Load Injected DC Current in Distribution Transformers: Investigation and Elimination

J. P. Karunadasa and H. M. A. I. Herath

Abstract: Due to heavy proliferation of power electronic and non-linear loads on a present day utility system, the DC current accumulated at the distribution transformer is significant. DC current shifts the operating point of the magnetization characteristic and hence causes the magnetizing current to exhibit severe asymmetry between positive and negative half cycles in magnitude and shape, owing to magnetic saturation. It affects the shape of input current and recreates a DC current at the input with magnitude even greater. This paper describes the work on influence of DC current on input current in a loaded transformer, and a system to divert DC current completely away from the transformer. Implementation was done with a specially designed current sensor and a fast responsive controlled current source. The later was implemented in power electronic with closed loop control. The work was challenging because measuring of small DC current superimposed with a large AC current was not straightforward, and also injecting a small DC current accurately against a large AC voltage was not straightforward. Both these challenges were successfully overcome and an extremely good DC current diversion system was developed. Details of the design and results of investigations are presented.

Keywords: DC cancellation, DC sensing, distribution transformer, load-injected DC current, magnetizing current, magnetic saturation, power quality

1. Introduction

POWER electronic based loads, grid-tie inverters and other non-linear loads in the present day utility system creates small DC current component on top of their normal AC current. Proliferation of such loads and inverters results in a significant net DC current accumulated at the secondary of the distribution transformer. This accumulated DC current, when it is comparable to the magnetizing current of the transformer introduces severe power-quality distortions in the system. In particular, DC current in the secondary shifts the transformer operating point on the magnetization curve forcing alternative half-cycles to undergo magnetic saturation, and thereby leading to severe asymmetry between positive and negative half cycles of the magnetization current, both in magnitude and shape. More importantly, the input current then starts carrying a DC current component with magnitude even higher than the DC current that was present in the secondary [1]. Further, transformer itself can undergo overheating, increased power losses and reduced lifespan etc. In addition to these problems, the accumulated DC current can cause 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.[3] -[6].

At the outset, to address the DC current issue in the utility system, the individual equipments that are likely to contribute DC need to be regulated through appropriate standards. For example, grid-tie inverter which is one of the influential equipments that injects noticeable DC current is regulated by standards given in Table 1. Secondly, to minimize the DC injection to the utility, the DC contributing equipments need to have adopted a proper method of interconnection with the utility, For examples, three methods of interconnection have been proposed in the literature for connecting grid-tie inverters with the utility, namely line frequency transformer interconnection, high frequency transformer interconnection and transformerless interconnection [3],[4],[7]-[10], [12], each having 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% [3], [7].

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

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]

Transformerless interconnection proposes a DC blocking capacitor in the inverter output but this requires a large and expensive AC capacitor [3]. Another transformerless interconnection proposes a half bridge inverter which is inherently blocking DC 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 [3],[8]. High frequency transformer interconnection does not guarantee DC component cancellation and has reduced efficiency/cost ratio due to several stages [10].

The sure option for eliminating the influence of DC current in the distribution transformer is to divert DC current away from the transformer. This can be done by using a power electronic converter in parallel with the transformer secondary to divert the DC current arriving at the transformer so that no DC current enters in to the secondary of the transformer. The converter must be supported with closed loop control of current to act as a current source of magnitude and shape exactly matching the incoming DC current. This requires an accurate current sensor that can measure small DC current superimposed with a large AC current. Hall-element based current sensors are not suitable for this purpose due to the noise and drifts of the sensors which make the extraction of DC current information very difficult and inaccurate. A good option is to sense the DC

voltage produced by the DC current in the secondary-resistance. One arrangement proposes to take the full voltage across the secondary and extract the DC part by removing the AC part with an equal and opposite AC component induced through an instrument transformer [4]. However, the instrument transformer itself is sensitive to DC current and also an ideal cancellation of the AC component is not feasible, hence resulting in significant measuring errors. Another proposal suggested to use a small instrument transformer across the secondary and to use its magnetizing current to extract the information of DC voltage by processing the asymmetry between positive and negative half-cycles [10], [11]. This method is relatively complex to implement and the accuracy depends largely on the methods used to acquire and process the magnetizing current signal.

