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Types of Power Quality Disturbances on AC Electric Traction Drives: A Survey

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Modern electric traction drive systems make use of power electronic devices which directly affect its performance and efficiency. Numerous power quality phenomena are associated namely: Voltage flicker, Harmonic voltage and current distortion, voltage dip, transient over voltages, voltage and current unbalances. It is important to emphasize the fact that all the above mentioned phenomena appear due to the non linearity of the loads, who by themselves act as harmonic current generators. This paper gives a brief overview of the power quality disturbances which cause significant impact on the traction drive system as well as the supply side.

Keywords: *Electric traction, AC Locomotives, Harmonics, Unbalance, Flicker and Thyristor.*

1.0 INTRODUCTION

Railways generally operate Diesel-electric or electrified locomotives for passenger or freight traffic. AC Electric locomotives form the workhorse of the railways owing to higher efficiency and less pollution. In India, the mainline railways operate at AC, Single phase, 25 kV, 50 Hz supply system. Usually the locomotive drive systems comprised of DC series motors (presently being replaced by 3-phase slip ring induction motors), requiring thyristor-based rectifier converters to provide voltage and speed control. As a result these locomotives not only draw a significant amount of lagging load current at the fundamental frequency but also act as a major power quality constraint. Railway traction systems are highly susceptible to severe harmonic distortion, poor voltage regulation and line resonances. Due to its continuous movement across the supply system, the locomotives present themselves as a time varying load and affect the impedances due its locomotion on the track. The Locomotive traction system generally consists of a contact feeder section with a longitudinal impedance and a shunt capacitance fed from a substation step-down transformer at 25 kV. The Figure 1 shows a block diagram representation of the system.

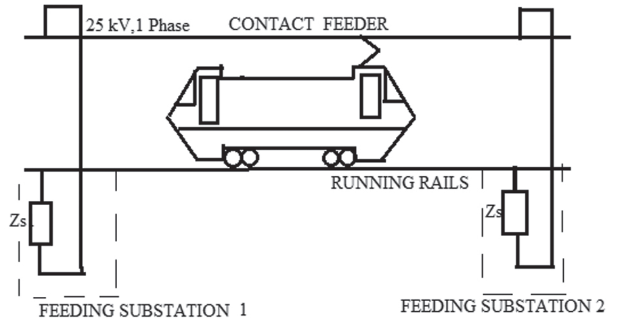

FIG. 1 TRACTION VEHICLE AND OVERHEAD SUPPLY SYSTEM [10].

In this paper, the different power quality disturbances associated with an AC locomotive load are studied and its effects are analysed. The study is supported by relevant data and statistics from other research papers and application notes. These power quality problems in the AC railway system have a detrimental effect on themselves as well as on the public grid.

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2.0 BACKGROUND

Generally, the power systems for conventional transmission and distribution, rely upon three-phase AC power, but there are specialized power systems that do not always depend on three-phase power, like the Railway electric traction system. This in itself, causes voltage unbalance and related problems, as the traction motors used in the locomotives are three-phase and the supply system is 1-phase. Since most of them are inverter fed locomotives, which make use of power electronics, the amount of harmonic content is high, leading to poor power factor and other associated problems. Many research papers have been published in the area of harmonics mitigation, reactive power compensation, voltage unbalance and the effect of flicker on the traction drive system and the supply.

This paper presents a brief survey on the research articles about the various power quality issues associated with the AC Locomotives.

3.0 LITERATURE SURVEY

The major power quality issues arising out of the locomotive systems may be classified as follows:

A. Harmonics:

A harmonic is defined as a component with a frequency that is an integer multiple of the fundamental frequency. The harmonic numbers indicates the harmonic spectra. The presence of PWM switching devices in the converter-inverter drive system act as a major source of harmonics, due to their non linear characteristics. Locomotive PWM Rectifiers employed in AC traction systems represent several megawatts of electrical load. Typically they use multiple rectifiers/converters in parallel in order to secure high power ratings and high frequency operation. The line-side converters inject current harmonics into the overhead supply system, propagating as travelling waves from either side of the feeding point. Switching frequency harmonics, although are small in magnitude, can be quite significant due to their interference with the railway line communication and signalling systems. The AC-DC converter is the main harmonic generator of the system. Lei Guo, et al. [1] has explained that each locomotive can be represented by an equivalent circuit formed by two elements: An equivalent reactance associated to the leakage inductances of the locomotive transformer. A harmonic voltage source whose magnitude and phase are coherent with the operating point. Figure 2 shows the basic circuit of a PWM converter.

