The Journal of CPRI,
Vol. 7, No. 2, September 2011 pp. 131–144

Harmonic Problem due to Saturable Devices in Steel Re-Rolling Plant – A Case Study

Vasudeo B Virulkar* and Mohan V Aware**

This paper investigates the causes of harmonic norms violations in the medium scale (less than 2 MW load) re-rolling industry paying for the penalty. The major drive motor in this industry draws the heavy current with deep in the voltage at the terminal of the motor when steel bars are re-rolled with steps passes. To overcome the problem of voltage deep, the taps of the distribution transformer supplying these loads are selected on higher side. This situation leads to the over excitation of the transformer during the light load condition (between the passes) of the re-rolling operation resulting the operation of transformer in nonlinear zone. During this operation the harmonics due to saturation are generated and injected into the distribution systems and are the cause for damages to the capacitor banks. This problem is analyzed by mathematical modeling of the load condition with the transformer. The site investigation is carried out using power analyzer Megger-PA-9 plus V604 and supported by the simulation in PSCAD/EMTDC. This investigation leads to suggesting the remedial measures which is implemented to accommodate the harmonics inconformity with IEEE-519 standard.

Keywords: *Filters, Harmonics, Nonlinear loads, Power factor correction capacitors, Saturable devices*.

1.0 INTRODUCTION

When electronic power converters first became commonplace in the late 1970s, many utility engineers became quite concerned about the ability of the power system to accommodate the harmonic distortion. Many dire predictions were made about the fate of power systems if these devices were permitted to exist. While some of these concerns probably overstated, the field of power quality analysis owes a great debt of gratitude to these people because their concern over this "new" problem of harmonics sparked the research that had eventually led too much of the knowledge about aspects of power quality [1]. Unlike other power quality problem which are transient in nature such as lightning that lasts for a few microseconds or voltage sags/ swell that last from few milliseconds to several cycles, harmonics are steady state periodic phenomenon that produce continuous distortion of voltage and current waveforms.

Harmonic problems counter many of the conventional rules of power system design and operation that consider only the fundamental frequency. The power system problems arise most frequently when the capacitance in the system results in resonance at a critical harmonic frequency that dramatically increases the distortion above normal amounts. While these problems occur on utility systems, the most severe cases are usually found in industrial power systems because of higher degree of resonance achieved.

Industrial facilities often utilize capacitor banks to improve the power factor to avoid the penalty charges. The application of power factor correction capacitors magnifies the harmonic

*Asst. Professor, Electrical Engineering, Govt. College of Engineering, Amravati-444604. E-mail: vbvirulkar@yahoo.com
**Professor, Electrical Engineering, Visvesvaraya National Institute of Technolog, Nagpur-440010. E-mail: mva_win@yahoo.com

current from the nonlinear loads, giving rise to resonance conditions within the facility. The highest voltage distortion level usually occurs at the facility's low-voltage bus where the capacitors are applied. Resonance conditions cause motor and transformer overheating, and misoperation of sensitive electronic equipment.

Nonlinear industrial loads can generally be grouped into three categories: power electronic loads, arcing devices, and saturable devices. Power electronic loads control the flow of power by drawing current only during certain intervals of the 50/60 Hz period. Thus, the current drawn by the load is no longer sinusoidal and appears chopped or flattened. The non-sinusoidal current can interact with system impedance to give rise to voltage distortion and in some cases, resonance. The arcing devices include arc furnaces, arc welders, and discharge type lighting with magnetic ballasts. The voltage-current characteristics of electric arcs are nonlinear. The electric arc itself is actually best represented as a source of voltage harmonics. However, the impedance of ballast or furnace acts as a buffer so that the supply voltage is only moderately distorted. The arcing load thus appears to be a relatively stable harmonic current source. Saturable devices produce harmonics due mainly to iron saturation, as in the case for transformers, machines, and fluorescent lamps (with magnetic ballasts). For economic reasons, most transformers and motors are designed to operate slightly past the knee of the iron core saturation curve. The resulting magnetizing currents are peaked and rich in the third harmonic. Unless blocked by a delta transformation, a synchronous machine will produce a third harmonic current of approximately 30 % of the fundamental [2].

In this paper, the modeling and analysis of the saturable reactor with load is carried out using PSCAD. The effects on nonlinearity of saturable reactor on quantum of harmonic generation are investigated. The site data under actual operating condition using the power analyzer Megger PA-9 plus are obtained and remedial measures are suggested. This study indicates that the pass based rolling should have a suitable selective setting on the transformer so as to avoid the over-fluxing of the transformer. This suggestion has been implemented by way of identifying the voltage variations in the rolling passes and effectiveness of such trial has given relief from the harmonic based penalty from the utility. This simplified suggestion has avoided the costly solution like notch filters and shunt active filters at the point of common coupling.

2.0 MAGNETIC NONLINEARITIES

An important class of nonlinear characteristic in electrical power circuits is the magnetizing impedance of saturated power transformer and shunt reactors. Saturated magnetic cores may generate harmonic currents during steady-state operation, as well as transient harmonic currents and temporary over-voltages following a major switching operation in the transformer's vicinity, with the critical case being the energisation of the transformer itself. The steady state magnetizing currents of the distribution transformers are only 1–2 % of the rated current but they may reach 10–20 times their rated value when transformers are switched on to the source, exhibiting a current spectrum which is reach in harmonics [3–6].

2.1 Modeling of Transformer

Transformers are one of the most prevalent components in power systems. The saturation effects of transformers and iron core reactors can be major source of power system harmonics. Harmonics are generated from the magnetic core saturation, which begins when the core flux enters the nonlinear region of the magnetization curve [7–11]. While some saturation occurs during normal operation, significant over-excitation can lead to excessive harmonic generation. Major line conditions likely to cause transformer significant over-excitation include:

(a) Temporary over-voltage caused by reactive power unbalance.

(b) Unbalanced transformer load. This can cause uneven distribution of magnetizing current among the transformer phases. Load unbalance can cause transformer saturation even if the fundamental line voltage is within its normal limits.

(c) Low frequency magnetizing current can bias the transformer core and cause symmetric saturation. This can be generated from Adjustable Speed Drive (ASD) load or through geomagnetic induction (Geo-Magnetically induced Current, GIC).

(d) Transformer energization, especially in over-voltage conditions. The asymmetric core saturation generates a slowly decaying inrush current, which can further cause excessive harmonic over-voltage.