This paper presents the work of a design and implementation of a total DC current diverting system at the secondary of a distribution transformer. The DC current sensor used in this paper has a specific design not involving instrument transformers. It is a voltage based sensor with a special AC cancellation technique. The sensor is found to be performing exceptionally well on a 400 V AC secondary with a superimposed small DC voltage component around 1.25 V DC. The power converter used in the implementation is an H-bridge converter, operated in current control mode. Current control is done in closed loop and the controller is designed after developing the model for the entire system. Current diversion is done separately from individual phases and the details presented are for the system of one phase only. Simulations are done in MATLAB/Simulink environment and the results prove the successfulness and the effectiveness of the proposed method.

2. Measured DC Current in a Sample Distribution System

To ascertain the order of DC current in the present day distribution systems, current measurements were done at the secondary of an 11 kV/400 V, 400 kVA, 50 Hz three-phase distribution transformer feeding a significant count of personal computers and electronic equipment among other loads. Measurement was done using the FLUKE 435 Power Quality Analyzer. Figure 1 gives a screen-shot of basic AC values and Figure 2 gives the spectrum of currents which indicates DC currents of 1.1 A, 1.5 A and 1.4 A in three phases, which are of the order of 10% of the magnetizing current for the

transformer. This is a significant level of DC current for the transformer.

Figure 1- Screen shot of Power Analyser on AC values at the transformer secondary [1]

Figure 2- Current spectrum at the transformer secondary [1]

3. Effects of DC Current on the Operation of a Transformer

To demonstrate that the DC current circulating through the secondary of a transformer create significant distortions and asymmetries between the positive and negative half cycles of the input (primary) current waveform a series of laboratory tests were conducted on a single-phase transformer, rated at 50 Hz, 230/400 V, 4 kVA.

3.1 Input current on no-load in normal operation

Figure 3- Tested input current on no-load at rated input voltage [1]

Figure 3 shows the input current measured at rated input voltage on LV side with HV side open. This current is mainly the magnetizing current drawn by the transformer. Waveform complies with the theoretical expectation having significant 3rd harmonic component and its positive and negative half cycles are similar implying symmetrical magnetization.

3.2 Input current on load

Figure 4 shows input current measured at 90% full load (resistive) on HV side. Current waveform is now sinusoidal because the magnetizing current is only a small fraction of the sinusoidal load-current.

Figure 4- Tested input current at 90% load (resistive) at rated input voltage [1]

3.3 Input current on load with heavy DC current injection

Figure 5 shows the input current at 90% full load (resistive) on HV side with a superimposed DC current amounting to 35% full load current. This is a heavy DC current unlikely to occur in practice but consciously chosen to magnify the effects. The waveform 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.

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.

Figure 5- Tested input current with 35% DC current at 90% load (resistive) at rated input voltage [1]

3.4 Input current on load with a small DC current injection

Figure 6 shows the input current at 90% full load (resistive) on HV side with a superimposed DC current amounting to 10% of rated current. Consciously, 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 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 [1]

4. Proposed System of Eliminating DC Current at the Point of Common Coupling (PCC)

Figure 7 gives an overview of the proposed system of eliminating DC current in each phase of the transformer. DC current created by the consumer-loads is sensed at the transformer secondary by a DC-current sensor and the information is directed to a closed loop current controller, which steers a power electronic converter with PWM control to deliver an equal DC current to the load. This way, the DC current circulating in the transformer secondary is eliminated.

Figure 7- Proposed arrangement of DC current cancellation system at PCC

4.1 DC Current Sensor

Figure 8- DC current detector circuit

Figure 8 shows the arrangement of the current sensor. Front end is a two-stage RC-divider to attenuate the AC voltage component in the measuring-voltage. Body resistances of the capacitors create a small attenuation of the DC component but this is predictable and can be accommodated in the design. AC voltage component present in the output of the RC divider is then removed by the AC cancellation circuit that has an RLC filter at its center. The DC component is finally taken through the gain-setting stage to restore the path attenuations. Figure 9 illustrates the functionality of the current sensor.

Figure 9- Functionality of DC current detector

The transfer function between V_{in} and V_o of the current sensor is given in equation 1[2].

$$\frac{V_o}{V_{in}} = \frac{1115(1690S^2 + 166.7S + 166666666.7)}{(S^2 + 166.7S + 166666666.7)(3S^2 + 173.8S + 1108.1)} \quad (1)$$

4.2 Power Electronic Converter

The function of power electronic converter is to inject cancelling DC current in to the transformer secondary, as requested by the closed loop current controller. Injection is done phase-wise and hence the standard H-bridge configured power converter arrangement, shown in Figure 10, was selected. To ensure satisfactory injection of current against the AC voltage present at the transformer secondary, the DC voltage input to the converter should be sufficiently greater than the peak value of the AC voltage present at the secondary. The 1-phase transformer used in this study had a secondary voltage of 400 V (rms) and hence 660 V (DC) voltage input was selected to give an adequate margin. An inductor L between the output of the converter and the transformer secondary is a must to enable the control of current.

