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Analysis of Power Quality Disturbances in Industrial Distribution System

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Abstract: Due to the increased globalization, industrial revolution is happening at a rapid pace,the modern day insustial loads comprises of different power converters,electromechanical devices, furnaces, electronic equipment and computing devices to perform various process according to the needs of industrial applications, stochastic and non linear loads used to perform the desired operation introduces variety of power quality disturbances to the grid and inturn distracts the operation and performance of the associated loads within the industry,the power quality issues like harmonics,interharmonics, voltage sag and voltage flicker are commonly observed phenomenon, in this paper an attemped is made to model and simulate the industrial loads and analyse the impact of the power quality disturbances in an interconnected industrial distribution system.
Keywords: Power quality, power converterselectric arc furnace (EAFs), voltage flicker, harmonics, voltage sag.

1. Introduction

The term electric power quality deals with the quality of the power delivered by the service provider to the consumer loads and the quality of the power supplied depends on the wide variety of electromagnetic phenomenon that describe the characteristics of the current and voltage at particular location on the power system many factors contribute to the growing concerns on electric power quality, primarily the consequences of poor power quality on the sensitive electronic components and processing units in the industries having direct impact on the productivity and indirect effect on the economics has gained significant interest amongst the customers as the power system networks are interconnected to cater the needs of power supply, consequences due to the poor power quality in an interconnected system will be experienced by both customer and service providers hence the monitoring and characterization of these power quality disturbances plays an vital role in assessment and suppression of the disturbances[1]

The power electronics based equipment are often used as power conditioners/power modulators to modulate the power and provide power conversions, such power modulators are widely used in power supplies, DC motor drives, battery chargers, variable speed drives ,electronic ballasts, power modulators are realized by power electronics switches which are inherently nonlinear in nature, the nonlinear phenomenon results in waveform distortion, represented by the presence of harmonics, inter harmonics, DC offset, notch and noise resulting in decreased power factor on the supply side and associated problems on the power system components. These nonlinear loads acts as major contributors of waveform distortion in a power system network. Harmonic currents developed by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC).These perturbations (harmonics) are the origin of severe problems affecting electrical equipment connected to the power supply. The negative impacts of harmonics includes increased core losses in magnetic circuits of induction motor and transformers, saturation and malfunctioning of distribution transformers, pseudo tripping of the protective devices ,electromagnetic interferences, destruction of consumer equipment reduction in performance and life of power system components, torque pulsation in induction motors few amongst the many consequences of harmonics [2-4]

The terms voltage sag according to IEEE and Voltage dip in accordance with IEC deals with the phenomenon of short duration voltage variations, here the system experiences a decreased voltage level between 0.1 and 0.9 P.U. in rms voltage at the power frequency for durations of 0.5 cycle to 1 min.

Voltage sag, voltage swell and short duration voltage interruption fall under the category of short duration voltage variations ,voltage sag are caused due to switching off of capacitor banks starting of heavy loads line to ground faults, high inrush current during starting of high power rated induction motors , the voltage is considered to be highly significant due to its characterization resulting in Motor load to start/ stop, Digital devices to reset causing loss of data, Equipment damage and /or failure.[5-6]

Power system network comprises of wide variety of loads characterized by intermittent or strong variations in power consumptions the nature of such loads are described by sudden increase in current resulting in voltage flickering leading to the rise in intensity of light specially observed in incandescent lamps, further flickering in intensity of the lamps can provide information pertaining to the electromagnetic compatibility. [7]

Modern day steel manufacturing industry makes use of EAFs for production of steel and these loads are characterized by time-variant and non-linear loads, the consequences of these loads imposes power quality disturbances like waveform distortions, voltage flickering and unbalanced voltages and currents.