Symmetric core saturation generates odd harmonics, while asymmetric core saturation generates both odd and even harmonics. The overall amount of harmonics generated by transformer depends not only on the saturation level of magnetic core, but also on configuration of the transformer. Several harmonic models can be used to represent a transformer. Commonly seen models are equivalent model as shown in Figure 1, the differential equation model, and duality-based model.

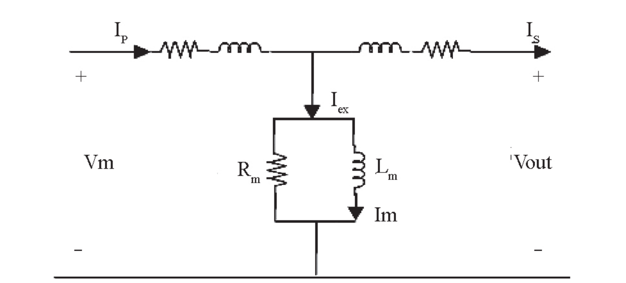

FIG. 1 SINGLE PHASE TRANSFORMER EQUIVALENT CIRCUIT

In harmonic studies where it is necessary to model transformers as harmonic sources, the first step is to model saturation of the main flux path in the core. In order to minimize the core size, power transformers are usually designed to operate just below the knee point as shown in Figure 2(a). Therefore, when the voltage increases above a certain value, the transformer magnetizing current becomes distorted; even at the nominal operating voltages the no load current THD can be as high as 20 %. The harmonic contribution from power transformers can be most likely noticed in a grid with many transformers installed, during low load hours, when the load current is low and the voltage rises [1].

In an iron-core power transformer, the flux *Φ* and the flux density *B* within the transformer core is proportional to the voltage V_l applied across the primary winding, according to Faraday's law. In sinusoidal case, it can be written [3]:

$$V_l = V_{lm} \sin \omega t = \frac{d\phi}{dt} \tag{1}$$

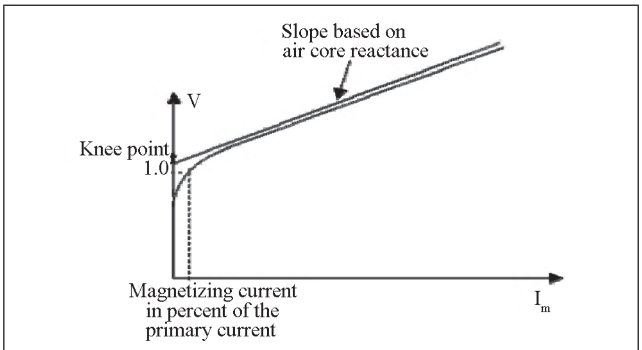

FIG. 2(A) TRANSFORMER MAGNETIZATION CHARACTERISTICS

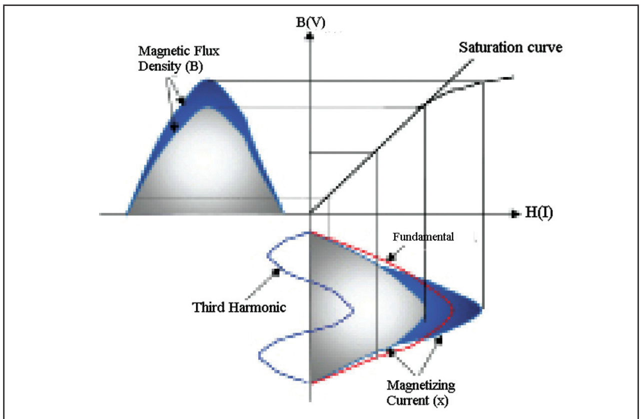

FIG. 2(B) TYPICAL RELATIONS BETWEEN MAIN FLUX Φ, SUPPLYING VOLTAGE V AND NO-LOAD (MAGNETIZING) CURRENT I (WITHOUT HYSTERESIS EFFECTS) [5]

$$\phi = \int V_{lm} \sin \omega t dt = \frac{V_{lm}}{\omega} \cos \omega t = \phi_m \cos \omega t \tag{2}$$

$$B = \frac{\phi}{S} = \frac{\int V_{lm} \sin \omega t dt}{S} \tag{3}$$

where S is the cross-section of the core in mm^2.

The resultant magnetizing current I_m needed to produce this sinusoidal flux is related to the magnetic field strength *H* by a constant value, which is the ratio of number of turns *N* to the total length of the magnetic path *l*:

$$H = I\frac{N}{l} \quad (4)$$

The magnetic flux density B is related to the magnetic field strength H by the magnetic permeability of the steel used in the transformer core μ:

$$B = \mu H \quad (5)$$

Equation (5) shows that if the magnetic permeability μ is linear and B is sinusoidal, the magnetic field strength H (and what follows, the magnetizing current I_m) will be sinusoidal. If the transformer operates in saturation, μ is no longer linear and the magnetic field strength H is non-sinusoidal, because the product of H with magnetic permeability μ must still produce the sinusoidal flux density B as shown in Figure 2(b). If the magnetizing current I_m is allowed to flow freely (low impedance path Z for all harmonics), after decomposing it to Fourier components, it will contain the fundamental frequency and all the odd harmonics: 3rd, 5th, 7th, 9th etc [10]. The waveform for magnetizing current of a transformer is shown in Figures 3(A) and (B).

