Investigation of the Effects of DC Current at the Point of Common Coupling on the Operation of Distribution Transformers

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Abstract - *Non-linear loads, such as ac and dc motor drives, computers etc. connected to the power distribution network inject a DC current component back to the network. Individual currents from different loads add at the point of common coupling (PCC) and the net value sometimes exceeds the upper limits specified in Standards. Heavy proliferation of power electronic intensive loads is mainly responsible for this unusual situation. The presence of DC current at the PCC creates operational issues in the distribution transformers and other components in the system, leading to significant power quality issues and long term reliability issues. This paper presents the findings of an investigation on the DC current injected by loads on a sample distribution system, and the effects of DC current on the operation of a power transformer. Both the experimental results and the simulation results with PSCAD are presented and discussed.*

Keywords— **Distribution Transformer, DC current injection, Magnetizing current, Power quality, PCC**

I. INTRODUCTION

The proliferation of nonlinear loads and power electronic driven loads on the power distribution system introduce power quality problems in the distribution network, such as harmonic distortions, voltage notches, voltage spikes, voltage unbalances, voltage sags, voltage swells etc. A significant cause behind these effects is injection of DC current back to the distribution network by the loads. DC current injected by individual loads add up to some significant level at the point of common coupling (PCC) and it directly influences the operation of the distribution transformer and associated other components and systems. Grid connected inverters, such as solar power inverters introduce a noticeable component of DC current in to the system.

Specific problems created by DC current in an AC power network are corrosion in underground equipment, errors in metering, malfunctioning of protective equipment, overheating of other grid connected equipment such as capacitor banks and AC machines etc. Perhaps the most detrimental influence of DC current is for the operation of distribution power transformers that creates problems of magnetic saturation, distortions in magnetizing current, distortions in supply current, increase in losses and hence temperature rise, reduced lifespan etc. (Ahfock et al.2010; Blewitt et al.2010; Bowtell et al.2010).

Country	Standard	Maximum permitted DC current
United Kingdom	ER G83/1	0.25 % of rated current of the inverter
Australia	AS 4777.2	0.5% of rated current of the inverter or 5mA , whichever greater
USA	IEEE 929-2000 IEEE 1547	0.5% of rated current of the inverter 0.5% of rated current of the inverter
Switzerland	IEC 61727	1% of rated current of the inverter
Germany	DINVDE 0126-1-1	1A (Total injection) [States in the case of DC current injection greater than 1A, disconnection is mandatory in 0.2S]

Table 1: Limits of DC current injection permitted by different countries for grid-tie inverters (LV system)

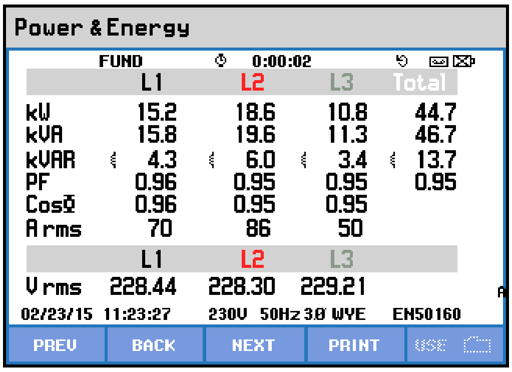
At the moment this problem of DC current is addressed by international or country-specific regulations that impose a limit to the maximum DC current injected by influential loads in to the grid. For example, Table 1 gives the existing status of guidelines and regulations in five selected countries for grid-tie inverters.

A significant attention has been given in the literature for limiting DC current injected by grid-tie inverters due to its relative significance. Three methods have been proposed for connecting inverters with the utility system (Armstrong et al.2006; Salas et al.2006), namely the Line frequency transformer interconnection, transformerless interconnection and high frequency transformer interconnection. Each has its own advantages and disadvantages.