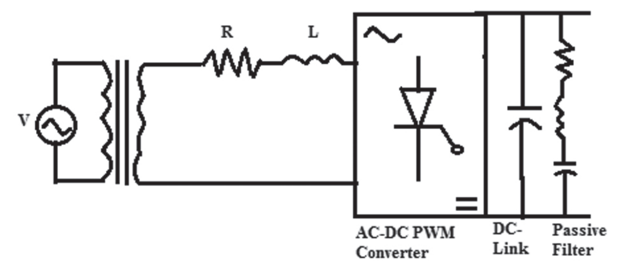

FIG. 2 BASIC CIRCUIT CONFIGURATION OF A PWM CONVERTER [1].

P C Tan, et al. [2] In the research paper on control of active filter in 25 kV AC Traction systems observed that harmonic currents injected by locomotives can cause a multitude of problems, including track side over-voltages, increased voltage form factor and excessive low order harmonic currents being fed back into the HV supply. Figure 3 illustrates the pantograph voltage waveform obtained at the end of a 35 km feeder section loaded with four 2.5 MW locomotives operating at full power. The voltage waveform shows a resonant over-voltage and an increased voltage form factor.

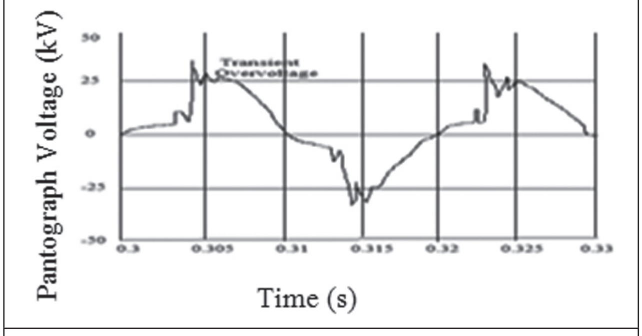

FIG. 3 TYPICAL PANTOGRAPH VOLTAGE WAVEFORM AT THE END OF A 35 km FEEDER [2].

Resonant over-voltages prematurely damage equipment connected to the system, while an increased form factor means that the power dissipation is increased [2]. There is also a possibility of magnification of the over-voltage at the point of power-factor correction, leading to potentially damaging consequences.

Figure 4 shows the harmonic currents produced by typical electric locomotives, of type SS4, SS6B. It can be observed that the 3rd and 5th harmonics are the dominant harmonics.

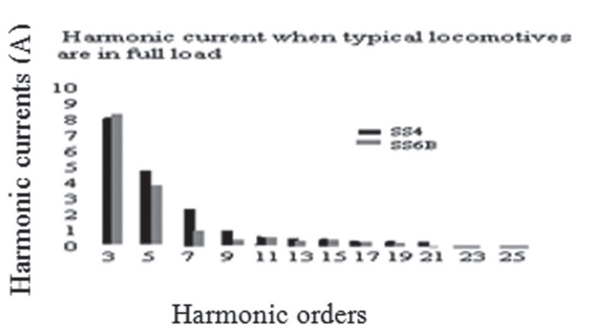

FIG. 4 HARMONIC CURRENTS GENERATED BY LOCOMOTIVE [3].

Yiwang Xiong, et al. [3] has explained the changes that can be observed in the harmonic currents flowing into the power grid through the traction network, by comparing the harmonic currents locomotives inject into the traction network and the grid-side actual measured harmonic currents. A distinct inequality is found between the grid-side measured harmonic currents injected into the grid and the harmonic currents produced by the locomotives. From Figure 5 on comparison, it can be easily observed that the 13rd, 15th and 17th high-order harmonic currents are significantly amplified in the process [3].

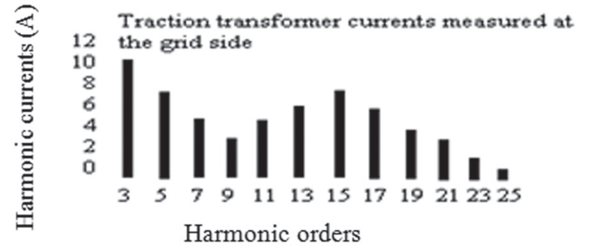

FIG. 5 HARMONIC CURRENTS MEASURED AT THE POWER GRID SIDE [3].

Table 1 shows the recommended limits according to IEEE 519-1992 standard for voltage distortion.

TABLE 1

VOLTAGE DISTORTION LIMITS ACCORDING TO IEEE 519-1992 STANDARD [11]

Bus voltage at PCC	**Individual voltage distortion (%)**	**Total harmonic distortion (%)**
< 69 kV	3.0	5.0
> 69 kV and < 161 kV	1.5	2.5
> 161 kV	1.0	1.5

Traditionally, different configurations of active harmonic filters have been used at the front end to mitigate dominant harmonic components. Some papers advocate the use of an Improved Power Quality Converter (IPQC), which by itself, behaves as a power factor correction equipment. FACTS devices like Static Var Compensator (SVC) and Custom Power devices like the Unified Power Quality Conditioner (UPQC) represent another alternative to compensate the issues. They can be connected series, shunt or a combination in the system to correct the power quality problems [4].