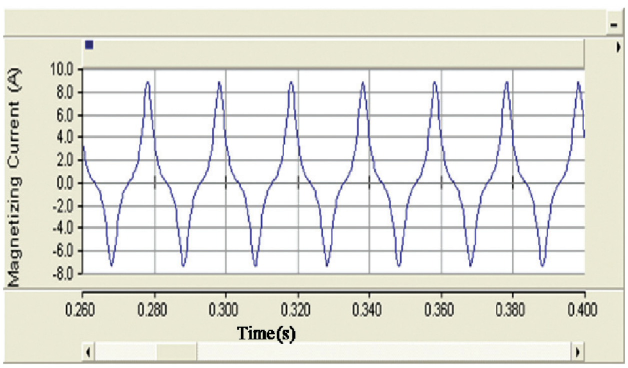

FIG. 3(A) MAGNETIZING CURRENT OF A TRANSFORMER

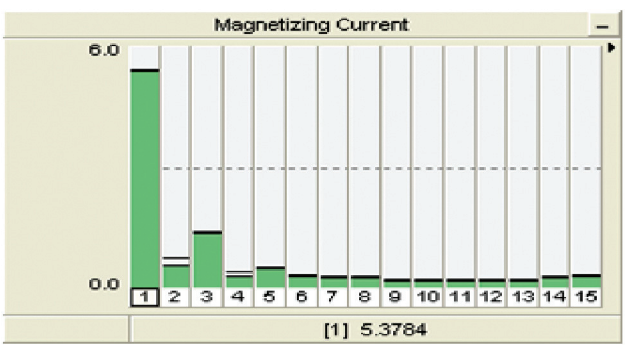

FIG. 3(B) HARMONIC SPECTRUM OF MAGNETIZING CURRENT

In industrial systems such situations may occur when large power factor correction capacitors exit at the secondary side of the transformer which, when combined with the predominantly inductive impedance of system at low harmonic frequencies, lead to a parallel circuit of high impedance. Moreover, if the ensuing parallel circuit is tuned to the harmonic frequency component of the magnetizing current then a voltage magnification will take place. In the long term, if the over-voltages occur frequently then the life expectancy of the capacitor bank will be very much reduced.

Modern distribution transformers with grain-oriented steel cores are designed to operate in the region 1.6–1.7 T, and have a sharply defined knee. Hence, over-excitation of 20 % and even 10% in some cases, above the rated value will push the transformer deep into saturation. The magnetizing current of single-phase iron core will be symmetric in most cases, with the harmonic current spectrum containing no even harmonics and no DC term, just the fundamental frequency component and odd harmonics. For most practical purposes, harmonic terms in the magnetizing current above the 15th are negligibly small and are not cause for any concern. Moreover, in most three-phase transformer applications at least one of the three-phase winding is delta connected to confine the zero sequence-like harmonic currents within this winding, and only the 5th , 7th, 11th and 13th harmonics currents would normally deserve attention [2].

2.2 Induction Motors

Induction motor could be a source of harmonic generating in the following aspects [5]:

(a) Stator winding configuration. Due to the fact that winding are not continuously distributed at the stator, the resulting Magneto Motive Force (MMF) will not be a continuous sinusoid with applied sinusoid stator voltage. However, this problem is minimized in the machine's design stage. Its contribution is often neglected in the models.

(b) Transients. When the induction motor just starts up from stall or the load is changing, both the stator current and rotor current will vary at high frequency to adapt the changing state of motor. Therefore, some harmonics will exist in the starting currents.

The above-mentioned phenomenon can generally be neglected, the primary contribution of induction motors is to act as impedance to harmonic excitation. At the fundamental frequency, it is well known that the model of induction motors involves more parameters than that of synchronous machines, therefore it is expected that the reaction of induction motor to the harmonic voltage and currents are more complex than that of synchronous machine. For system harmonic analysis, detailed modeling is rarely of necessity. The motor is either modeled as impedance for balance systems. The balanced equivalent impedance can be derived from equivalent T model for h order harmonic frequency as shown in Figure 4. This is modification of well-known induction motor model, where s_h is defined as

$$s_h = \frac{h \pm (1-s)}{h} \tag{6}$$

Where *s* is full load slip at fundamental frequency, and *h* is the harmonic order.

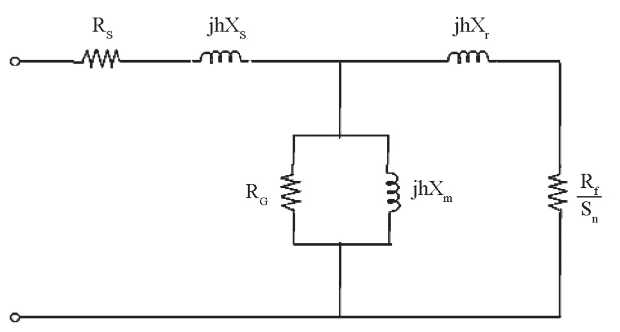

FIG. 4 EQUIVALENT T MODEL FOR INDUCTION MOTOR

3.0 IMPACT OF HARMONICS ON INDUSTRIAL LOADS

Harmonic currents produced by nonlinear loads are injected back into the supply systems. These currents can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors causing additional losses, overheating, and overloading. These harmonic currents can cause interference with the telecommunication lines and errors in power metering.

3.1 Impact on Capacitors

The capacitor is subjected principally to two harmonics: the fifth and seventh. The voltage distortion consists of 4 percent fifth and 3 percent seventh. This results in 20 percent fifth harmonic current and 21 percent seventh current.

3.2 Impact of Harmonic on Transformer

Transformers are designed to deliver the required power to the connected loads within minimum losses at fundamental frequency. Harmonic distortion of the current, in a particular, as well as voltage will contribute significantly to additional heating. The transformer in which the current distortion exceeds 5 % is the candidate for de-rating for harmonics. The K factor commonly found in power quality literature concerning transformer de-rating can be defined in terms of harmonic currents as follows [10]:

$$K = \frac{\sum \left(I_h^2 \times h^2\right)}{\sum I_h^2} \tag{7}$$

Where h is harmonic number and I_h is harmonic current.

3.3 Impact of Harmonic on Induction Motor

Induction Motors can be significantly impacted by the harmonic voltage distortion. Harmonic voltage distortion at the motor terminals is translated into harmonic fluxes within the motor. Harmonic fluxes do not contribute significantly to motor torque, but rotate at a frequency different than the rotor synchronous frequency, inducing high frequency currents in the rotor. The effect on motors is similar to that of negative sequence currents at fundamental frequency. The additional fluxes do little more than induced additional losses. Decreased efficiency along with heating, vibration, and high-pitched noises are indicators of harmonic voltage distortion.

4.0 ANALYSIS OF SYSTEM UNDER INVESTIGATION

An industry having the power distribution network as shown in Figure 5 and Table 1 give the ratings of these components. The induction motors are used as a drive load for drawing the steel bars. The loads are cyclic in nature.

Due to cyclic nature of load, it is vulnerable to the flicker problem. To overcome the flicker problem the industry has put the tap of the distribution transformer to upper side. Subsequent to the regular survey of supply utility to monitor the harmonic, the industry received the notice of violation of norms for injection of harmonic. To analyze the performance of the system for harmonic analysis the complete system is simulated using PSCAD/EMTDC simulation software. Table 2 shows the motor data for EMTP Type 40 options for simulation [12,13].

