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Quality Problems in Railway Transportation Systems

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Abstract: *It has become a compulsory to analyze the effects that railway transportation systems on power systems since they have become widespread. Power quality measurements of a Metro Istanbul Co. station are presented in this study. Harmonic, flicker, voltage change, voltage imbalance and power factor change are observed and results are evaluated in consideration of legal arrangements. The aim of this paper is to emphasize on the power quality systems that can be encountered at railway systems in order to provide an insight to those who are dedicated to the design of these systems. PQ measurements of the examined system indicate that the system can have adverse effects on the connected grid based on the dynamic behaviors of the loads. Hence, these sort of issues can be foreseen at the design stage and new methods can be developed to avoid exceeding the limits set by the standards.*

Keyword: *Power Quality, Railway System, Harmonics, Flicker, Power Factor, Voltage Unbalance*

1. INTRODUCTION

The demand-based propagation of railway transportation has increased due to its numerous benefits for both passenger and burden transmission. Together with its contribution to help extenuating the traffic congestion and providing high capacity, comfort, high velocity and reliance, railway system has become an essential in Turkey due to the growth rate of population. Hence, first step of railway construction was taken in 1869 and after a period of stagnation many railway networks have been put into practice through sizable investments during last 20 years. It would seem to suggest that several power quality problems can arise from considerable increases at traction systems. The energy consumption of 293.953.325,56 kWh utilised by traction systems in 2016 demonstrates that its effects on power grid shouldn't be underestimated on behalf of other connected loads. As predicted, deteriorated power quality is expected to lead such problems as overheating, extra losses in transformers and lines and malfunctioning of protective system.

A great deal of the problems ordinarily seen in railway systems consists of power quality issues that are originated from nonlinear and unbalanced loads. With the aim to provide a perspective of the power quality issues through railway electrification developement and PQ supression techniques, Gazafrudi et al. have classified the topics for better comprehension[1]. Haojing Wang et al. , analyzed the transmission and permeability characteristics of the harmonics and negative currents by PSCAD/EMTDC software. Similarly, voltage profiles and harmonic impacts of high speed trains are investigated by using dynamic fundamental/harmonic power flow (DF/HPC) method to predict the right PQ impacts of railway systems [33]. Many researches are done about Railway Power Conditioners (RPC) by comparison [3], using of dif-

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ferent combinations with various transformers [23] [24] [28] and investigating hybrid [29][30] or novel [11] configurations to obtain better efficiency. Since traction loads as freight trains inject large unbalanced currents into the power grid, Railway Power Flow Controllers for single phase [25] and two phase loads[31] are both simulated and experimented for PQ improvement. In addition, installation schemes of Static Var Compensators (SVC) are compared for their compensation effects.

Besides these general mitigation techniques, there are several studies which focus on one specific issue. Harmonic pollution of the traction power-supply system is counted so an important concern that modelling methods [27] [32] and characteristics of traction equipments [2] [17] have been investigated. [36] Shengjun Qiu et al. analyzed the impacts of power system harmonics on line protection and bus protection. Due to performing good performance Hybrid Power Quality Control System (HPQCS) [9] [10] and passive filtering are examined [14] [15] [18] [37] by simulating and/or experimentation. Moreover, new control methods much better than selective harmonic elimination (SHE) or PWM in order to shape the spectrum of catenary current harmonics are proposed in [35] and [38]. A novel topology of a single phase 7-level asymmetrical cascaded converter has been examined [34] to supply the traction system with improved power factor at minimum harmonic distortion. NSC compensation is carried out with a balance transformer in YN/VD connection and a three-phase converter in [22] by adopting non-linear passive control method for the converter. However, adapting the RPC into V/v traction power supply with an intelligent algorithm based on sequential quadratic programming (SQP) method [21] can be evaluated as a more control-based optimisation. Another paper has a comparative approach on three different NSC compensator topologies as two level converter with a DC link capacitor, delta-connected modular multilevel converter (MMC) and double star MMC topologies under symmetrical and non-symmetrical characters of the traction substation [13]. Both NSC suppression and reactive power compensation are achieved with a new system consists of a YNvd-connected balance transformer and multiplex back-to-back converters in [26]. The efficiency of RPC based on boost choppers was proven by referring experimental results of a real system [44] and similarly with intent to utilize power electronics technology, IGBT based Shunt Active Power Filter (SAPF) is presented by R. Thomas et al. [4]. In order to observe the influences and voltage fluctuation caused by traction loads, a research [8] has stated the methodology and challenges involved in simulating traction loads. As a feasible solution, applying SVC in shunt with the transmission line is supposed to compensate the dip voltage intrinsically.

