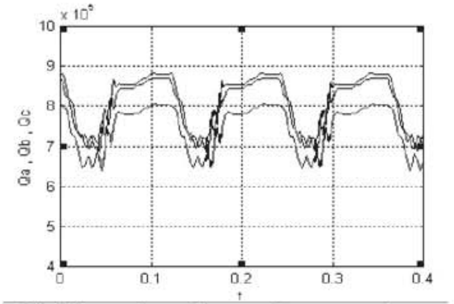

***Fig. 10:** Three-phase furnace input reactive power variation waveform without SVC*

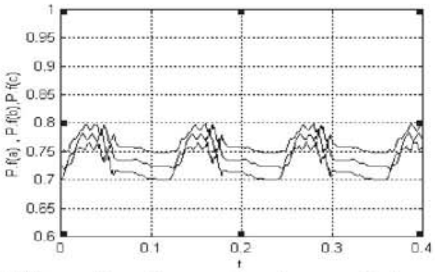

***Fig. 11:** Three-phase furnace input power factor variation waveform without SVC*

Since the three phase resistances are different from each other, the three-phase current of the system is unbalanced which is obvious through studying the current waveform of the sum of the three phases which is different from zero.

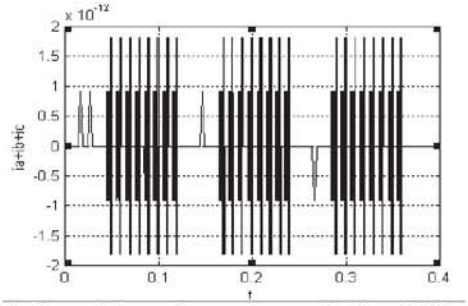

***Fig. 12:** Sum of three phase currents feeding EAF without SVC that shows load unbalancing*

The same simulations are done for the distribution system considering the proposed TCR-FC as SVC where the system current and voltage waveforms are shown in Figures 13 and 14, respectively. Studying these waveforms and comparing them with Figures 8 and 9, the effectiveness of the proposed method in load balancing and voltage fluctuation reduction is verified.

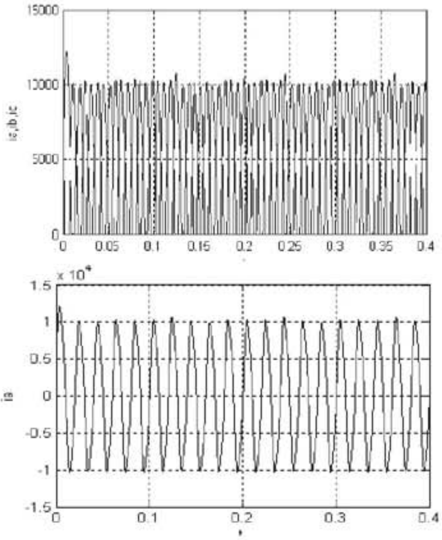

***Fig. 13:** Three-phase and single-phase currents of arc circuit of EAF load with SVC for load balancing*

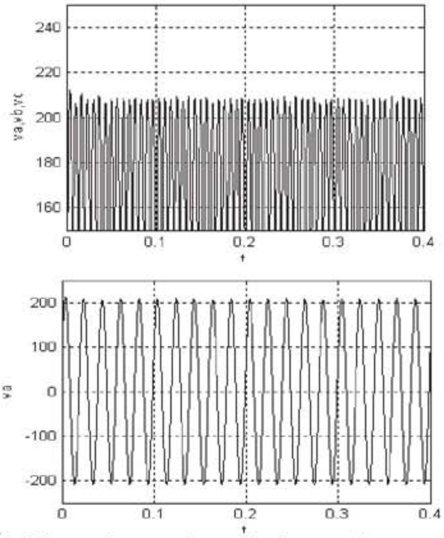

***Fig. 14:** Three-phase and single-phase voltages of electric furnace with SVC for load balancing and voltage flickers*

Comparing the reactive power and power factor variation waveforms for the system with SVCs shown in Figures 15 and 16 and comparing them with Figures 10 and 11, the efficiency of the proposed structure in reactive power compensation and power factor improvement is verified.

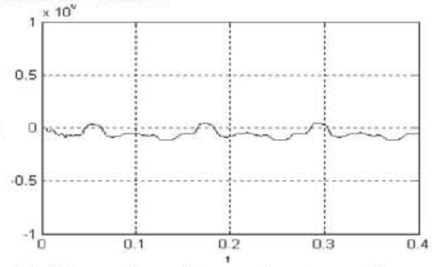

***Fig. 15:** Three-phase furnace input reactive power variation waveform with SVC for load balancing*

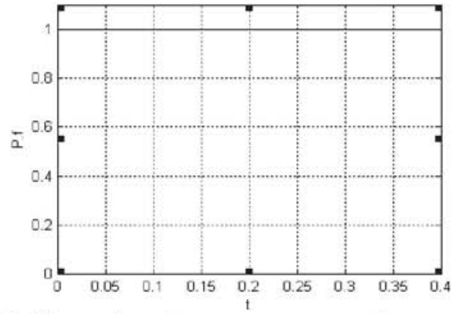

Fig. 16: *Three-phase furnace input power factor variation waveform with SVC for load balancing*

Also, studying the waveform of the sum of the three phases of the system current as shown in Fig. 17 which is zero, proves that the TCR-FC has been capable of balancing the load current, efficiently.

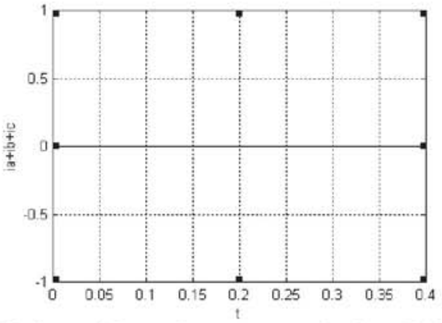

Fig. 17: *Sum of three-phase currents feeding EAF with SVC that shows Load balancing*

5. CONCLUSION

In this paper, an efficient static var compensator in the structure of TCR-FC was proposed and applied for load balancing, voltage fluctuation and flicker reduction, reactive power compensation and power factor improvement of an electric arc furnace load. Electric arc furnaces are unbalanced, nonlinear and time variant loads which cause unbalancing, flickers in voltage and low power factor. Through the simulation results carried out by *Matlab/Simulink* software, the efficiency of the proposed structure was verified.

6. REFERENCES

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Table 1: *Results of calculations for turn-on angles of the thyristors of TCR-FC for different arc impedances in EAFs*

Arc impedances			*Load balancing and voltage flicker elimination*					
$Z_{arc}(a)$	$Z_{arc}(b)$	$Z_{arc}(c)$	$\alpha(ab)$	$B_L(ab)$	$\alpha(bc)$	$B_L(bc)$	$\alpha(ca)$	$B_L(ca)$
0.0112	0.011418	0.011599	121.38	5.88	123.46	6.22	133.29	7.85
0.0099343	0.0099635	0.010099	103.73	4	105.98	4.19	122.75	6.10
0.0095999	0.0095999	0.009699	96.92	3.46	99.16	3.64	119.52	2.08