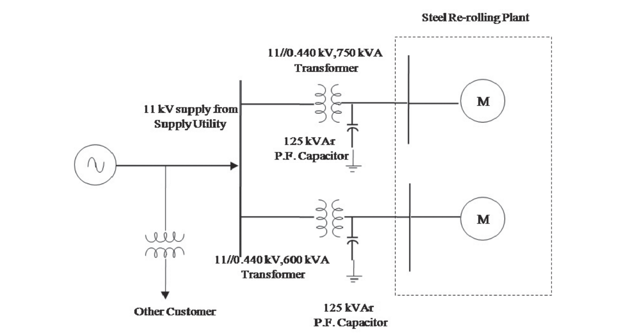

FIG. 5 LOAD PATTERN OF INDUSTRY

Table 3 shows the transformer data for simulation. The PSCAD transformer model used in the simulation is a three-phase two-winding transformer model based on classical modeling approach with a current inject1ion routine to model magnetizing characteristics as shown in Figure 6 [14–16]. The saturation is represented with a compensating current source across the winding wound closest to the core. The 2 % saturation in distribution transformer and mutual reactance and leakage reactance saturation are considered for magnetic nonlinearities of the distribution transformer and induction motors [17–20].

TABLE 1

RATINGS OF THE ELECTRICAL SYSTEM

Sl. No.	Loads	Quantity	Ratings
1	Rolling Machine-1	1	450 kW, 3-Phase Induction Motor
2	Rolling Machine-2	1	355 kW, 3-Phase Induction Motor
3	Distribution Transformer-1	1	11/0.440 kV 750 kVA
4	Distribution Transformer-2	1	11/0.440 kV 600 kVA
5	Power Factor Correction Capacitor	1	125 kVAr

TABLE 2

MANUFACTURER MOTOR DATA FOR SIMULATION

Output kW	Speed r/min	Efficiency full load 100 %	Power factor	Current			Torque		Moment of inertia
				IN A	$\frac{I_S}{I_N}$	TN Nm	$\frac{T_S}{T_N}$	$\frac{T_{max}}{T_N}$	kgm^2
450	1491	96.6	0.87	772	7.4	2882	1.9	2.7	12
355	1489	96.6	0.86	615	7.5	2277	2.4	2.7	6.9

TABLE 3		
TRANSFORMER DATA FOR SIMULATION		
Rated voltage		11 kV/440 V; line-to-line, rms
Rated Power		T1:750 kVA; T2: 600 kVA
Positive sequence leakage reactance		0.1 pu
No load losses		0.005 pu
Copper losses		0.005 pu
Saturation property (current injection approach)	Saturation placed on	Secondary winding
	Air core reactance	0.2 pu
	Knee point	T1: 1.2 pu; T2: 1.2 pu
	Magnetizing current	2 % of the primary current

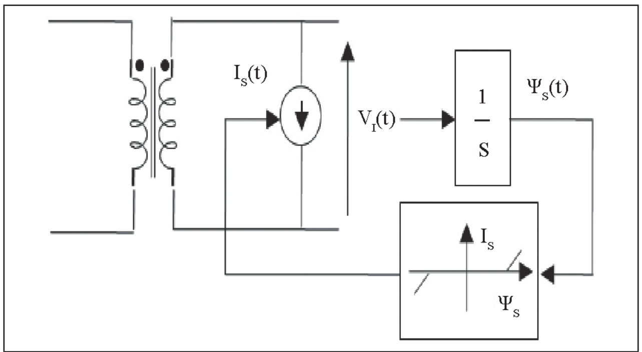

FIG. 6 SATURATION PROCESS USED IN THE TRANSFORMER

The Figures 7, 8 and 9 depict the rms voltage, instantaneous voltage, and harmonic spectrum of the voltage respectively when the tap of the transformer is set at higher side. Total harmonic distortion is shown in Table 4. In the Figures 10–12 it has been shown that the current under off duty period is rich in harmonic due to nonlinear behavior of core, which is getting saturated due to high voltage resulting from the tap on highest among the six tap.

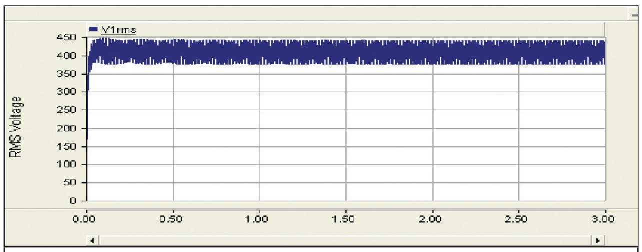

FIG. 7 RMS VOLTAGE AT PCC

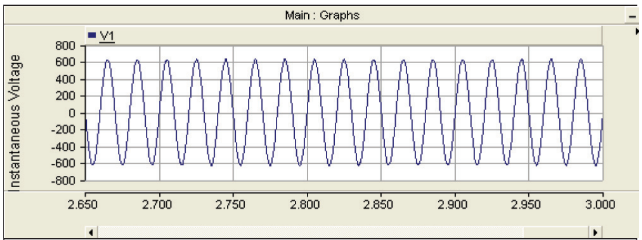

FIG. 8 INSTANTANEOUS VOLTAGE AT PCC

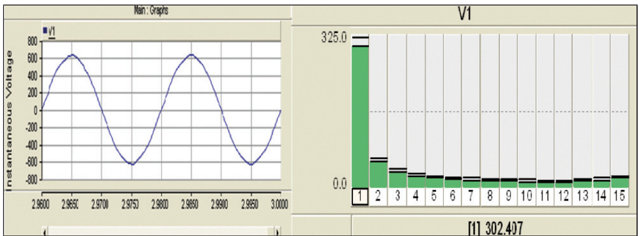

FIG. 9 HARMONIC SPECTRUM OF VOLTAGE AT PCC

TABLE 4						
TOTAL HARMONIC DISTORTION (THD)						
Event	Phase-A		Phase-B		Phase-C	
	Voltage	Current	Voltage	Current	Voltage	Current
1	0.92 %	4.50 %	1.16 %	2.11 %	1.22 %	3.95 %
2	0.94 %	2.10 %	1.35 %	3.74 %	1.20 %	4.95 %
3	1.03 %	3.20 %	1.38 %	4.01 %	1.29 %	3.97 %
4	1.11 %	4.50 %	1.58 %	3.98 %	1.37 %	2.64 %
5	1.17 %	4.20 %	1.66 %	2.95 %	1.61 %	3.08 %
6	0.95 %	3.20 %	1.23 %	3.68 %	1.13 %	2.04 %
7	0.55 %	3.55 %	0.59 %	3.98 %	0.59 %	4.95 %
8	0.66 %	4.10 %	0.64 %	2.09 %	0.75 %	3.98 %