In a conventional catenary system, since the pantograph and overhead contact wire has a sliding contact the dynamic oscillation of train will result in a varying air gap between the section that leads to pantograph arcing and so the waveform of voltage and current will be distorted. In literature, pantograph arcing is known to be influenced by different factors such as the speed of the train, current, presence of inductance and also the sub zero temperature [6-27]. The phenomena is carried out experimentally by high speed photography in a laboratory simulation system [45] and synchronized electrical parameters were investigated. Connection of a capacitance of a proper size in parallel with the HV side of the power traction transformer would undertake the energy loss of pantograph arcing and curb the overvoltage [6]. By taking into account the weather conditions, the influences of an ice layer are examined and some mitigation techniques for icing problems are addressed in [5]. As a consequence, running the trains at a lower power factor by addition of inductance is specified as the most effective mitigation technique amongst others.

The rest of this paper is organized as follows; in section 2, this research explores the causes of power quality issues commonly encountered in traction systems and gives an outline of proposed PF correction techniques from recent studies. In the section 3, the real measurements of harmonics, voltage fluctuation and power factor taken from Metro Istanbul Co. railway as precedent are discussed. Together with the results, their comparison with standards complement the subject in an interpretive way. Finally, a brief inference is given regarding the observed system as a conclusion in section 4.

2. POWER QUALITY ISSUES IN RAILWAY SYSTEMS

The deteriorated quality of power in traction system will end up with several issues in either upstream network or signaling and communication system. Hence, obligatory measures have been taken by contemplating many researches and developing modern techniques in order to suppress the PQ problems. As a threshold matter, figuring out the root of the problem would serve as a window to a developement of the solution and following observations would make inroads to mitigate the obstacles.

2.1 Harmonics

Harmonics are defined as a distortion of normal voltage and current waveform which deviates from sinusoidal wave due to the presence of nonlinear loads. Specially connected transformers such as Scott, Le Blanc or YNvd and fed through rectifiers have direct impact on the harmonic spectrum of three-phase power system. As distinct from the rectifiers, traction transformers are proved to reduce the total harmonic distortion and hence improving the power

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quality in a co-phase traction system. [2]. As a reference harmonic pollution limits have been recommended in IEEE 519-1992 standard that should be ordinarily prompted in case of excessive level of harmonics.

Two common terms that are used in relation to harmonics are Total Harmonic Distortion (THD) and Total Demand Distortion (TDD). THD refers to the percentage comparing the harmonic components to the fundamental component of a signal and TTD the total root-sum-square harmonic current distortion in percent of the maximum demand load current. THD expressions for both voltage and current distortion and TDD can be indicated as in Equations (1)-(3) where the RMS voltage and the current of fundamental frequency is stated as U_1 and I_1, RMS voltage and the current of n. th harmonic is stated as U_n and I_n respectively.

$$\mathrm{THD_v} = \left(\frac{1}{U_1}\sum_{n=2}^{\infty} \mathrm{U_n^2}\right)^{1/2} \tag{1}$$

$$\mathrm{THD_I} = \left(\frac{1}{I_1}\sum_{n=2}^{\infty} \mathrm{I_n^2}\right)^{1/2} \tag{2}$$

$$\mathrm{TDD} = \left(\frac{1}{I_L}\sum_{n=2}^{\infty} \mathrm{I_n^2}\right)^{1/2} \tag{3}$$

Beyond giving the basic knowledge, our aim is to take a closer look at harmonics primarily challenged in traction system equipment as transformers and rectifiers. A traction transformer isn't expected to initiate high levels of harmonics unless the iron core of the transformer is saturated. Generation of odd multiple of third harmonics are observed by Bangcheng Sun et al. [17] concentrating on the effects of excitation and magnetising inrush currents under the transient condition. Consequently the exigence for comparing special structures of traction transformers is revealed in order to suppress THD effects. The Scott, YNvd, Leblanc and Impedance Matching Transformers with both active compensation achieved by an ac–dc–ac converter and uncompensated system are analyzed [2], the IM transformer eventuated in a distinguished performance.

