PERFORMANCE EVALUATION OF COMPOSITE FILTER FOR POWER QUALITY IMPROVEMENT OF ELECTRIC ARC FURNACE DISTRIBUTION NETWORK

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Abstract: *Electrical Arc Furnace (EAF) is one of the responsible cause for deteriorating power quality in the distribution network by, introducing harmonics, propagating voltage flicker and causing unbalance in voltages and currents. This paper presents performance evaluation of composite filter for power quality improvement of EAF distribution network. The composite filter is consisting of a shunt LC passive filter connected with a lower rated voltage source PWM converter based series active power filter (SAPF). Performance of the composite filter (CF) is compared and analyzed with that of passive filter to improve power quality at point of common coupling (PCC). Simulation for a typical EAF distribution network along with the passive filter and the composite power filter has been carried out to validate the performance. The simulations have been carried out in MATLAB environment using SIMULINK and power system block set toolboxes.*

Index Terms-- Active filter, harmonics, harmonic distortion, arc

1. Introduction

The increasing popularity of EAF in metallurgical industries to melt scrap causes significant impacts on power system and on electrical power quality. EAF is one of responsible source for deteriorating the power quality in the connected network [1-3]. The EAF is inherently non-linear, time-variant load and it can cause power quality problems such as current-voltage harmonics, voltage flicker and voltage unbalance. Odd and even harmonic currents are generated by EAF operations. These harmonic currents, when circulated in the electric network can generate harmonic voltages which in turn can affect other users connected in the distribution network. Flicker is the sensation that is experienced by human eye when subjected to changes in the illumination intensity. The maximum sensitivity to change in illumination is in the frequency range of 5 to 15 Hz [4]. As EAF is a large source of flicker, causes voltage fluctuation in the connected electric network which is a major power quality issue. This in turn affects operation of other connected load also. Hence, modeling of EAF has attracted attention of power system engineers to solve these problems of power quality issues pertaining to EAF. The paper is organized as follows: Second section deals with the modeling of EAF as non-linear load. Third section deals with the EAF modeling with power system. Fourth section shows power quality improvement by composite filter. Fifth section discusses performance evaluation of composite filter. Sixth section concludes the paper. Seventh section describes nomenclature.

2. EAF Modeling as Non-linear Load

Mathematical model of Cassie-Mayr EAF model expressed as in [1, 5]:

$$g = g_{\min} + \left[1 - \exp\left(-\frac{i^2}{I_0}\right)\right] \cdot \frac{v \cdot i}{E_0^2} + \exp\left(-\frac{i^2}{I_0}\right) \cdot \frac{i^2}{P_0} - \theta \cdot \frac{dg}{dt} \quad (1)$$

$$\theta = \theta_0 + \theta_1 \cdot \exp(-\alpha \cdot |i|) \quad (2)$$

$$v = \frac{i}{g} \quad (3)$$

Typical values of and E_0, θ_0 , θ_1, α, P_0, I_0, and $g_{\min}$ are tabulated in Table 1[4-6].

Table 1 Cassie-Mayr EAF Model Parameters

Parameter Description	Parameter	Value
Mimimum arc conductance	$g_{\min}$	0.008

Parameter Description	Parameter	Value
Tansition current	I_0	10 A
Momentarily constant steady state arc voltage	E_0	250 V
Momenttarily power loss	P_0	110 W
Time Consatnat	θ_0	110 µs
Time Consatnat	θ_1	100 µs
Constant	α	0.0005

3. EAF Modeling with Power System

Fig. 1 shows EAF connected with the power system.

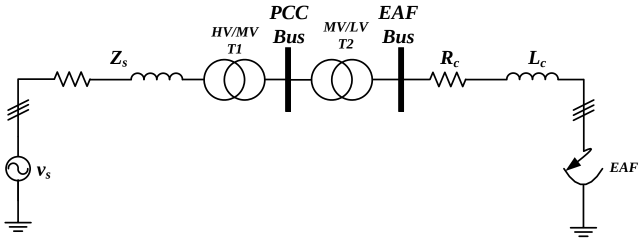


Fig. 1. EAF connected in power system

The system parameters along with proposed EAF Model are tabulated in Table 2 [7].