The cumulative consequences of various power quality disturbances on equipment cab be briefed as instantaneous and accumulated. On the broader scale, the effects of voltage flicker is normally not considered as a serious threat and hence neglected, and is considered as merely a fluctuation in light intensity, Several literature suggests ,an instantaneous response due to flickering phenomenon are of most concern many investigations discuss the severe impacts of voltage flicker on power system components one such study describes the response of induction motor response to regular voltage fluctuations , author puts forward several the simulation results related to the effect of the voltage fluctuation phenomenon on electrical equipment performance, including motors, PWM-VSI converters, linear and switched sources .the obtained simulation results discusses that machine performance parameters such as motor torque and speed, converter voltages and switched source output voltages show considerable deviations from its standard operation when the flicker index P_st is unity[8]

Further, the long-term accumulated effect appearing due to voltage flicker cannot be ignored, for example, the machine winding extra power loss and relative temperature increase, etc. Paper [9] carries a detailed investigation on accumulated effects on voltage flicker, harmonics and unbalanced conditions on induction motor and proposes a new PQ index determined from temperature rise test in induction motor windings subjected for longer duration operation.

In this paper, an attempt is made to model and simulate the time domain modelling of electric arc furnace to evaluate the power quality disturbances due to EAFs, simulation of power converters for harmonics and simulation of induction motor for voltage sag analysis are studied, the combined network of a typical industrial distribution system is simulated to analyse impact of the interconnected system in the polluted power quality environment.

2. Load Modelling Of EAF

The nonlinear characteristic of the furnace at any instant of time is dependent on the conditions of the EAF and is time variant in nature.

The time response of an EAF is basically dependent on topology of the external circuit, length of arc and positions of electrodes, literature suggests several works to describe an electric arc. The balanced steady state equations are employed in [9, 10]. The differential equations based time domain methods are presented in [11, 12].Some of the models are based on stochastic characteristics of the EAF which are mainly suitable for voltage flicker analysis [13, 14].

Time domain analysis of an EAF considers the parameters are determined based on the unbalanced currents and distorted voltage source. But the time domain models also uses an approximated step [11]

Comparative study of different EAF model in the frequency and time domain [9], describes that analysing the parameters of an EAF has achieved better in time domain, nevertheless the frequency domain models are provides beneficial information for harmonic analysis of the external network.[11,15]

The above mentioned methods for modelling of EAF pose certain limitations with regards to initial conditions for the differential equations, balanced situation of the three phase currents and application of complex equations, this paper proposes a new approach for the modelling of an EAF model for the EAF in the time domain. Without any approximations of initial conditions, to provide the sensible information regarding the voltage flicker sinusoidal noise are introduced to analyse the effect of EAF.

Hyperbolic Model

Here, Arc voltage as a hyperbolic function of the arc current is expressed as in equation 1.

$$v = sign(i)[v_{at} + \frac{C}{D+|i|}] \quad (1)$$

Where, i: Arc current

v: Arc voltage

v_{at}: Threshold voltage

Exponential Model

Arc voltage as a exponential function of the arc current is expressed as in equation 2,

$$v = v_t\left(1 - e^{\frac{|I|}{I_0}}\right) sign(i) \quad (2)$$

I_0: current constant is employed to realize the slope of positive and negative currents.

Exponential-Hyperbolic Model

In this model, the combination of Hyperbolic and exponential is presented, the VI Characteristics of this model is expressed by equation 3.

$$v = \begin{cases} \left[v_{at} + \frac{C}{D+|i|}\right], & \frac{di}{dt} > 0, i > 0 \\ v_t\left(1 - e^{\frac{|I|}{I_0}}\right), & \frac{di}{dt} < 0, i > 0 \end{cases} \quad (3)$$

The increase in the arc current is expressed as a hyperbolic function and decrease in the arc current is represented as an exponential function.

The dynamic behaviour of an EAF is significant for the flicker analysis, dynamic analysis is obtained by replacing the static behaviour of the above models with dynamic behaviour.

3. System Consideration for Study

In order to study the power quality disturbance effect due nonlinear loads, a typical industrial load distribution system is proposed and is as shown in the figure 1.