DC traction loads are supplied through the pulse width modulation (PWM) controlled rectifier connected to the secondary of traction transformer. Related to the pulse number of PWM drive the harmonic spectrum at supply stage will have different patterns. For instance, in theory a 12-pulse rectifier will propagate harmonic currents at the 11th, 13th, 23rd, 25th, etc. multiples of the fundamental.

Based on nonlinear load characteristic of railway systems, identification of the harmonic disturbance and its reduction in the system has eventually become necessary so as to prevent the problems in both upstream and protection systems. The well-known issue caused by harmonics is extra losses and overheating in transformers and cables whereby the aging of equipment would accelerate and the power capacity of system would reduce. In addition, the tremendous levels of harmonics can also initiate an undesired trip signal even in regularly operating of traction system. By virtue of the fact that voltage and current sampling is based on the fundamental components, any distortion in system engenders transmission line control systems either.

The conventional solution for mitigating the harmonic distortion generally agreed by researchers is passive filtering. In spite of being low cost, passive filters are lacking in providing efficient PQ improvement facilities for dynamic nonlinear loads due to their constant LC parameters. The method of shunt Active Power Filter (APF) has been mentioned sanguinely by means of providing fast and dynamic response [10] when its inefficiency in compensating NSC is excluded. Specially connected traction transformers with and without compensation are proved [2] to diminish harmonic distortion to allowable ranges subject to transformer type. Besides this topologies, the control methods which were tolerance-band control in [2] and direct power control in [16] must be evaluated utterly during compensation.

2.2 Voltage Fluctuation

Since the single phase traction loads are connected to the power supply via rectifiers to the power supply, voltage fluctuation at the point of common coupling will be inevitable. Sudden shifts of traction loads give instantaneous rise to step changes in voltage that ends up voltage fluctuations on the grid, thus affects the operation and efficiency of connected voltage sensitive loads [7]. However, excessive loading of locomotives on traction line spawns dip in voltage and in the meantime increases the flow of current which triggers the relay without any fault on line. The disturbance of fluctuations may be perceived from lighting equipment more in particular which is called as flicker.

Asymmetrical loading of the phase power system results in a remarkable amount of Negative Sequence Currents (NSC). Unbalanced systems can be analyzed mathematically by the method of Symmetrical Components where asymmetrical set of N phasors can be expressed as a linear combination of symmetrical sets of phasors as shown in Figure 1.

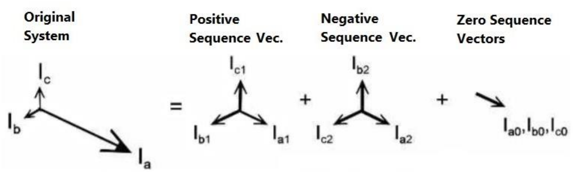

Figure 1 Symmetrical components phasor diagram

When an "a" vector is defined as a=1 ∠120° the phase currents will be calculated by following Equations.

$$I_a = I_{a0} + I_{a1} + I_{a2} \quad (4)$$
$$I_b = I_{a0} + a^2 I_{a1} + a I_{a2} \quad (5)$$
$$I_c = I_{a0} + a I_{a1} + a^2 I_{a2} \quad (6)$$

As indicated in Figure 1, I_a, I_b and I_c are the current ratings of a, b, c phases where the positive, negative and zero sequence components of a phase are denominated by 1,2 and 0 indices.

The feature that makes NSCs different from positive sequence components is having same magnitude but rotating in opposite direction in the power system. This reverse rotating magnetic fields induces double frequency currents into the rotor body of cylindrical rotating machines as motors and so results in overheating. Even an unbalance of 5% can cause reduction in the motor power by 25% while it continues to draw the same current as before unbalancing. In addition, the existence of harmonics and NSCs affects the operation of protective relays connected to the network via current transformers. Moreover, the existence of both harmonics and NSCs affects the operation of protective relays connected to the network via current transformers. Under this circumstances, saturation of CTs can happen and during high fault conditions CT will distort the current waveform while delivering to the overcurrent relay.