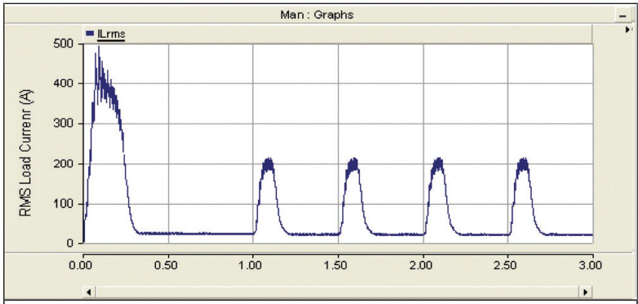

FIG. 10 RMS LOAD CURRENT

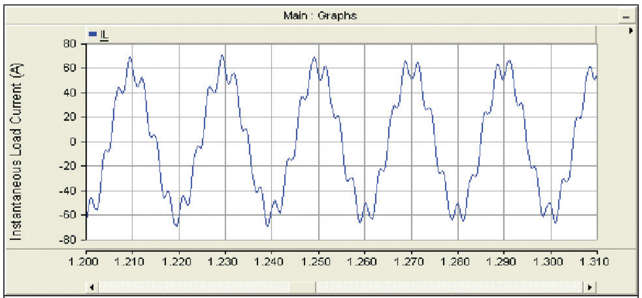

FIG. 11 INSTANTANEOUS LOAD CURRENT UNDER OFF DUTY PERIOD

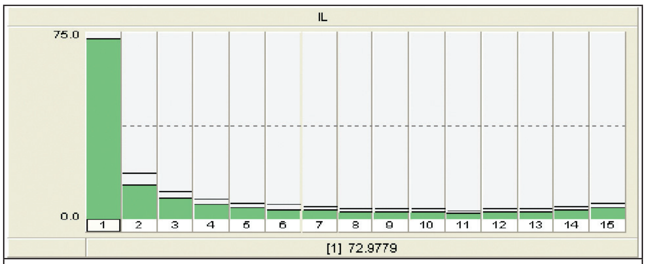

FIG. 12 HARMONIC SPECTRUM OF LOAD CURRENT

4.1 Remedial Measure with Tap at Lower Side

To mitigate this problem simulation was run with tap on lower side and the current under off duty period is shown in Figures 13 and 14 which shows the significant reduction in harmonic. Due to tap at lower side, it will not increase the voltage under off duty period and will not cause the saturation of core. As a result, the distortion in the current is reduced.

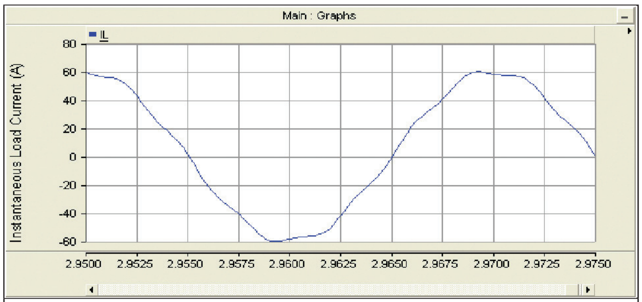

FIG. 13 INSTANTANEOUS LOAD CURRENT UNDER OFF PERIOD WHEN TAP IS AT LOWER SIDE

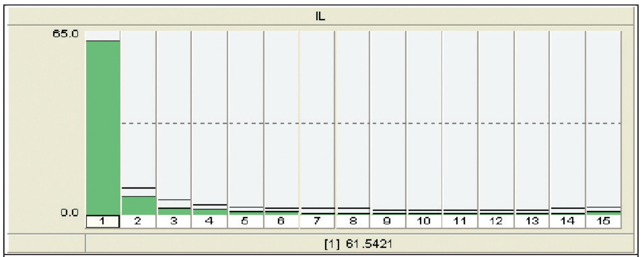

FIG. 14 HARMONIC SPECTRUM OF LOAD CURRENT UNDER OFF PERIOD WHEN THE TAP IS AT LOWER SIDE

4.2 Remedial Measure with Notch Filter

A single tuned 5th harmonic notched filter is used to suppress the 5th order harmonic from the distribution transformer [21]. In this notched filter the power factor correction capacitor is combined with dry-type iron core reactor. The procedure for calculation of filter parameter is given in Appendix. The load current obtained with the 5th harmonic notched passive filter connected in shunt with the load is depicted in Figures 15 and 16. It is found that with the notched filter the total harmonic distortion and distortion of individual harmonic are within the limits set by IEEE 519 1992 standards.