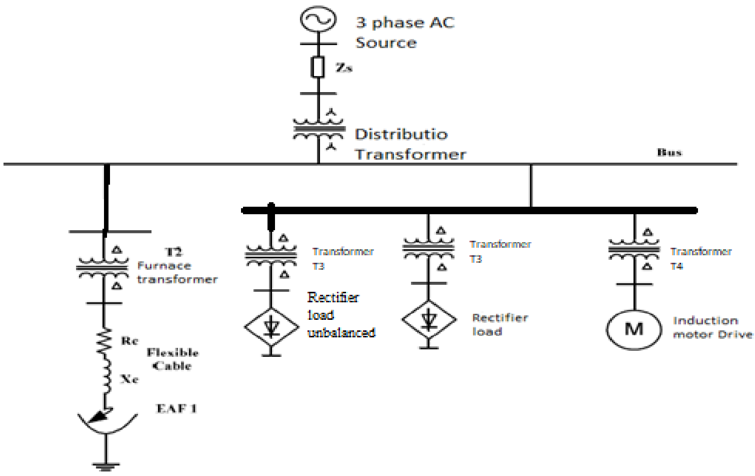


Fig 1: Typical industrial load distribution system

The system configuration of a typical industrial load distribution system considered for the study is assumed to be comprising of four major loads and they are Electric Arc Furnace, balanced uncontrolled Bridge Rectifier, Unbalanced uncontrolled bridge rectifier and an Induction motor load.

Load 1: An Electric Arc Furnace used for melting of steel is represented by its hyperbolic characteristic equation; where the operation of an EAF injects Current harmonics, Inter harmonics and Voltage Flicker into the system.

Load 2: It is a balanced uncontrolled bridge rectifier, used for AC/DC Conversion; the operation of the rectifier injects the harmonics into the system.

Load 3: It is an unbalanced uncontrolled bridge rectifier, used for AC/DC Conversion; the operation of the rectifier injects the harmonics into the system of variable THD according to the load conditions.

Load 4: Induction motor Drive System, used for various drive requirements in the industry, due to high inrush starting current of an induction motor which creates voltage sag at the supply bus.

4. Results And Discussion

The characteristics of various arc models can be studied by considering a simple EAF in single phase. The EAF system configuration is shown below.

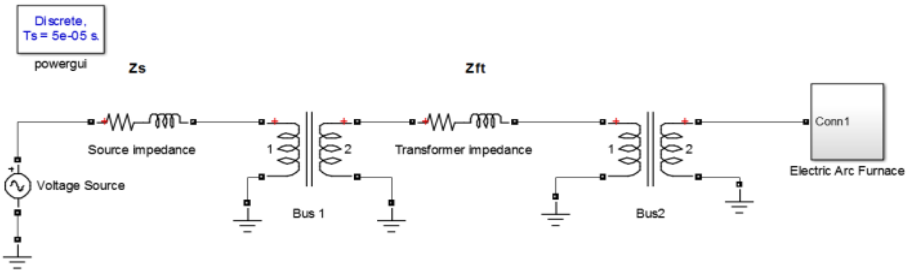


Fig 2: Single phase system of Electric arc furnace

Figure 2 represents the single phase test system developed for analysis of the power quality disturbance due to electric arc furnace, system comprises of single phase AC source feeding an EAF through networks parameters, the specifications of the network parameters are as mentioned in the table 1.

Table 1: specifications of the modelled single phase EAF system

Specifications of simulated circuit	
Utility	Short Circuit Power=7250 MVA Utility Voltage=380 kV R=0.071 m Ω, L=0.027 mH
Step down Transformer	Transformer Voltage Level=380kV/34,5Kv Transformer Power=100 MVA %z=15 R=0.096 m Ω, L=2.469 mH
EAF Transformer	Transformer Voltage Level=34,5kV/719V Transformer Power=60 MVA %z=4.9 R=0.527 m Ω, L=1.343 mH
Line	R=0.004 m Ω, L=0.010 mH
Secondary Circuit	R=0.6112 m Ω, L=12.69 mH
Hyperbolic Model	V_{at}: 289.75 V C_i:190 kW C_d:39 kW $D_{i,d}$:5000
Exponential Model	V_{at}: 289.75 V I_0:10 kA
Exponential- Hyperbolic Model	V_{at}: 289.75 V C_i:190 kW C_d:39 kW $D_{i,d}$:5000