Specially connected balance transformers and their combinations with control systems have been the most frequently referred solutions for assuaging NSCs. While the Scott and Impedance Matching Transformers are known to produce the least NSCs, Y-D11 and YnVD connected transformers are preferred by researchers for theoretical analysis and simulation because of their simplicity in design [19] [22]. By employing three adjacent traction transformers and phase shift method, the consequent traction loads are supplied by different phases of upstream network in order to keep the loads in balance. This passive techniques should be perceived as effective providing the loads of each phase are equal and thereby dynamic methods are adopted for alleviating NSCs. Static Var Compensator (SVC) is a commonly examined equipment for having the ability of both reactive power and NSC compensation. A mechanism of SVC that consists of fixed capacitors and thyristor controlled reactance is analyzed by Steinmetz's law principles in [19] with simulation results to establish its performance. However, the recommendation of installing the SVC in the side of railway supply is given [19] and a comparative analysis that supports this proposal with the scheme in Figure 4 is made [20]. As might be expected, installing the SVC in high voltage primary side is not an economical method but still more appropriate than STATCOM. A comparison study based on determining the minimum device-rating requirements in the steady state is made between two level modular multilevel converter topologies when utilizing the three-phase STATCOM connected to LV side of transformer [13].

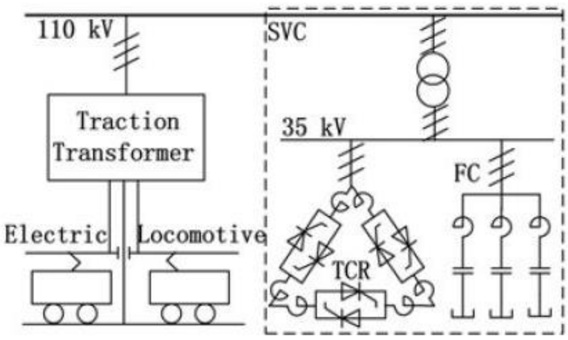

Figure 2 Connection scheme of SVC to supply network

Another novel approach for mitigating power quality issues is Reactive Power Compensator (RPC) which utilizes back-to-back converters in conjunction with a dc link bus. Each converter with dc-link capacitor have the ability of exchanging power between two single-phase loads so that utilization factor of traction transformer can be promoted. Meanwhile, elimination of harmonics and compensation of reactive power can be carried out by proper control method. In order to take the advantage of mentioned system, a Traction Power Compensator (TPC) composed of a converter with three legs and six power switches, three inductances and two single-phase Y-D11 step-down transformers is designed [12]. The simulation resulted in a resplendent decrease of %96,1 in NSC index despite of the worst case scenario probably encountered in traction systems. Likewise, a new NSC compensation system with passive-based control is introduced [22] by emphasizing its robustness and simplicity in system integration. Adapting the RPC into V/v traction power supply with an intelligent algorithm based on sequential quadratic programming (SQP) method [21] can be evaluated as a more control-based optimisation.

Comprehension of the traction load behavior in Electrical Railway Systems is the first step for the analysis of voltage fluctuation and flicker problems. Therefore, experiencing the challenges of modelling and simulation of a railway system, an illustrative study has been made by using DigSilent software in 2014 [8]. As an overcoming technique, SVCs efficiency in voltage profile while operated with closed loop control of voltage magnitude inputs is indicated [7]. With the advancement techniques of compensation such as hybrid railway power quality control system (HRPQC) with full bridge converter [9], the greater part of power quality issues in railway systems can be dealt with fundamentally.

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2.3 Power Factor & Reactive Power

In traction systems, there are several reasons of both inductive and capacitive reactive power in operational or solution based cases. Since the system is composed of reactive characterized equipments like traction transformer, smoothing reactors, traction motors, air cooling fans and auxiliary motors for compressors, reactive power precisely becomes more of an issue. The amount of reactive power is altered according to the increasing or decreasing number of operating locomotives. Moreover, reduction in the speed of locomotive while coasting at Phase Breaks that are isolated sections between different feeder regions will also affect the generated reactive power. As well as having an inductive characteristic, capacitive power can be observed particularly when the transportation system is inoperative after midnight due to the no-load condition of long cables.