B. Power Unbalance:

Voltage unbalance is regarded as any differences in the 3-phase voltage magnitudes and/or shift in the phase separation of the phases from 120^0. Figure 6 illustrates the concept with respect to a symmetrical three-phase system. B R Lakshmikantha, et al. [5] is of the view that, the system voltages at a generation site are generally highly symmetrical due to the construction and operation of synchronous generators used in large centralised power plants. Therefore, the central generation does not in general contribute to unbalance.

Figure 7 shows a 1-phase 25 kV, 50 Hz locomotive loads operating on a 3-phase supply system. It is the primary reason for causing asymmetry at the distribution system. This affects each and every load connected to the 3-phase substation at the point of common coupling (PCC).

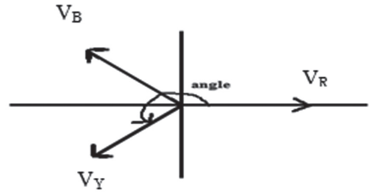

FIG. 6 PHASOR DIAGRAM OF SYMMETRICAL 3-PHASE SYSTEM [6].

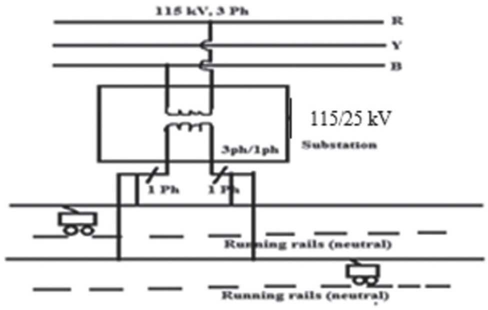

FIG. 7 3-PHASE SUBSTATION FEEDING A 1-PHASE TRACTION LOAD.

The degree of current and voltage imbalances depend upon the locomotion of the train, the dynamic changes in load and the supply system. Giulio Burchi, et al. [7], while estimating the voltage unbalance for high speed railways conclude that the system voltage and current unbalances overheat rotating machines, leading to significant loss of life, also, they change the symmetry of the PWM switching waveforms due to magnitude and phase angle unbalance. The power factor correction Capacitor banks also are influenced by the unbalance, such that, the reactive power compensation varies with each and every phase. Unsymmetrical faults cause voltage sag in one or more phases and over-voltage in the other phases , thereby altering the system behaviour. The application note on Railway power system enumerates on the major abnormalities due to AC traction [8]. Below table shows the voltage/current imbalances in the three-phase system at the 132 kV traction substation, as well as at the PCC. The imbalance is due to negative sequence only. It is expected current imbalance will be normally reduced with more sections in the system. But the current imbalance due to traction load is over 25%.

Martin Slivka et al. [6], while commenting on the main factors causing asymmetry within a power distribution system explains that the voltage unbalance has a negative impact on various other devices connected to a three phase power system, such as the increased warming of electrical machines, etc. To quantify the size of the unbalance in the system was introduced so-called voltage unbalance factor. This is determined by the ratio of negative sequence voltage to positive sequence voltage. Martin Slivka et al. [6] analyses the voltage unbalance by carrying out Measurements (14–20th February 2012) in traction transformer Blansko and also infers that the voltage unbalance factor depends on the load. The histogram depicting frequency versus voltage unbalance factor is indicated in Figure 8 and the dependence of Voltage unbalance factor on electric power is shown in Figure 9.

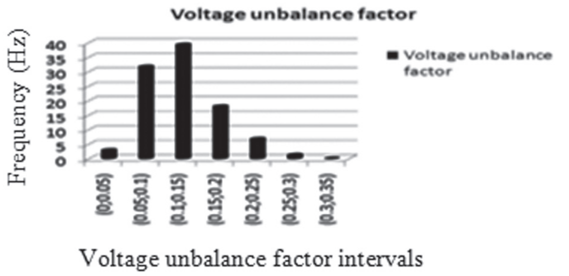

FIG. 8 HISTOGRAM OF VOLTAGE UNBALANCE FACTOR [6].

Power unbalance can be eliminated by making controlled power transmission paths between two or three single phases owing to power electronic switching circuits.