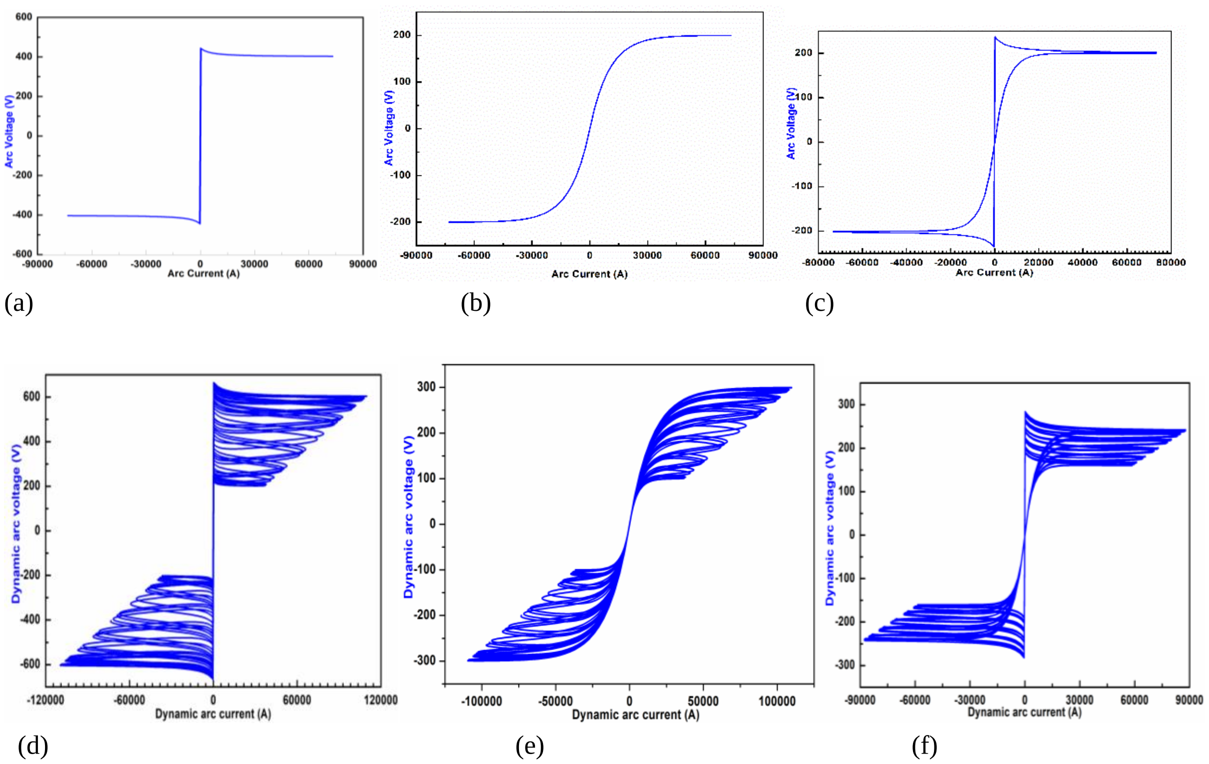


Fig 3: static and dynamic characteristics of time domain models of EAF

Figure 3 represent the static and synatic VI characteristics of time domain models, figure 3a-3c describes the static VI characteristics of hyperbolic, exponential and exponential-hyperbolic respectively and figure 3d-3f represents the static VI characteristics of hyperbolic, exponential and exponential-hyperbolic respectively.

From the static characterists it is inferred that the VI characterisics are non linear in nature and hence shows the exixtentce of harmonic currents in the system.the dynamic characteristics indicates the existence of the voltage flicker in the system,

Detailed harmonic analysis and flicker analysis is carried out for the modelled EAFs, the harmonic content and THD are tabulated as below.