Line frequency transformer is large, heavy and forms a substantial cost in the grid connected system and it contributes to significant power losses, lowering inverter efficiency by about 1–2% (Blewitt et al. 2010; Haeberlin 2001). Transformerless interconnection proposes a DC blocking capacitor in the inverter output but this requires a large and expensive AC capacitor of low reactance at 50Hz line frequency (Blewitt et al. 2010). An alternative transformerless interconnection uses a half bridge inverter at the inverter output which is inherently blocking DC current but this requires a DC link voltage twice the inverter output voltage, and correspondingly higher rating of inverter components, adding to higher cost and reduced system efficiency (Blewitt et al. 2010; Armstrong et al.2006). Another transformerless interconnection proposes a DC offset sensor and current controller, which too adds to drawback of larger size, high cost and losses to the system (Ahfock et al.University of Southern Queensland). High frequency transformer interconnection does not guarantee DC component cancellation and has reduced efficiency/cost ratio due to several stages (Buticchi et al.2011).

II. DC CURRENT IN A SAMPLE DISTRIBUTION SYSTEM

To study the significance of DC current in a real system, a sample power distribution system of the Arthur C Clark Institution of Modern Technologies was chosen. This system is fed by an 11kV/400V, 400kVA, 50Hz three phase step down transformer and the loads comprised a significant count of personal computers and electronic equipment among other loads. Measurements were carried out using FLUKE 435 Power Quality Analyzer at the transformer secondary, which is the PCC for the particular power system. Screen-shot of Figure 1 gives the values of different measurement of the load, and Figure 2 gives the spectrum of currents for one phase. It is observed that the net DC current at the PCC of three phases are 1.1 A, 1.5 A and 1.4 A, all of which are well above the upper limit given in the standards in Table 1.



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	L1	L2	L3	Total
kW	15.2	18.6	10.8	44.7
kVA	15.8	19.6	11.3	46.7
kVAR	4.3	6.0	3.4	13.7
PF	0.96	0.95	0.95	0.95
Cosϕ	0.96	0.95	0.95	
A rms	70	86	50	

	L1	L2	L3
V rms	228.44	228.30	229.21

02/23/15 11:23:27 230V 50Hz 3Ø WYE EN50160

Figure 1. Sample system measured data at PCC

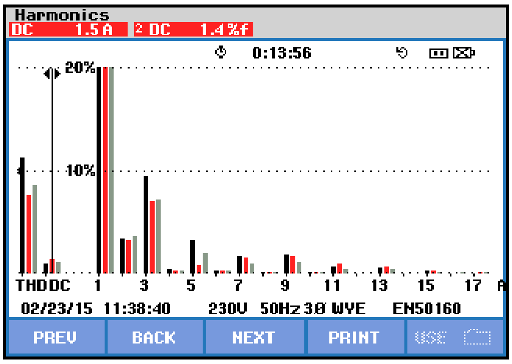
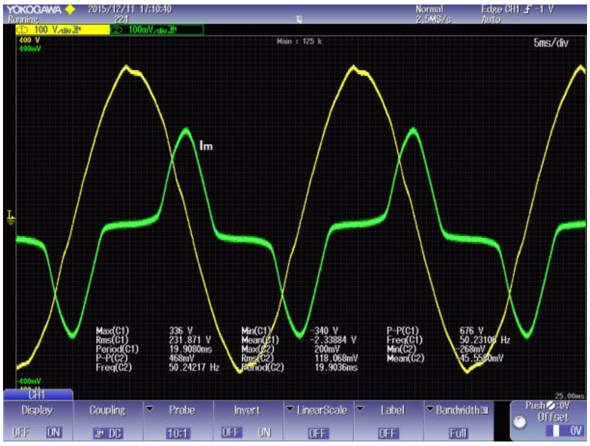


Figure 2. DC current measured in phase 2 at PCC

III. PRACTICAL INVESTIGATION OF THE EFFECT OF DC CURRENT IN A TRANSFORMER

To study the effects of DC current on the operation of a transformer, a 4kVA, 230/400V single phase laboratory transformer was selected, in the first place.