Table 2 Distribution Network Parameters

Parameter Description	Parameter	Value
Source voltage	V_s	115 kV
Supply frequency	f	50 Hz
Sorce impedance	Z_S	12.19 Ω/82.9 deg
Apparent power	S	100 MVA
Transformer T1 (HV/MV)	$V_P\ /V_S$	110/13.8 kV
	S	30 MVA
Transformer T2 (MV/LV)	$V_P\ /V_S$	13.2/0.55 kV
	S	42 MVA
Cable	R_c	0.38 mΩ
	L_c	8.589 µH

Voltage flicker assessment is also one of the important aspects of power quality study. The assessment of voltage flicker involves the derivation of system RMS voltage variation and the frequency at which the variation occurs. The voltage flicker usually expressed as the RMS value of the modulating waveform divided by the RMS value of the fundamental value, as follows [17-19]:

$$\%\,Voltage\ Flickr = \frac{V_{2P} + V_{1P}}{V_{2P} - V_{1P}} \quad (4)$$

Equation (4) is useful for estimating voltage flicker. A variety of perceptible/limit curves are available in published literature which can be used as general guidelines to verify whether the amount of flicker is a problem [17].

4. Power Quality improvement by Composite Filter

Harmonic distortion in power distribution network can be suppressed using two approaches namely, passive and active filtering. Passive filtering is the simplest conventional solution to mitigate the harmonic distortion. Passive filter (PF) consists of passive parameters C_f, L_f and R_f, calculated by:

$$C_f = \left(\frac{Q}{V^2 \cdot 2\pi f}\right) \quad (5)$$

$$L_f = \left(\frac{1}{C_f \cdot (2\pi f_r)^2}\right) \quad (6)$$

$$R_f = q \cdot 2\pi f_r \cdot L_f \quad (7)$$

Although simple and least expensive, the use passive elements do not always respond correctly to the dynamics of the power distribution systems and it inherits several shortcomings [11, 14, and 16].

A Series active voltage source power filter (SAPF) typically consists of a three phase pulse width modulation (PWM) inverter. When this equipment is connected in series to the ac source impedance it is possible to improve the compensation characteristic of passive filter connected in parallel. This combined topology is known as composite filter shown in Fig. 1, where the series active filter acts as controlled voltage source. Voltage v_c is the voltage that the said inverter should generate to improve the power quality.

There are various control strategies for series active filter control is surveyed in the literature [12, 13 and 15]. In [16] control strategy based on the dual formulation of the electric power vectorial theory is implemented for balance and resistive load. In this paper an attempt is made to apply the same control theory for unbalanced and non-sinusoidal voltage conditions for randomly varying load as an electric arc furnace (EAF). Voltage reference signals for

SAPF under unbalanced and non-sinusoidal load environment are given by:

$$\begin{bmatrix} v_{ca}^* \\ v_{cb}^* \\ v_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{c\alpha}^* \\ v_{c\beta}^* \end{bmatrix} \quad (8)$$

Where,

$$\therefore v_{c\alpha}^* = \left(\frac{P_L}{I_1^{+2}} - \frac{p_L}{(i_\alpha^2 + i_\beta^2)} \right) \cdot i_\alpha - \frac{q_L}{(i_\alpha^2 + i_\beta^2)} \cdot i_\beta \quad (9)$$

$$\therefore v_{c\beta}^* = \left(\frac{P_L}{I_1^{+2}} - \frac{p_L}{(i_\alpha^2 + i_\beta^2)} \right) \cdot i_\beta + \frac{q_L}{(i_\alpha^2 + i_\beta^2)} \cdot i_\alpha \quad (10)$$

Where, I_1^+ is defined as:

$$I_1^+ = \sqrt{i_{1a}^{+2} + i_{1b}^{+2} + i_{1c}^{+2}} \quad (11)$$

Where, i_{1a}^+, i_{1b}^+ and i_{1c}^+ are fundamental components of the positive sequence currents of phases a, b and c respectively. The load and series active filter will behave as a resistor with R_e value for the reference signal supplied by (8). Reference signals are obtained by means of reference calculator shown in Fig. 2. The input signals are the voltage vector measured at the load side and the current vector measured at the source side. By means of calculation block, $v_{\alpha\beta}$ and $i_{\alpha\beta}$ vectors in $\alpha\beta$ coordinates can be calculated. The real instantaneous power is divided by $i_{\alpha\beta}^2$ as shown in Fig. 2. The result is multiplied by the current vector $\bar{i}_{\alpha\beta}$, which allows the first term in the compensation voltage in (9)-(10) to be determined.