Table 2: Harmonic Component Comparisons of Different Stages of Operation

Harmonic order	**Hyperbolic model**		**Exponential model**	**Exponential hyperbolic model**
	Melting stage	**Refining stage**		
3^{rd} order(%)	10.530%	8.150%	4.470%	0.350%
5^{th} order(%)	2.810%	2.400%	1.100%	0.180%
7^{th} order(%)	1.100%	1.010%	0.660%	-
9^{th} order(%)	0.690%	0.600%	0.400%	-
THD (%)	15.950%	11.860%	11.810%	8.400%

Table 2 presents the order of harmonic distortion in an arc furnace current of the above time domain models. Melting stage in an EAF is characterized by highly unstable arcing phenomenon, hence it displays highly nonlinear characteristics during the melting stage resulting in injection of highly dominant lower order harmonics contributing for the increased total harmonic distortions, whereas the refining stage is comparatively stable, hence the harmonic distortions are observed to be less during the refining stage in hyperbolic model.

exponential and Exponential- Hyperbolic model of an EAF signifies that , VI characteristics gradually align towards the linear region, hence Exponential- Hyperbolic model indicates distortions in comparison with hyperbolic model.

It is also evident that the harmonics spectrum comprises of inter harmonics in addition to the harmonics, which cumulatively results in the overall increase of distortion levels in the system.

TABLE 3: Voltage Flicker of Different Time Domain Models

Model	% Voltage Flicker
Hyperbolic Melting Stage	1.54
Hyperbolic Refining Stage	2.01
Exponential	10.85
Exponential hyperbolic	23.45

Table 3 put forward the information regarding the flicker levels of the time domain models, it is observed that the voltage flicker is high is case of hyperbolic-exponential model than the others.

The simulation studies are carried out to evaluate and analyze the power quality disturbance as per the system described in figure 1.simulations are carried out to for various cases to evaluate the power quality disturbances individually and the combined model to analyze the cumulative effect of all the nonlinear loads put together.

Simulations carried out for various loads as below
Case1: Balanced uncontrolled rectifier
Case2: Unbalanced uncontrolled rectifier
Case 3: Hyperbolic model of EAF
Case 4: Induction Motor
Case 5: Balanced and Unbalanced uncontrolled rectifier with EAF
and Induction motor.

Case 1: Balanced uncontrolled rectifier

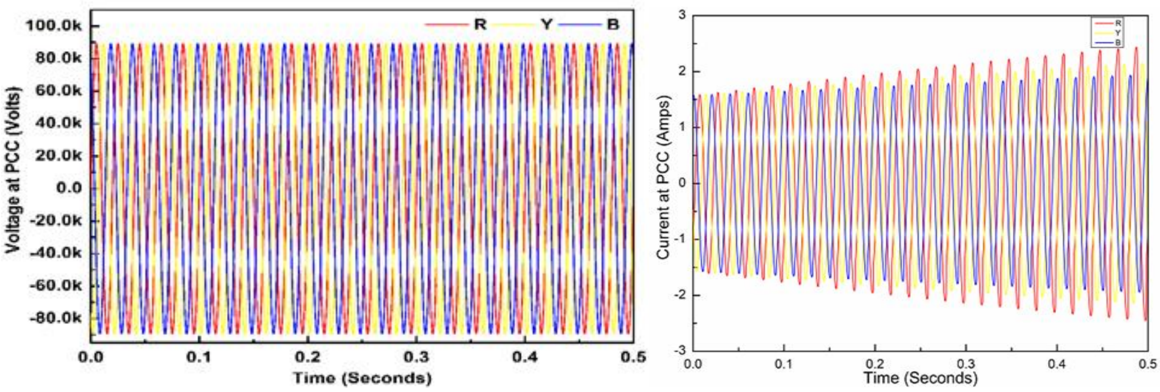
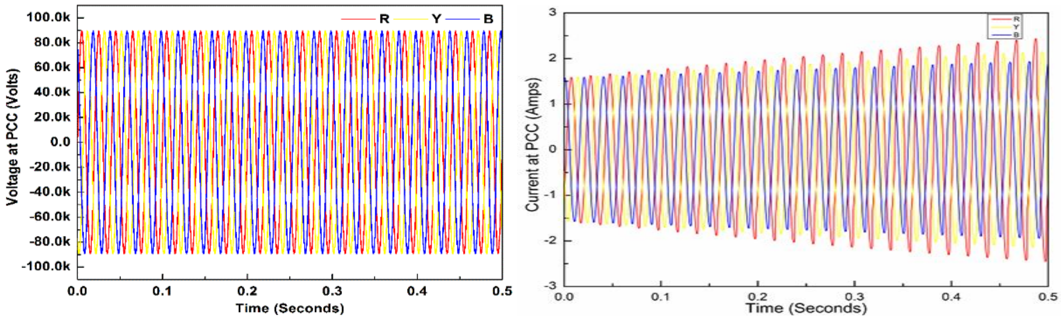