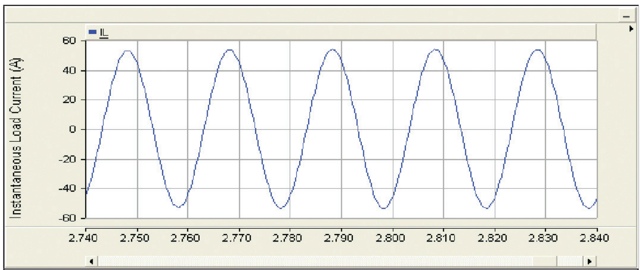

FIG. 15 INSTANTANEOUS LOAD CURRENT UNDER OFF DUTY PERIOD WITH NOTCH FILTER

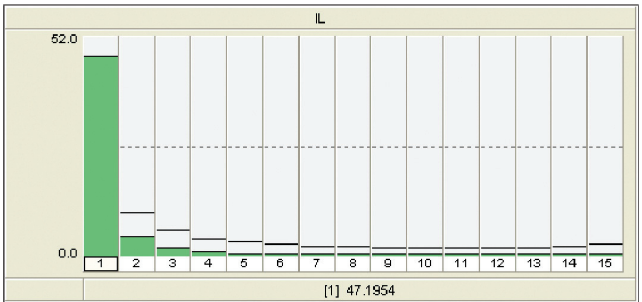

FIG. 16 HARMONIC SPECTRUM OF LOAD CURRENT UNDER OFF PERIOD WITH NOTCH FILTER

5.0 CASE STUDY

5.1 Site Measurement and Analysis

The investigation was undertaken to investigate and estimate the harmonics in the electric network. Subsequent to power quality analysis with power analyzer PA-9 V604 of a steel re-rolling mill, the results obtained are shown in Figures 17–22. The voltages at the terminal of the motors were recorded and presented in Figure 17–19. The voltage does not have significant distortion as recorded and presented in Table 5. The harmonic contents are very low. The 3rd, 5th and 7th harmonic contents are around 1.4, 3.1 and 4.2 respectively. The THD value obtained is 1.33 %. However, the load current recorded is shown in Figure 20 it is distorted. These harmonics are recorded and presented in Table 6. From the Figure 21, it is observed that line current more predominated with 5th and 7th Harmonics, which are present due to magnetic nonlinearity of transformer and induction motor. The third and fifth harmonics values are 8.539 % and 12.53 % respectively. The Total Harmonic Distortion (THD) is around 16.25 %. The total harmonic distortion is more than the requirement of IEEE 519-1992 standard.