As a matter of fact that reactive power will appear in traction systems because of the inductive characteristics of equipment and its necessity for NSC mitigation, dynamic compensation has been required to keep it under acceptable level. The existence of reactive power increases the losses of transformers and transmission lines that results in overheating of the equipment and voltage collapse at supply stage. When the political approach is consulted, high amounts of penalties might be encountered in case reactive–active power ratio exceeds the ratio determinated by the government. On the purpose of avoiding penalties and being supplied with more stabilised power from the grid, three basic compensation methods comprised of shunt-connected, series-connected and phase angle compensation can be examined. Whilst fixed capacitors and inductors are commonly used passive elements for compensation, their response to dynamic variation of reactive power can be inadequate. Thus profiting from the availability of high power semiconductor devices by combining them with passive equipment, a variety of power electronics controlled systems have been developed by the researchers. Foremost among them, SVCs have maintained its importance in compensation of both reactive power and NSC however the constraint of series and shunt resonance between capacitor banks and impedance of supply stage have remained as a disadvantage. Thereby eliminating the disadvantages of SVCs, STATCOMs that operate with variable source converters and energy storage devices have started to be installed at power system if the increased cost due to the need for a high-voltage three-phase step-down transformer is neglected.

In literature, various combinations of passive and active equipment are proposed and simulated considering the regulation of voltage fluctuation and mitigation of harmonic distortion either. For the systems operated with high voltage AC supply, an IGBT based Shunt Active Filter with a simple PI controller is developed in [4] so as to provide dynamic compensation. An optimised partial compensation algorithm is implemented by Minwu Chen et al. [25] in a system consisting of a single-phase traction transformer and an active Power Factor Controller. Besides solving power quality problems in grid side, the system has the advantage of cost and reduction in the capacity of transformer and PFC. In a recent study, since the demand for cost reduction has gained importance as well as PQ correction, the integration of multiplex back-to-back converters (MBTBC) via cascade connection which decreases the number of isolation transformers is investigated [26] where the advantages of partial compensation can be noticed thoroughly.

3. POWER QUALITY MEASUREMENTS OF METRO ISTANBUL

In this paper, as an illustration the results of harmonic, power factor and voltage fluctuation measurements of Metro Istanbul railway are given and compared with standard values. The system is supplied from 34,5 kV medium voltage grid with a Dy5d0 connected step-down transformer that has two secondaries of 580 Volts. Connected to the secondary of transformer, a 12 pulse PWM controlled rectifier with 750 V DC output is employed to feed the traction loads.

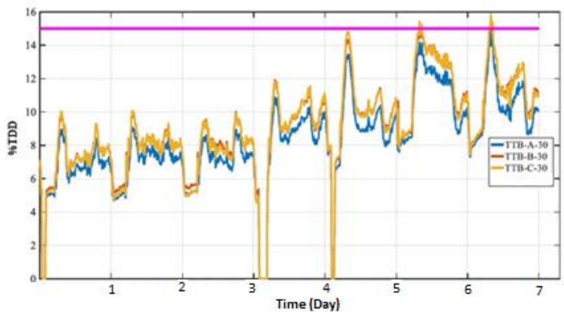

Figure 3 TDD values according to one week measurements

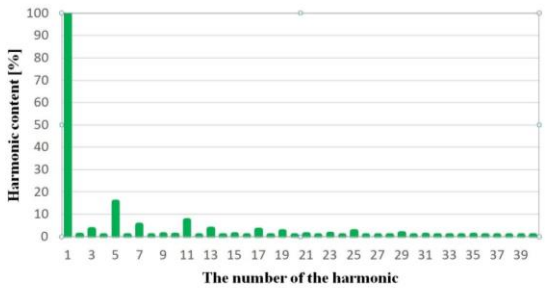

Figure 4 Harmonic spectrum for one phase

Total Demand Distortion (TDD) is calculated from averages of 10 minute's samplings taken in every 3 seconds after one week measurement.