TABLE 2

IMBALANCE FOR MULTIPLE SECTIONS IN A SYSTEM [8]

Number of sections	1	2	3	4	5	6	7	8	9	10
Overall imbalance	100%	50%	0%	25%	20%	0%	14%	13%	0%	10%

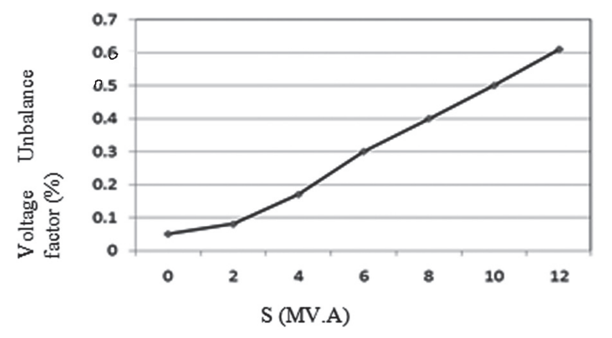

FIG. 9 VOLTAGE UNBALANCE FACTOR DEPENDENCE ON ELECTRIC POWER [6].

C. Voltage Fluctuations

As the trains present rapidly time varying loads, there occur fast Voltage Magnitude changes due to load variations, which are Voltage fluctuations. Voltage fluctuation is also the flickering experienced by other consumers at the point of common coupling (PCC) caused by the frequent train on/off and load changes, e.g. the 10 Hz flicker is most unpleasant to human eye. P. E. Sutherland, et al. [9] in his analysis of Harmonics, Unbalance and flickers caused due to single phase traction loads estimates the effect of short-term and long-term flickers through measurements. Figure 10 illustrates the Short-term flicker (Pst) variations over a ten-minute interval. The normal criterion for evaluating these results is that the Pst should be < 1.0 (usually evaluated at either the 95% or 99% probability level).

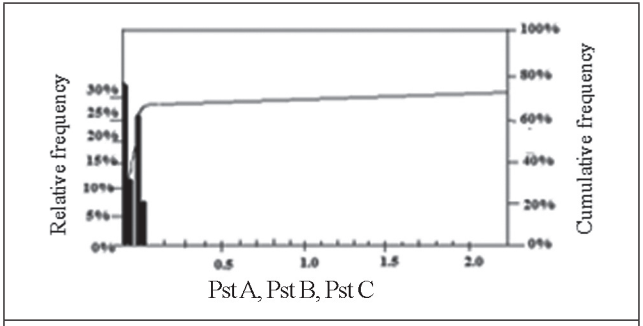

FIG. 10 HISTOGRAM OF 17 DAYS MEASUREMENT OF SHORT TERM FLICKER SHOWING 95% PROBABILITY OF PST BEING AS MUCH AS 0.1% [9].

Figure 11 shows that the flicker levels are very low. Some of the individual 10 minute Pst values are caused by voltage sags or other disturbances, that may not be associated with load variations. Long term flicker variations over a two-hour interval were also measured.

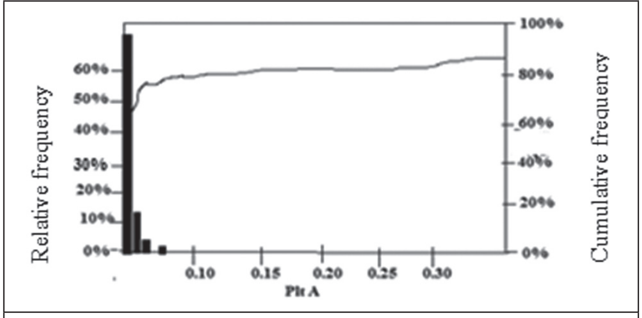

FIG. 11 HISTOGRAM OF 17 DAYS MEASUREMENT OF LONG-TERM FLICKER SHOWING 95% PROBABILITY OF Plt BEING AS MUCH AS 0.1% [9].

There are several measures for flicker mitigation, some of them being, use of static VAR compensators, injection of reactive power during motor starting etc.

A.J. Griffin [12] comments on the methods to regulate the voltage, some of them being,

(i) Reducing the distance between 25 kV supply substations.

(ii) A higher fault level at each 25 kV supply station.

(iii) Transformer type series regulators in the overhead line.

(iv) On-load tap changing transformers installed for each substation.

4.0 CONCLUSION

(i). The effect of different power quality issues due to 1-phase traction loads have been highlighted through results and analysis based on different research articles.

(ii). The studies reveal that the issues are a cause of significant concern on the power system operation.

(iii). The large unbalanced traction loads may cause system voltage and current unbalances and, therefore, overheat rotating machines.

It is also observed that the voltage unbalance factor depends on the load.

(iv). Though the power electronic interface, with its fast switching characteristics and dynamic control of speed dominate the space in modern locomotives, it has also considerably given rise to harmonic problems.

(v). The propagation of these components in turn give rise to transient over-voltages and magnification on the distribution system. Also, a locomotive is subjected to fluctuations, when it moves from a contact feeder section energized by one substation to another section. This in turn affects the other loads along the feeder section as well.

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