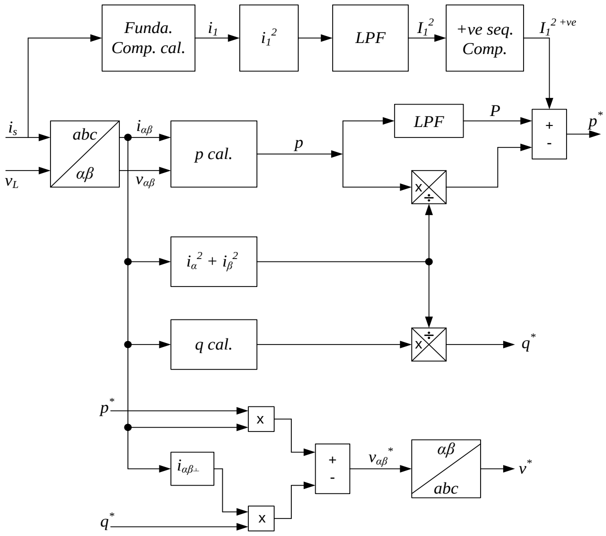
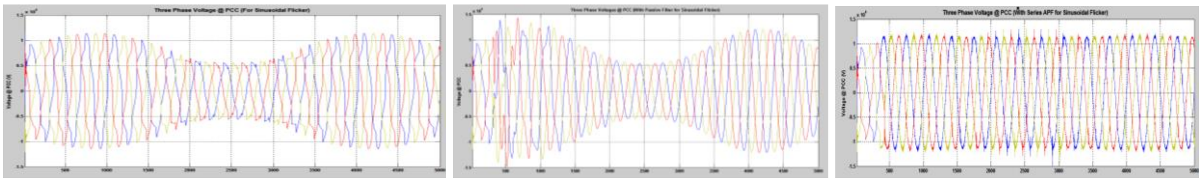


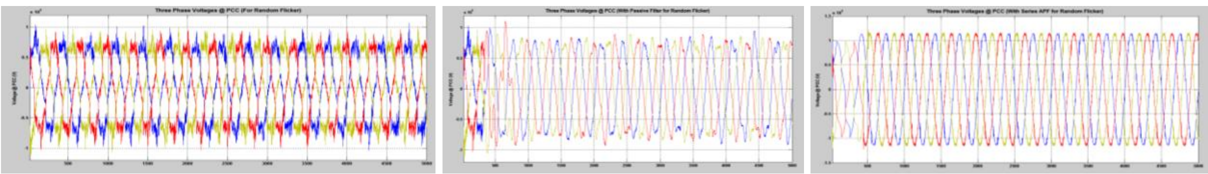
Fig. 2. Reference signal calculator

On the other hand, the imaginary instantaneous power is obtained and divided by $i_{\alpha\beta}^2$ and then multiplied by the current vector $\bar{i}_{\alpha\beta\perp}$. This determines the second term in the compensation voltage (9)-(10).



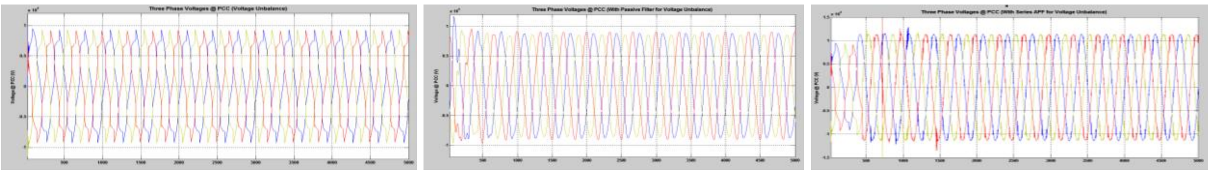
(a) **(b)** **(c)**

Fig. 3. Three phases V_{PCC} for sinusoidal flicker (a) Without filter (b) With Passive Filter (c) With Composite filter