A. *Magnetizing current in normal operation*



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Max(C1)     336 V          Min(C1)     -340 V         P-P(C1)     676 V
Rms(C1)     231.871 V      Mean(C1)    -2.33884 V     Freq(C1)    50.23106 Hz
Period(C1)  19.9080ms      Max(C2)     200mV          Min(C2)     -268mV
P-P(C2)     468mV          Rms(C2)     118.068mV      Mean(C2)    -45.5580mV
Freq(C2)    50.24217 Hz    Period(C2)  19.9036ms
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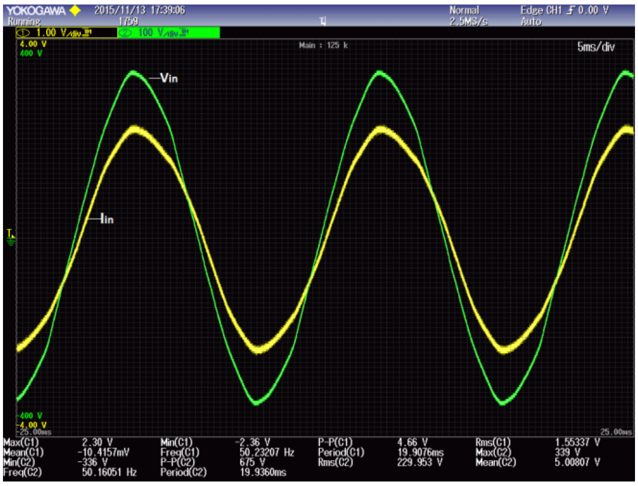
Figure 3. Tested magnetizing current at rated input voltage

Magnetizing current measured at rated voltage on LV side is given in Figure 3 which complies with theoretical expectations, having a significant 3rd harmonic component. This is an obvious consequence of the inherent magnetic saturation of the core but the positive and negative half cycles are similar implying symmetrical magnetization.

B. Input current on load

Although the magnetizing current is having 3rd harmonic distortions the net input current of a loaded transformer is generally sinusoidal, because the magnetizing current is only a small fraction of the total current. The tested input current at 90% full load (resistive) is given in Figure 4 and it clearly shows that the current waveform is sinusoidal, and inphase with the voltage.



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Max(C1)      2.30 V        Min(C1)     -2.36 V        P-P(C1)     4.66 V        Rms(C1)    1.55337 V
Mean(C1)   -10.4157mV      Freq(C1)    50.23207 Hz    Period(C1)  19.9076ms     Max(C2)    339 V
Min(C2)    -336 V          P-P(C2)     675 V          Rms(C2)     229.953 V     Mean(C2)   5.00807 V
Freq(C2)     50.16051 Hz   Period(C2)  19.9360ms
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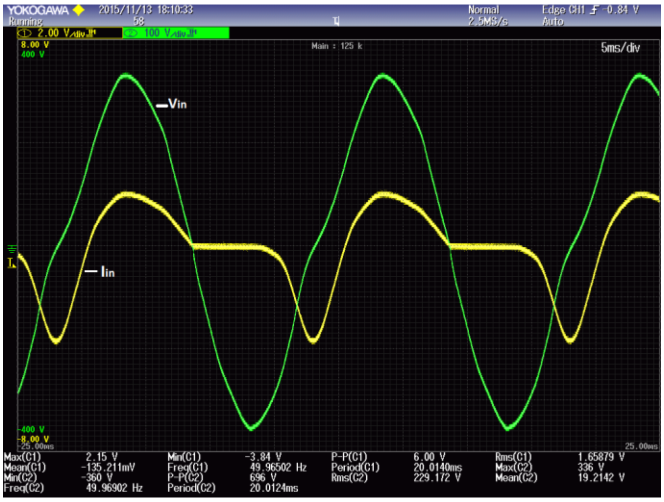
Figure. 4. Tested input current at 90% load (resistive) at rated input voltage