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As a reference harmonic pollution limits have been recommended in IEEE 519-1992 standard that should be ordinarily prompted in case of excessive level of harmonics. Since the limit values given in Table 1 are checked, the graph can be interpreted as the load current has a TTD exceeding the limit which decreases the capacity of the grid. However, when the harmonic spectrum for one phase of mentioned system shown in Figure 4 is investigated, odd harmonics can be counted to constitute the majority.

TABLE I. LIMIT VALUES OF HARMONICS ACCORDING TO IEEE STD. 519

Odd Harmonics						
I_{SC}/I_L*	<11	11≤h< 17	17≤h <23	23≤h <35	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	**12.0**	**5.5**	**5.0**	**2.0**	**1.0**	**15.0**
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited with %25 of value identified for following odd harmonics.						

Voltage changes for one and three phases that are measured throughout a week are shown in Fig 4, Fig 5 and Fig 6 respectively. The lowest voltage is measured as 32,8 kV at phase two throughout the measurement period. However the highest rating of voltage is measured as 35 kV at first and third phases.

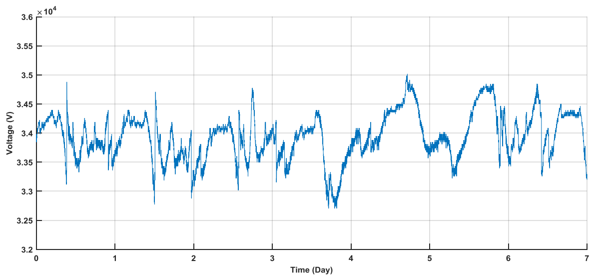

Figure 5 Voltage profile of one phase

When the Figure 5 is observed, the voltage change seems to be within allowable limits of %5. Similarly, the voltage unbalance is within the limits as can be seen in Figure 6.

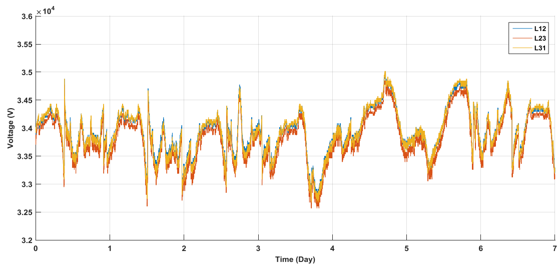

Figure 6 Voltage profiles of all phases

The variation during the measurement period of power factor over the system is indicated in Figure 7. In this period, average rating of power factor is determined as 0,96. While the minimum power factor is 0,5 , the maximum rating is measured as 1. Within the time intervals when the system is overloaded, the power factor tends to be closer to 1, in spite of that when the line is less or not loaded, the power factor tends to decrease to very low levels which can be obviously seen in Figure 7 .

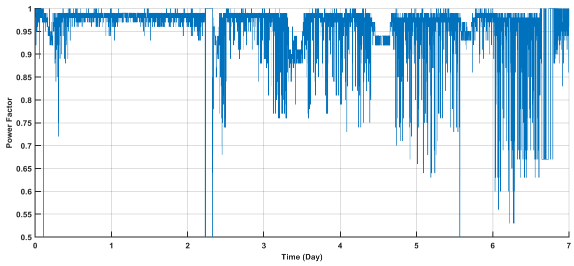

Figure 7 Power factor values

4. CONCLUSION

Rail transportation systems have started to extend to wider areas of usage with its fast, reliable and comfortable structure. On the other hand, the effect of rail transportation systems over the power supply system has increased. Thus, analyzing the effects of railway systems over the power network has become an obligation regarding this issue.

In this study, the power quality measurements of a subway belonging to Metro İstanbul Co. operation are presented and their effects over the power grid are examined. As a result of performed measurements, it is observed that the current harmonics exceed the limits at certain time intervals of measurement period. When the voltage rating and phase voltage unbalance level remains within the limits, the decrease of power factor rating below the desired level in case of under loading of the system has been observed clearly.

As a result, the current harmonic limits are not provided on the considered station, but all other power quality limits are met. It is recommended to use a high pulse rectifier or harmonic filter to reduce the current harmonics in the direction of this observation.

5. ACKNOWLEDGEMENTS

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