(a) **(b)** **(c)**

Fig. 4. Three phases V_{PCC} for random flicker (a) Without filter (b) With Passive Filter (c) With Composite filter



(a) **(b)** **(c)**

Fig. 5. Three phase voltage unbalance (a) Without filter (b) With Passive Filter (c) With Composite filter

Table 3Voltage Harmonic Analysis

Parameter	Refining Cycle			Melting Cycle (Random Flicker)			Melting Cycle (Sinusoidal Flicker)		
	Without Filter	*With Passive Filter*	*With Composite Active Filter*	*Without Filter*	*With Passive Filter*	*With Composite Active Filter*	*Without Filter*	*With Passive Filter*	*With Composite Active Filter*
Vpeak (V)	10130	9433	11400	7306	7777	11400	5312	5599	11180
Vrms (V)	7166	6670	8064	5166	5499	8064	3756	3959	7906
THDv (%)	14.43	1.45	1.85	15.19	5.38	1.85	5.83	1.32	2.32
H2 (%)	0	0	0	2.29	1.64	0.01	0.53	0	0.04
H3 (%)	0	0	0	1.85	3.15	0.01	0.09	0.25	0.06
H5 (%)	10.78	1.29	0.64	8.74	0.75	0.64	4.34	0.71	0.17
H7 (%)	7.24	0.53	0.44	6.62	0.79	0.44	2.84	0.24	0.15
H11 (%)	4.04	0.08	0.23	2.88	0.06	0.23	1.68	0.03	0.09
H13 (%)	3.17	0.05	0.18	4.09	0.12	0.18	1.2	0.06	0.06
H17 (%)	2.13	0.16	0.09	1.37	0.16	0.09	0.68	0.03	0.08

Table 4 Current Harmonic Analysis

Parameter	Refining Cycle			Melting Cycle (Random Flicker)			Melting Cycle (Sinusoidal Flicker)		
	Without Filter	*With Passive Filter*	*With Composite Active Filter*	*Without Filter*	*With Passive Filter*	*With Composite Active Filter*	*Without Filter*	*With Passive Filter*	*With Composite Active Filter*
Ipeak (A)	977.4	1459	150.5	1932	1848	150.5	2374	2284	210.6
Irms (A)	691.1	1032	106.4	1366	1307	106.4	1679	1615	148.9
THDi (%)	9.09	0.63	4.03	3.35	2.94	4.03	0.81	0.32	1.61
H5 (%)	8.04	0.6	3.53	2.38	0.36	3.52	0.7	0.11	0.73
H7 (%)	3.86	0.17	1.74	1.29	0.19	1.74	0.31	0.04	0.4
H11 (%)	1.37	0.02	0.56	0.36	0.12	0.56	0.1	0.01	0.05

Table 5 Power Analysis

Parameter	Refining Cycle			Melting Cycle (Random Flicker)			Melting Cycle (Sinusoidal Flicker)		
	Without Filter	*With Passive Filter*	*With Composite Active Filter*	*Without Filter*	*With Passive Filter*	*With Composite Active Filter*	*Without Filter*	*With Passive Filter*	*With Composite Active Filter*
P (KW)	5249	5863	527	5249	5863	527.8	3732	4574	404.1
Q (KVAr)	2720	3808	123.5	2719	3808	118.1	2923	3917	106.3
PF	0.89	0.84	0.97	0.89	0.84	0.98	0.79	0.76	0.97

Table 6 Filter Performance in Voltage Harmonics

Parameter	Refining Cycle		Melting Cycle (Random Flicker)		Melting Cycle (Sinusoidal Flicker)	
	With Passive Filter	*With Composite Active Filter*	*With Passive Filter*	*With Composite Active Filter*	*With Passive Filter*	*With Composite Active Filter*
H5 (%)	88.03	94.06	91.42	92.68	83.64	96.08
H7 (%)	92.68	93.92	88.07	93.35	91.55	94.72
H11 (%)	98.02	94.31	97.92	92.01	98.21	94.64
H13 (%)	98.42	94.32	97.07	95.60	95.00	95.00
H17 (%)	92.49	95.77	88.32	93.43	95.59	88.24
THD_V (%)	89.95	87.18	64.58	87.82	77.36	60.21