C. Input current on load with DC current injected to the secondary

To investigate the effects of DC current on the operation of the transformer, a DC current component amounting to 35% full load current was injected to the secondary while the secondary is delivering 90% full load to a resistive load. This is a heavy DC current unlikely to occur in practice but consciously chosen for the test to magnify the effects. The input current waveform under this condition is given in Figure 5 and it clearly shows excessive distortions inflicted on the waveform. The negative peak of the input current waveform now occurs just about 90° ahead of the positive peak and this is purely a magnetizing current peak. Its value has now reached staggering 38.4 A from its nominal value of 2.6 A in Figure 3. The positive peak is almost unchanged (21.5A) which is determined purely by the load. This behavior is in complete agreement with the theoretical predictions. The DC current injected at the secondary lowers the operating point of the iron core in the flux current characteristic, pushing the negative half cycle of flux deep in to saturating region resulting in a large negative peak of magnetizing current. The amplitude of this negative peak of magnetizing current is well above the negative peak of the load related input current. Thus the negative peak of the resultant input current occurs right at the location of the same of the magnetizing current, which is 90° behind the negative peak of the voltage. The positive peak of the magnetizing current does not change much as the positive half of the flux waveform is now virtually inside the linear portion of the characteristic, and remains near 2.6 A. Therefore, the resultant input current waveform retains its positive peak at the same location of the load related current, which is coinciding with the positive peak of voltage, with almost the same value of 21.5 A. Thus, the phase angle shift between the negative and positive halves of the resultant input current waveform becomes nearly 90°. DC current injection for this test was done by way of connecting a diode in series with the load in the secondary. This is the reason for not having the part of input current waveform in phase with the negative half cycle of voltage.



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Max(C1)      2.15 V        Min(C1)     -3.84 V        P-P(C1)     6.00 V        Rms(C1)    1.65879 V
Mean(C1)  -135.211mV       Freq(C1)    49.96502 Hz    Period(C1)  20.0140ms     Max(C2)    336 V
Min(C2)    -360 V          P-P(C2)     696 V          Rms(C2)     229.172 V     Mean(C2)   19.2142 V
Freq(C2)     49.96902 Hz   Period(C2)  20.0124ms
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Figure 5. Tested input current with 35% DC current at 90% load (resistive) at rated input voltage

Input voltage waveform is also now showing some distortions, especially a dip in the value near the positive going zero crossing of the waveform. This is mainly due to the voltage drop in the supply side impedance. This introduces asymmetry to the waveform and thereby a notable 2nd harmonic component.

D. Input current on load with a small value of DC current injected at the secondary

To investigate the effects of smaller values of DC current on the operation of the transformer a DC current amounting to 10% of rated current was injected to the secondary while the secondary is delivering 90% rated current to a resistive load. This time the DC current was injected with the negative polarity to cause an opposite shifting of the magnetic operating point and saturation in the positive half cycle.

The resulting input voltage and current waveforms are given in Figure 6. The positive half cycle of current is now "broadened" beyond the zero-crossing of the voltage but the negative half cycle remains relatively unchanged. This behaviour of current is again due to the asymmetry of the magnetizing current, caused by the injected DC current. Now the magnetic operating point is shifted up on the flux-current characteristic and hence the positive half cycle of flux is driven in to hard saturation, resulting in a very high positive peak of magnetizing current. Although the DC current injected was only 10% rated current the saturation has raised the positive peak of the magnetizing current from its nominal value of 2.6 A (see Fig.3) to about 18 A, as seen in the current waveform at the point 90° behind of the voltage peak. The summation of large positive peak of magnetizing current and the positive peak of load current, which is inphase with the voltage, results in a broader positive half cycle of the input current. The negative half cycle of input current remains as of the load related current because the negative peak of the magnetizing current is only below 2.6 A, which is too small compared to the load related current peak of 23 A.