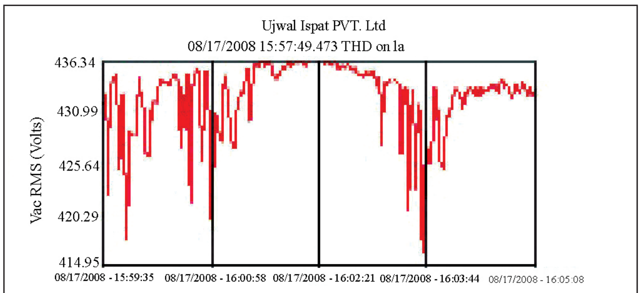

FIG. 17 RMS VALUE OF VOLTAGE

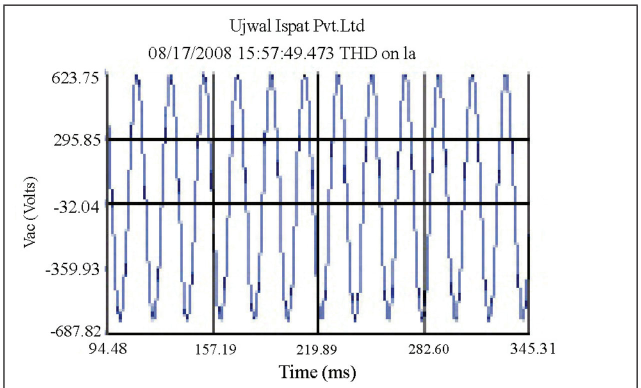

FIG. 18 INSTANTANEOUS VOLTAGE

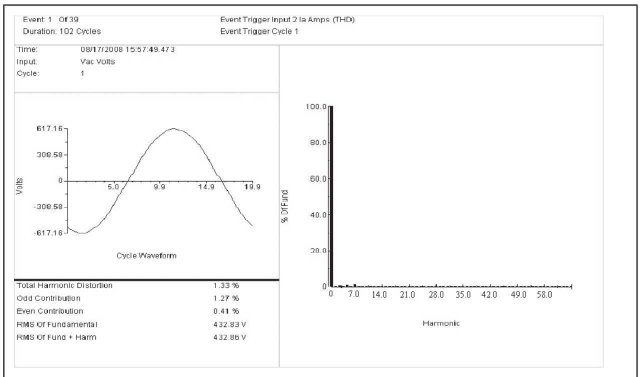

FIG. 19 HARMONIC SPECTRUM OF VOLTAGE

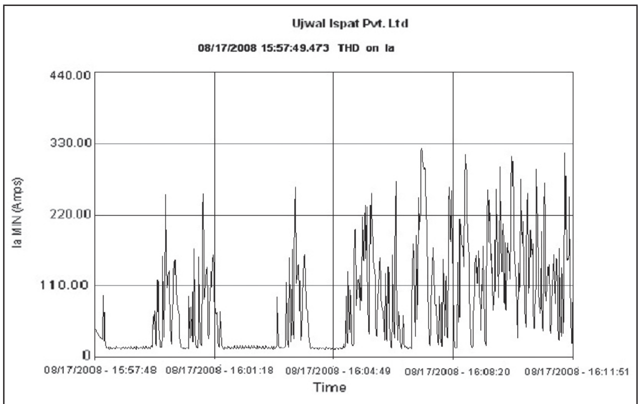

FIG. 20 RMS VALUE OF LOAD CURRENT

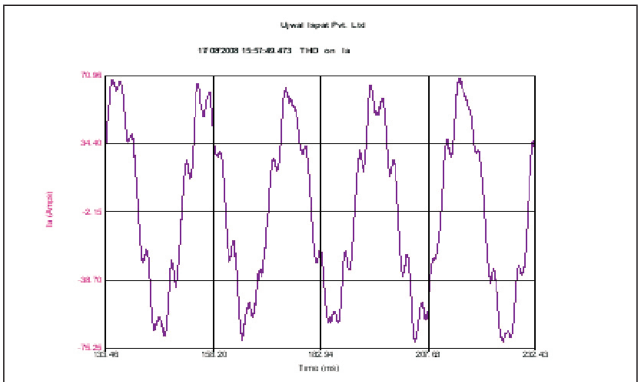

FIG. 21 INSTANTANEOUS LOAD CURRENT

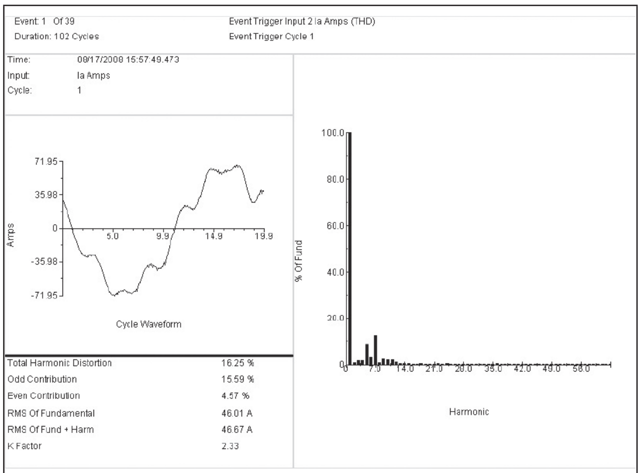

FIG. 22 HARMONIC SPECTRUM OF LOAD CURRENT

TABLE 5							
HARMONIC ANALYSIS OF VOLTAGE							
Harm fund	**% of fund**	**V**	**Angle**	**Harm**	**% of fund**	**V**	**Angle**
1	100.00	432.8	0	2	0.26	1.1	90°
3	0.33	1.4	160°	4	0.09	0 4	144°
5	0.71	3.1	162°	6	0.13	0.6	327°
7	0.97	4.2	198°	8	0.07	0.3	19°
9	0.12	0.5	208°	10	0.22	0 9	19°
11	0.15	0.7	246°	12	0.12	0.5	191°
13	0.06	0.3	303°	14	0.03	0.1	19°
15	0.03	0.1	163°	16	0.07	0.3	230°
17	0.05	0.2	335°	18	0.04	0 2	183°
19	0.03	0.1	276°	20	0.03	0.1	19°
21	0.03	0.1	164°	22	0.01	0.0	185°
23	0.05	0.2	353°	24	0.02	0.1	115°
25	0.02	0.1	243°	26	0.01	0.0	355°
27	0.01	0.1	112°	28	0.01	0.0	258°
29	0.01	0.0	15°	30	0.02	0.1	120°
31	0.02	0.1	243°	32	0.01	0.0	341°
33	0.00	0.0	129°	34	0.01	0.1	271°
35	0.01	0.0	29°	36	0.01	0.0	97°
37	0.01	0.0	263°	38	0.01	0.0	339°
39	0.01	0.0	109°	40	0.01	0.1	232°
41	0.01	0.0	5°	42	0.01	0.0	95°
43	0.02	0.1	210°	44	0.01	0.0	305°
45	0.01	0.1	76°	46	0.01	0.0	202°
47	0.00	0.0	280°	48	0.01	0.1	67°
49	0.00	0.0	133°	50	0.01	0.0	326°
51	0.00	0.0	133°	52	0.02	0.1	272°
53	0.01	0.1	323°	54	0.02	0.1	96°
55	0.01	0.0	190°	56	0.02	0.1	288°
57	0.01	0.0	34°	58	0.01	0.0	118°
59	0.00	0.0	264°	60	0.00	0.0	74°
61	0.01	0.1	138°	62	0.00	0.0	345°
63	0.01	0.0	6°				
Total Harmonic Distortion						1.33 %	
Odd Contribution						1.27 %	
Even Contribution						0.41 %	
RMS of Fundamental						432.83 V	
RMS of Fund + Harm						432.86 V	

TABLE 6							
HARMONIC ANALYSIS OF LOAD CURRENT							
Harm fund	**% of fund**	**A**	**Angle**	**Harm**	**% of fund**	**A**	**Angle**
1	100.00	46.0	0°	2	0.78	0.4	249°
3	1.74	0.8	208°	4	1.82	0.8	331°
5	8.53	3.9	34°	6	3.01	1.4	125°
7	12.53	5.8	35°	8	0.72	0.3	306°
9	2.26	1.0	191°	10	2.22	1.0	328°
11	2.03	0.9	223°	12	1.07	0.5	96°
13	0 57	0.3	304°	14	0.38	0.2	103°
15	0.34	0.2	254°	16	0.27	0.1	231°
17	0.20	0.1	337°	18	0.32	0.1	254°
19	0.23	0.1	59°	20	0.05	0.0	274°
21	0.09	0.0	327°	22	0.44	0.2	317°
23	0.28	0.1	200°	24	0.32	0.1	12°
25	0.08	0.0	35°	26	0.28	0.1	351°
27	0.06	0.0	143°	28	0.13	0.1	74°
29	0.02	0.0	258°	30	0.06	0.0	12°
31	0.07	0.0	47°	32	0.04	0.0	304°
33	0.15	0.1	109°	34	0.30	0.1	230°
35	0.20	0.1	87°	36	0.33	0.2	240°
37	0.09	0.0	47°	38	0.15	0.1	332°
39	0.25	0.1	88°	40	0.06	0.0	87°
41	0.23	0.1	179°	42	0.15	0.1	340°
43	0.14	0.1	194°	44	0.13	0.1	69°
45	0.15	0.1	200°	46	0.03	0.0	260°
47	0.30	0.1	353°	48	0.10	0.0	70°
49	0.08	0.0	86°	50	0.22	0.1	133°
51	0.08	0.0	116°	52	0.11	0.0	195°
53	0.08	0.0	296°	54	0.19	0.1	308°
55	0.06	0.0	159°	56	0.17	0.1	254°
57	0.15	0.1	185°	58	0.19	0.1	339°
59	0 07	0.0	162°	60	0.20	0.1	41°
61	0 16	0.1	292°	62	0.18	0.1	85°
63	0 10	0.0	306°				
Total Harmonic Distortion						16.25 %	
Odd Contribution						15.59 %	
Even Contribution						4.57 %	
RMS of Fundamental						46.01 A	
RMS of Fund + Harm						46.67 A	
K Factor						2.33	

5.2 Remedial Measures

There are number of devices available to control harmonic distortion. They can be as simple as capacitor bank or a line reactor or as complex as active filter.

A simple mitigation action such as adding or resizing, or relocating a shunt capacitor bank can effectively modify an unfavorable system frequency response, and thus bring the harmonic distortion to an acceptable level. Similarly, a reactor can perform the same function by detuning the system off harmful resonances.

It is found that the harmonic problems of this industry are due to the magnetic nonlinearity and the cyclic nature of load pattern. The loads remain off intermittently, causing intermittent light load condition which leads to over excitation of transformer due to higher tap setting.

The compensating capacitor bank becomes more vulnerable under this situation and leads to over-voltages during off period. The required setting of the transformer is adjusted by considering the transformer drop under full load current during the full pass condition. This has set the transformer to two step lower tap change to match the rated voltage under full load current. This has proved to be better control over the over excitation situation under off period. However, small voltage variation ~ 1 % is observed during the full on period of the rolling pass.

It is suggested that the notch filter shall help in mitigating the problems of this nature. The simulation results show the effectiveness of such filter. The design of notch filter is given to the rolling mill for further implementation.