Table 7 Filter Performance in Current Harmonics

Parameter	Refining Cycle		Melting Cycle (Random Flicker)		Melting Cycle (Sinusoidal Flicker)	
	With Passive Filter	*With Composite Active Filter*	*With Passive Filter*	*With Composite Active Filter*	*With Passive Filter*	*With Composite Active Filter*
H5 (%)	92.54	56.09	84.87	-47.90	84.29	-4.29
H7 (%)	95.60	54.92	85.27	-34.88	87.10	-29.03
H11 (%)	98.54	59.12	66.67	-55.56	90.00	50.00
THD_I (%)	93.07	55.67	12.24	-20.30	60.49	-98.77

Table 8 Filter Performance in Voltage Unbalance

Parameters	Without Filter	With Passive Filter	With Composite Filter
Peak Voltage Unbalance (%)	4.69	4.48	94.24
RMS Voltage Unbalance (%)	4.69	4.48	93.60

Table 9 Voltage Flicker Analysis

Parameters	Without Filter	With Passive Filter	With Composite Filter
Voltage Measurement			
V_{1P} (Volts)	5000	5100	11500
V_{2P} (Volts)	12000	12000	11800
% Flicker Calculation			
% Voltage Flicker	41.18	40.35	1.29

Table 10 Filter Performance in Reducing Voltage Flicker

Parameters	Without Filter	With Passive Filter	With Composite Filter
% Voltage Flicker	41.18	40.35	1.29
% Improvement	-	2.01	96.87

5. Performance Evaluation Composite Filter

Fig. 3(a) represents three-phase voltages at PCC during melting cycle of an EAF (considering sinusoidal flicker generation). Fig. 3(b) and Fig. 3(c) show performance of passive filter and composite filter respectively. It indicates that the passive filter fails to clear sinusoidal voltage flicker where as composite filter reduces voltage flicker from 41.18 % to 1.29 % as tabulated in Table 9, calculated as per (4). For 4 Hz of frequency pulsation applied and for 1.29 of %voltage pulsation (%voltage flicker) with composite filter, the operating point lies in non-perceptible [9]. Similarly Fig. 4 shows performance of passive and composite filter during melting cycle of an EAF for random flicker generation condition. It clearly indicates best performance of composite filter in removing random flicker compared to passive filter. Detailed quantified voltage and current harmonic analysis at PCC is tabulated in Table 3 and Table 4 respectively. Table 5 shows power analysis. Table 6 shows best performance of composite filter compared to passive filter in removing voltage harmonics. Similarly, Table 7 shows performance of composite filter compared to passive filter in removing current harmonics. Table 8 shows performance comparison of composite and passive filter in clearing voltage unbalance. Table 10 indicates performance comparison of composite filter and passive filter in clearing voltage flicker. Performance evaluation of composite filter compared to passive filter under various operating cycles of an EAF shows that composite filter performs better than the passive filter alone, as per Table 6 to Table 10.

6. Conclusions

This paper describes performance evaluation of composite filter for power quality improvement of electrical electric arc furnace distribution network. First of all, distribution network is simulated using Cassie-Mayr EAF model. The simulated EAF distribution network is used for power quality analysis including voltage-current harmonics, voltage flicker and voltage unbalance. Next, a control strategy for a composite filter, which is connected with the existing passive filter, is proposed for taking care of the unbalance, non-sinusoidal and randomly varying EAF. The control strategy is based on the dual vectorial theory of power. Finally, detail performance of composite filter is evaluated by comparing its performance with passive filter for various operation cycles of EAFs connected distribution network. Performance comparison shows that, the proposed composite filter performs better than the passive filter alone for harmonic compensation, voltage flicker mitigation, and for clearing voltage unbalance on EAF load side.

7. Nomenclature

i =Arc current
v =Arc voltage
g =Arc conductance
E_0 =Momentarily constant steady state arc voltage
θ =Arc time constant
θ_0 =Constant
θ_1 = Constant
α = Constant
P_0 =Momentarily power loss
I_0 =Transition current
g_{min} =Minimum conductance
THD_I =Total Current Harmonic distortion
THD_V = Total Voltage Harmonic distortion
Q =Reactive power to be generated by the filter at fundamental frequency

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