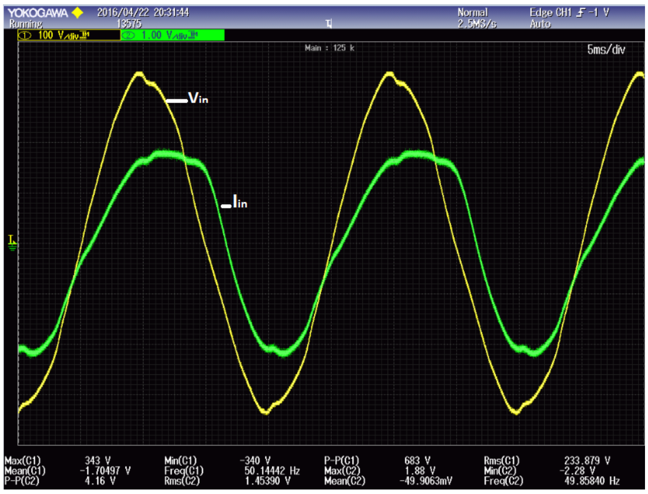

Figure 6. Tested input current with 10% DC current at 90% load (resistive) at rated input voltage

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IV. SIMULATION OF THE EFFECTS OF DC CURRENT IN A TRANSFORMER

Practical investigations carried out and described in section III represent only few handpicked cases. A good simulation model is required for a comprehensive investigation of the effects of DC current on the operation of the transformer, under different operating conditions. Therefore a PSCAD simulation model for the chosen 4 kVA, 230V/400V, single phase laboratory-transformer was developed. Table 2 gives different values of parameters used in the model.

Table 2: Parameters for the model of transformer

Transformer capacity	4 kVA
Primary winding voltage (rms)	230 V
Secondary winding voltage (rms)	400 V
Operating Frequency	50 Hz
Leakage reactance	0.02 pu
No load losses	0.01 pu
Copper losses	0.0125 pu
Ideal transformer model	Yes
Tap changer on winding	None
Saturation enabled	Yes
Place saturation on winding	Primary wdg
Air core reactance	0.04 pu
Inrush decay time constant	1 S
Knee voltage	0.88 pu
Time to release flux clipping	0.1 S
Magnetizing current	7.50%

A. Simulation of magnetizing current with normal operation

Transformer was simulated giving 230 V across the primary with open circuited secondary. Input current under these conditions is given in Figure 7, and this is mostly the magnetizing current. The waveform exhibits a very high degree of matching with the corresponding practical magnetizing current waveform given in Figure 3, justifying the validity of the model with regard to magnetic saturation.

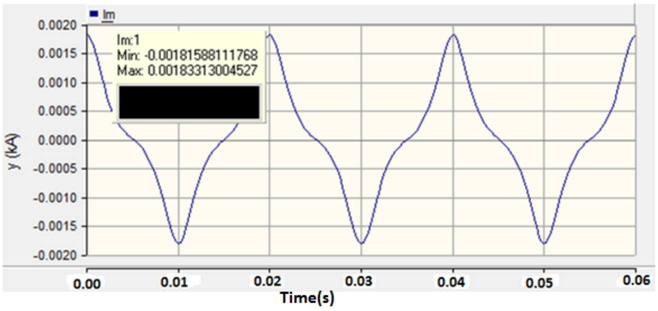

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Figure 7. Simulated magnetizing current at rated input voltage

B. Simulation of input current with load on secondary

To investigate the relative insignificance of magnetizing current in a loaded transformer, the transformer was simulated giving 230 V across the primary and a load on the secondary that draws 90% rated current. The resulting input current waveform is given in Figure 8. This again exhibits a high degree of matching with the corresponding practical input current waveform given in Figure 4, justifying again the validity of the model.