6.0 CONCLUSION

Harmonic Analysis of the re-rolling mill is performed and it is found that 5th and 7th order harmonics are present in significant proportion despite the absent of any power electronic and arc current load at the secondary side of the transformer. This case study reveals that magnetic nonlinearity of the core of distribution transformer and mutual reactance and leakage reactance saturation of induction motor are responsible for harmonics pollution. At the first instant, transformer saturation may not be considered as a major problem in most of these applications. The significant voltage variations are associated with the rerolling process. The voltage variations during the rolling passes drive the transformer into the intermittent saturation. The amount of saturation depends on the voltage variation. For the first pass, this variation is going to be large. This is conventionally taken care by selection of the taps on higher side to avoid the flickers. In this investigation it has been observed that the content of current harmonics is significant during the off period of the rolling passes. This can be avoided by an appropriate tap setting. The guidelines are set to select the transformer tap by considering the voltage variation during the passes. In most of these cases, transformer tap should be set to the average of the voltage change under first pass added to the rated voltage. This has been implemented and this rolling mill has come out of the penalty zone. The solution of notched filter which is a combination of reactor with power factor correction capacitance will also helps to mitigate the harmonic pollution significantly. This needs to have design efforts with the justified cost. In another approach, complete solution can be implemented by use of active filter to mitigate the harmonics. However the cost and its complexity in its operation do not have any acceptance in medium scale steel re-rolling mills in India.

APPENDIX

Reactance of the Filter:

Reactance of the Filter is given by

$$X_{Filt} = \frac{kV^2(1000)}{kVAr} \tag{7}$$

Where X_{Filt} is the difference between the capacitive reactance and inductive reactance at fundamental frequency:

$$X_{Filt} = X_{Cap} - X_L \tag{8}$$

For tuning at h harmonic

$$X_{Cap} = h^2 X_L \tag{9}$$

The desired capacitive reactance can be determined by

$$X_{Cap} = \frac{h^2 X_{Filt}}{h^2 - 1} \tag{10}$$

Filter reactance can be calculated from wye-equivalent capacitive reactance determined in (9)

$$X_{L(Fund)} = \frac{X_{Cap(wye)}}{h^2} \tag{11}$$

REFERENCES

[1] Dugan R C, McGranaghan M F, Santoso S and Beaty H W. "Electrical power system quality", *Mcgraw-Hill, New York,* 2002.

[2] Arrilaga J and Watson N R. "Power system harmonics. *John Wiley & Sons, London,* 2003.

[3] Mack Grady W and Surya S. "Understanding power system harmonics", *IEEE, Power Eng. Rev.*, pp. 8–11, 2001.

[4] Fuchs E F and Yiming Y. "Measurement of λ-I characteristivs of asymmetric three-phase transformers and their applications", *IEEE, Trans. on Power Delivery*, Vol. 17, No. 4, pp. 983–990, 2002.

[5] Chang G, Hatziadoniu C, Xu W, Ribeiro P, Burch R, Grady W M, Haplin M, Liu Y, Ranade S and Ruthman D. "Modeling devices with nonlinear voltage-current characteristics for Harmonic studies", *IEEE, Trans. on Power Delivery*, Vol. 19, No. 4, pp. 1802–1811, 2004.

[6] Martinez J A and Mork B A. "Transformer modeling for low- and mid-frequency Transients- A Review", *IEEE,Trans. on Power Delivery*, Vol. 20, No. 3, pp. 1625–1632, 2005.

[7] Martinez J A, Walling R, Mork B A, Maryin-Arnedo J and Durbak D. "Parameter Determination for modeling system transients-Part III: Transformers", *IEEE, Trans. on Power Delivery*, Vol. 20, No. 3, pp. 2051–2062, 2005.

[8] Abdulsalam S A, Wilsum X, Washington L A, Neves, and Xian L. "Estimation of transformer saturation characteristics from inrush current waveforms", *IEEE, Trans. on Power Delivery*, Vol. 21, No. 1, pp. 170–177, 2006.

[9] Afshin R-Z, Majid S-P, Mossein M, Shahrokh F and Reza I. "Analysis of ferroresonance using preisach-type hysteric magnetizing inductance", *IEEE, Trans. on Power Delivery*, Vol. 22, No. 2, pp. 919–929, 2007.

[10] Mohammad A. S. Masoum, Moses P S and Masoum A S, "Derating of three-phase transformers serving unbalanced non-linear loads", *IEEE, Trans. on Power Delivery*, Vol. 23, No. 4, pp. 2033–2041, 2008.

[11] Liu Y and Wang Z, "Modeling of Harmonic sources-magnetic core saturations", *IEEE, Tutorial on Harmonic Model.*, IEEE 1998 WM and SM, ch. 5.

[12] He Y.-K and Lipo T A. "Computer simulation of an induction machine with spatially dependent saturation", *IEEE-PAS Trans*, Vol. PAS-103, No. 4, pp. 707–714, 1984.

[13] Chee-Mun Ong. "Dynamic simulation of electric machinery", *Prentice Hall PTR,* New Jersey, pp. 101–102.

[14] ANSI/IEEE Standard C57.110-1998, Reccomended practice for establishing transformer capability when supplying nonsinusoidal load currents.

[15] Manitoba HVDC Research Centre: "PSCAD/EMTDC User's manual guide", Version 4, 2004.

[16] Halian X, Lennart A and Nee H-P. "Compariosion of voltage and flux modulation schemes of stat coms regarding transformer saturation during fault recovery", *IEEE, Trans. On Power systems*, Vol. 23, No. 4, pp. 1653–1661, 2008.

[17] Pedra J, Candela I and Sainz L. "Modeling of squirrel-cage induction motors for electromagnetic transient programs", *IET,*

Electr. Power Appl., Vol. 3, No. 2, pp. 111–122, 2009.

[18] Task Force on harmonics modeling and simulation, IEEE PES Harmonic Working group, "Characteristics and modeling of harmonic source-power electronics devices", *IEEE, Trans. Power Delivery*, Vol. 16, No. 4, pp. 791–800, 2001.

[19] Pedra J, Sainz L, Corcoles F, Lopez R and Salichs M. "P Spice computer model of a nonlinear three phase three legged transformer", *IEEE, Trans. Power Delivery* Vol. 19, pp. 200–207, 2004.

[20] Chen X and Venkata S. "A three-phase three-winding core type transformer model for low frequency transient studies", *IEEE, Trans. Power Delivery*, Vol. 12, pp. 775–782, 1997.

[21] Davood Y, Alireza B, Gwza J, and Mohsen M, "A real-time extraction of harmonic and reactive current in nonlinear load for gid-connected converters", *IEEE, Trans. on Indust. Electron.*, Vol. 56, No. 6, pp. 2185–2189, 2009.