Fig 4: Voltage and Current waveforms for system feeding a Balanced Uncontrolled Rectifier load

Figure 4 presents the waveforms of current and voltages at the PCC for a system feeding Balanced Uncontrolled Rectifier load, Since the nature of the uncontrolled rectifier is nonlinear in nature the following observations are made:

The current THD for R phase Y phase and B phase are 8.01%, 8.12% and 8.07% respectively, as the load is balanced it is observed that the Current THD of all the line currents almost equal and the voltage THD is observed to be <1%,the average DC voltage is found to be 1100V.

Case2: Unbalanced uncontrolled rectifier

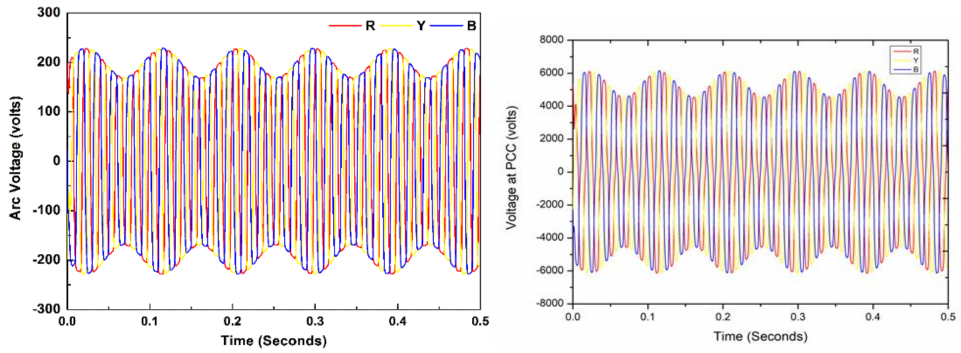


(a) (b)

Fig 5: Voltage and Current waveforms for system feeding a Balanced Uncontrolled Rectifier load

Figure 5 presents the waveforms of current and voltages at the PCC for a system feeding Unbalanced Uncontrolled Rectifier load, The current THD for R phase Y phase and B phase are 11.62%, 12.61% and 10.09% respectively, since the load is unbalanced in nature, it is observed that the Current THD of all the line currents are different depending on the load conditions and voltage THD is observed to be <1%,

Case 3: Hyperbolic model of EAF



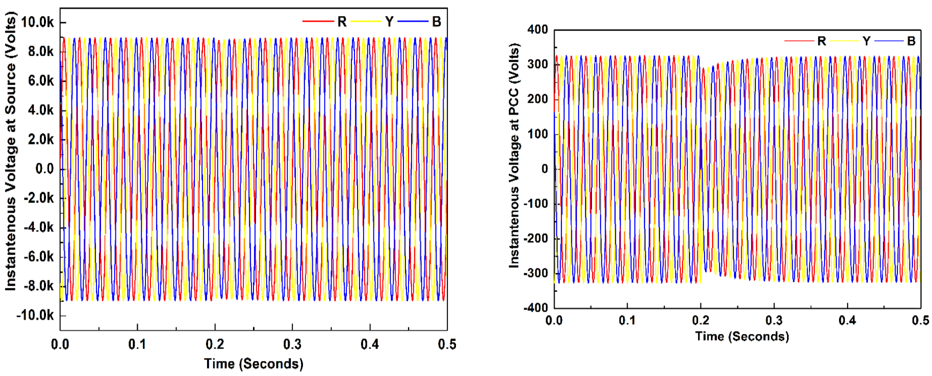
(a) (b)

