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Performance evaluation of composite filter for power quality improvement of electric arc furnace distribution network

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ABSTRACT

Electric 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 (CF) for power quality improvement of EAF distribution network. The performance of CF is evaluated in terms of harmonic and voltage flicker mitigation capability of CF. 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 PF and the CF 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.

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 [1–7]. Barker et al. have done the Niagara Mohawk Power Corporation's Research and Development Department sponsored a major power quality study of two distribution feeders in the Buffalo, New York region [1]. The different phases in the operation of the arc furnace are described in detail and illustrated with measurements in [2]. By measurements of flicker, harmonics content in voltage and current, active and reactive power and power factor, the preservation of the reference levels for the supply voltage and emission limits for the furnace as a customer are evaluated. A three-phase electric arc furnace power quality indices such as flicker severity index, PCC voltage and load current disturbances, reactive power, harmonics, inter-harmonics and imbalance are presented in [3]. Electrical Power Quality of Iron and Steel Industry in Turkey is presented in [4]. The various electrical quantities like voltages, currents, frequency, and flicker, regarding power quality are measured and recorded at different voltage buses; the same are compared with power quality standards in [5]. Experimental survey presented in [6] show that EAFs represent a substantial source of electric disturbances, such as voltage fluctuations, flicker, harmonics, and unbalance between phases. A Saudi Steel Mill Case Study presented in [7] describes measurement of various power quality indices.

Thus, 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. 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 [8–10]. 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 5–15 Hz [11].

This paper describes application and performance evaluation of composite filter for power quality improvement of electrical electric arc furnace connected distribution network. First of all, distribution network is simulated using Cassie–Mayr EAF model. The simulated EAF distribution network is used for detailed power quality analysis including voltage-current harmonics, voltage flicker and voltage unbalance under sinusoidal and distorted

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Nomenclature

i	arc current	$g_{\min}$	minimum conductance
v	arc voltage	THD_I	total current harmonic distortion
g	arc conductance	THD_V	total voltage harmonic distortion
E_0	momentarily constant steady state arc voltage	C_{dc}	DC link capacitor
θ	arc time constant	v_{ref}	reference voltage
θ_0	constant	v_{dc+}, v_{dc-}	monitored dc voltage
θ_1	constant	v_{inv}	inverter output voltage
α	constant	PF	passive filter
P_0	momentarily power loss	CF	composite filter
I_0	transition current	PI	proportionate integral

voltage source conditions. 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 of PF and CF for sinusoidal source voltage, for distorted source voltage and for +10 variations in filter parameters values is evaluated by MATLAB-Simulink platform. The CF performance found satisfactory in refining cycle and in melting cycle (considering sinusoidal flicker and random flicker) of an EAF under sinusoidal and under distorted source voltage conditions. Performance of CF is not affected by changes in the tuning frequency of the passive filter for an EAF demanding even random power variation in melting cycle. Furthermore, the reactive power variation is compensated by the APF. Series and/or parallel resonance with the rest of the system are avoided because composite filter presents resistive behavior. 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.

EAF modeling as non-linear load

Mathematical model of Cassie–Mayr EAF model expressed as in [8,12]:

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

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

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

Typical values of and E_0, θ_0 , $\theta_1, \alpha, P_0, I_0$, and $g_{\min}$ are tabulated in Table 1 [11–13].

EAF modeling with power system

Fig. 1 shows EAF connected with the power system.

The system parameters along with proposed EAF Model are tabulated in Table 2 [14–17].

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 [18–20]:

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

where V_{1P} is lower peak of modulating voltage and V_{2P} is upper peak of modulating voltage. Eq. (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 [18].

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:

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

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

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

Q is reactive power to be generated by the filter at fundamental frequency, V is voltage at which filter is to be installed, q is quality factor, f is fundamental frequency and f_r is tuning frequency where r is harmonic order. The filtering performance of the passive filter is determined by this impedance except for resonant frequency. Therefore, the capacitance value should be as high as possible and inductance value should be as low as possible to obtain low characteristic impedance. However large capacitance value makes the passive filter bulky and results in a high reactive current. Selecting a low inductance value also increases the switching ripples. By considering all these criteria and to minimize the initial cost of the system, a 2720 kVAr passive filters at 13.8 kV line voltage tuned for 5th, 7th and 11th harmonic order are decided to used in the hybrid power system. L_f and C_f parameters are calculated using (5)–(7) as follows:

Table 1
Cassie–Mayr EAF model parameters.

Parameter description	Parameter	Value
Minimum arc conductance	$g_{\min}$	0.008
Transition current	I_0	10 A
Momentarily constant steady state arc voltage	E_0	250 V
Momentarily power loss	P_0	110 kW
Time constant	θ_0	110 µs
Time constant	θ_1	100 µs
Constant	α	0.0005