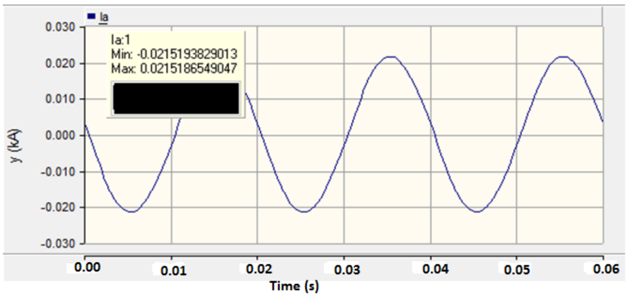

Figure 8. Simulated input current at 90% load (resistive) at rated input voltage

C. *Input current on load with higher DC current injected to the secondary*

The tested conditions involving a high DC current in the secondary amounting to 35% rated current when the transformer is loaded to 90% with 230 V across the primary were also simulated, and the resulting input current waveform is given in Figure 9. This waveform too exhibits a very close of matching with the corresponding practical input current waveform given in Figure 5.

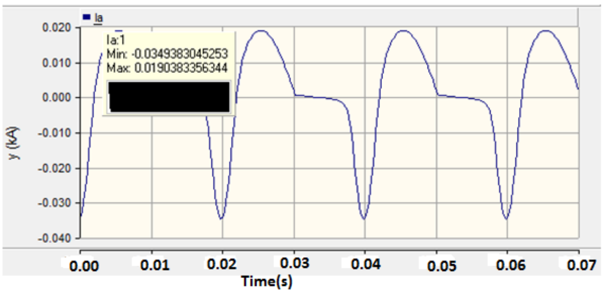

Figure 9. Simulated input current with 35% DC current at 90% load (resistive) at rated input voltage

D. *Input current on load with small DC current injected to the secondary.*

Other test condition involving a small DC current amounting to 10% rated current in the secondary when the transformer is delivering 90% load with 230 V across the primary was also simulated, and the resulting input current waveform is given in Figure 10. This again shows a very close agreement with the corresponding practical input current waveform given in Figure 6, proving the validity of the model beyond doubts.

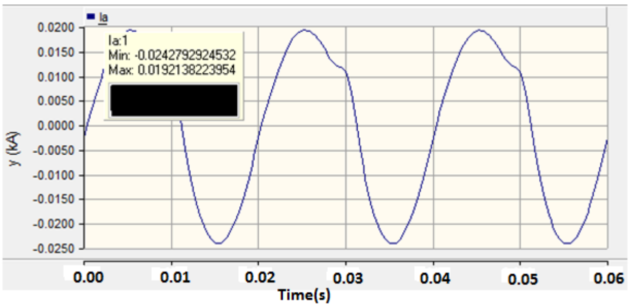

Figure 10. Simulated input current with 10% DC current at 90% load (resistive) at rated input voltage

V. CONLUSION

Investigations carried out on test transformer revealed very important facts regarding the influence and effects of load-injected DC current on the operation of a transformer. Experimental results and the simulation results were in very close agreement.

The injected DC current has a significant influence on the no load current, both in the magnitude and the shape. For example, the peak value of no load current was 7 times greater for a DC current amounting to 10% rated current in the load. This increase occurred only in one half cycle of the waveform depending on the polarity of DC current, determined by the direction of shift of the iron-core operating point. Shape is heavily distorted by 3rd harmonic caused by deep magnetic saturation.

DC current in the secondary creates significant effect on the shape of the input current on a loaded transformer too. One half cycle of the current waveform gets widened while the other half cycle gets narrowed, creating asymmetry in the current waveform and also adding a phase lag. These effects on the current waveform reflect some distortions on the transformer voltage due to coupling with the supply source impedance.

A higher level of DC current in the load side creates prohibitive distortions in the no load current, full load current and full load voltage, all. A test at a DC current amounting to 35% rated current showed the effects very clearly. Although a distribution transformer is highly unlikely to be loaded with this level of DC current, it shows the damage that may accrue on the transformer should it happened, may be due to a rare case of high power half-bridge rectifier type loads. DC current influences the core losses and creates additional copper losses and this aspect needs to be investigated further using the transformer model.

The results provide convincing information about the unsuitability of operating a transformer with a level of DC current above the acceptable limits. Therefore, appropriate DC current cancellation or compensation measures should be implemented on transformers which are likely to experience high dose of DC current from the loads.

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