Fig 6: Voltage waveforms for system feeding an EAF

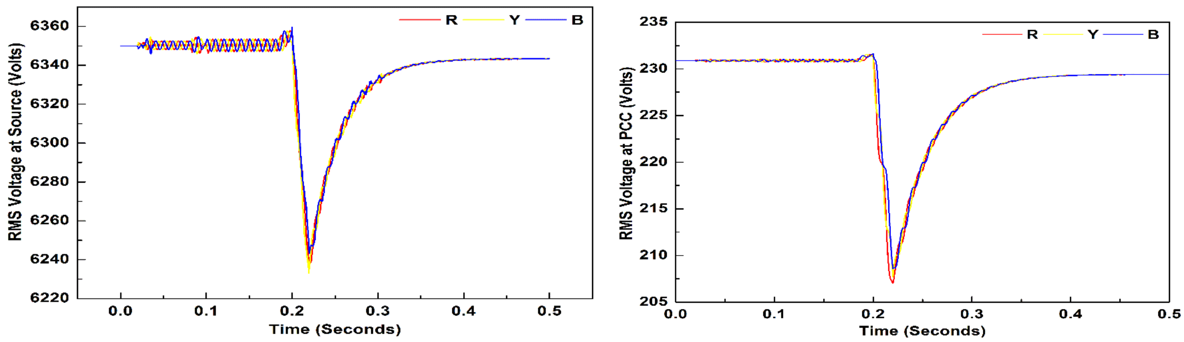
Figure 6(a) and 6(b) presents the waveforms of voltages at the PCC and the arc voltage at terminals of an EAF for a system feeding EAF. As described earlier, the characteristic of EAF load is highly nonlinear and chaotic in nature, the disturbance levels will be high.

The current THD for R phase Y phase and B phase are 9.58%, 9.60% and 9.58% respectively, the voltage THD is observed to be 12.07%, 12.07% and 12.09% it is also observed that the voltage flicker observed at the terminals of EAF transformer is 14.2% and voltage flicker observed at the PCC is 13.40%.

Case 4: Induction Motor



(a) (b)



(c) (d)

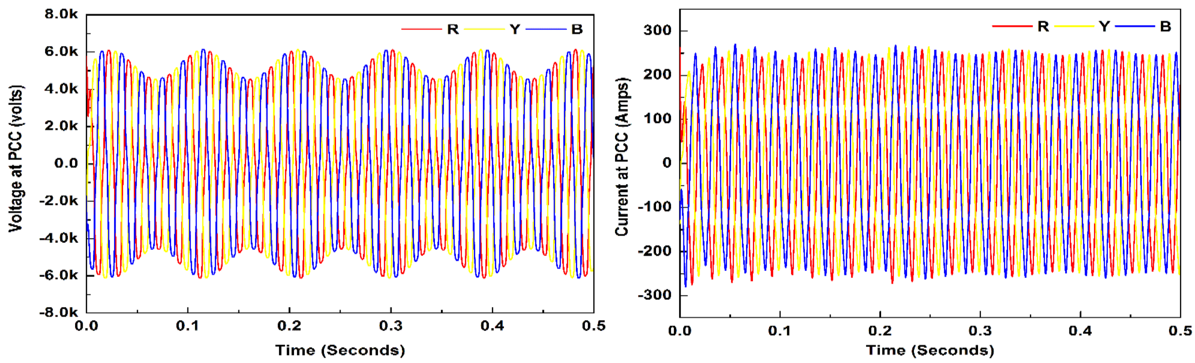
Fig 7: Instantaneous and RMS voltage waveforms for system feeding an Induction motor**.**

Figure 7(a) and 7(b) presents the waveforms of instantaneous voltages at the PCC and the terminals of Induction motor, it is evident from figure 7(b) that, as the induction motor is started at time instant of 0.2 seconds, it is observed that there is a sudden decrease in the instantaneous voltage at the bus near an induction motor, and the instantaneous voltage reaches the normal value after a short duration of time.

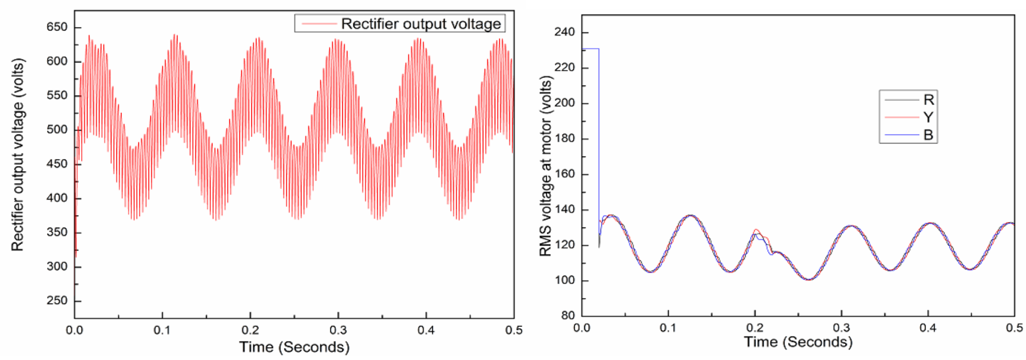
Figure 7(c) and 7(d) presents the waveforms of RMS voltages at the PCC and the terminals of Induction motor, it is inferred from the figure 7(c) and 7(d) that, voltage sag is observed both at the PCC and at the bus near an induction motor.

It is further observed that ,voltage THD for R phase Y phase and B phase at PCC is less than 1%, the voltage THD is observed to be terminals of motor transformer is 2.6%, 2.86% and 2.13% respectively, it is also observed that the voltage sag observed at the terminals of motor transformer is transformer is 0.89 per unit and voltage sag observed at the PCC is 0.98 per unit, since the induction motor is connected to weak bus, the sag observed is higher near the induction motor in comparison with the source .

Case 5: Balanced and Unbalanced uncontrolled rectifier with EAF and Induction motor.



(a) (b)



(c) (d)

Fig 8: Instantaneous voltage and current waveforms of system feeding Balanced and Unbalanced uncontrolled rectifier with EAF and Induction motor.

Figure 8(a) and 8(b) represents Instantaneous voltage and current waveforms of system feeding Balanced and Unbalanced uncontrolled rectifier with EAF and Induction motor, it is evident from the figure 8(b) that, as EAF is highly nonlinear load drawing a large current, the effects of the EAF is dominant in the combined system, hence the performance of the other interconnected loads are dependent on the EAF characteristics.

For the combined system, it is observed that current THD for R phase Y phase and B phase are 9.59%, 9.67% and 9.62% respectively, the voltage THD is observed to be 12.09%,12.18% and 12.12% and the flicker is observed at bus is 13.40%.

From figure 8(c), it is seen that, there is a considerable reduction in the average DC voltage and is found to be 620V, further it is noticed that the ripple levels are extremely high.

From figure 8(d), it is found that the RMS voltage at the bus near induction motor experiences a sudden reduction in voltage and it is further inferred that the system fails to recover to its normal state and the momentary voltage sag has grown into a sustained under voltage.

5. Conclusion

Power system comprises of wide variety of loads to perform the operation according to the industrial requirements. Simulation studies are carried out to observe and analyses the effects of nonlinear loads to monitor the power quality disturbances caused by these loads. Several EAF modelling methods are studied and the simulation on time modelling models of EAF is carried out to analyses the harmonics distortion and voltage flicker effects of EAF.

Power modulators realized by simulation of balanced and unbalanced uncontrolled rectifiers provides the information on existence of harmonics and inter harmonics.

Starting of a high power rated induction motor creates a voltage sag at the bus near the load and the effect of voltage sag is not severe at the PCC. Finally the simulation on the combined system was analyzed to study the impact on performance of industrial loads in the interconnected system, the results clearly infer that the dominating EAF load distracts the normal operation of rectifier load and induction motor load.

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