Figure 10- Circuit of Power Electronic Converter

At any instant of time, switching Q_1 & Q_2 causes the current I to rise, and switching Q_3 & Q_4 makes the current to fall. Minimum switching frequency occurs at the positive or negative peak of the AC voltage waveform and maximum switching frequency occurs at the zero crossing points of the AC voltage waveform. This converter operates at 4.6 kHz and 16.7 kHz as minimum and maximum switching frequencies. Transfer function of the power electronic converter was derived considering action of the converter with hysteresis current control in converting a step input at the current controller

to the actual current injected to the transformer secondary.

Figure 11 shows the schematic of the hysteresis current controller, power electronic converter, and the transformer secondary. Current feedback from the output of the power converter to the hysteresis-controller was made with a gain of 0.25 because the actual current in the transformer secondary was sensed (by the current sensor) as a voltage drop across the 0.25 Ω secondary-resistance of the transformer.

Figure 11- Schematics of Power Electronic Converter with Hysteresis Controller function to derive transfer function

- v_x = Input to the current controller
 v_y = Feedback of output current at the current controller
 S = Switching signal to the H-Bridge
 I = Current injected to transformer secondary, by the H- Bridge

Transfer function of the current controller and power electronic converter was derived with reference to step response between V_x and V_y . The resulting transfer function is given in equation 2.

$$F(S) = \frac{1320}{(S + 1320)} \quad \dots(2)$$

4.3 Closed Loop Compensator

Closed loop compensator is a crucial unit in the entire DC current elimination strategy to hold the DC current flowing in the transformer secondary at zero, irrespective of DC current returned by the load.

Main functions to be served by the compensator are:

- To guarantee zero steady-state DC current in the transformer secondary.
- To settle transient DC current fast in the transformer secondary.
- To restrict peak-overshoot of transient DC current within range in the transformer secondary

Figure 12 shows the schematic of the system from a control point of view. The set-input to the closed-loop current controller is zero. Feedback-signal out from the current sensor contains a disturbance in the form of a transient, caused by the secondary AC voltage component, which need not be passed on to the closed loop compensator. Therefore, a signal limiter was placed on the output of the current sensor to clip out the disturbance component. The limiter was set at $\pm 3V$ which was found adequate to stop the disturbance without significantly affecting the speed of response.

Figure 12- Details of Feedback current controller

As long as there is a net DC current in the transformer secondary, the DC current sensor output has a non-zero value, and accordingly integral compensator output keeps rising. The power electronic converter which converts compensator output to DC current, thus, keeps raising the DC current injected in to the transformer. Transformer secondary takes the difference between the converter-injected DC current and the load-produced DC current, which becomes zero when the injected DC current matches the DC current produced by the load. At this instant, the current sensor output becomes zero and the integral compensator output stops further increase. Thus, the control action stops, and the secondary DC current continues to remain at zero. Subsequently, if changes occur in the load-produced DC current, the closed loop controller will act and respond appropriately to bring the DC current in the transformer secondary back to zero.

MATLAB. Figure 17 shows the simulation model. Figure 18 shows the response of output current (v_y) for a step input (v_x) of magnitude 2V to the hysteresis current controller. The response clearly shows that the output current is having approximately linear-building transient followed by constant current sustained by the action of hysteresis current controller. Half-width of hysteresis current controller was set at 10 mV.

Figure 17- MATLAB simulation model of Converter, hysteresis Current controller and transformer

Figure 18- Step response of output current of the power electronic converter

5.3 Overall Performance of the Current Elimination System

Overall performance of the complete current elimination system was investigated by simulating the final system in MATLAB for different levels of DC current created by loads. The following representative cases were investigated by simulation, and in each case the elimination of DC current component from the transformer secondary was found perfect.

a) Case of 40% DC current in the load produced by half wave rectification of load current

Figure 19 shows the schematic of the system that was simulated. A series combination of 45Ω resistive load and a diode on the transformer secondary created a DC current, approximately 40% (4A) of rated rms current (10 A rms) of the secondary.

Figure 19- System schematic for 40% DC current in the load produced by half wave rectification of load current

Figure 20 shows the current waveform in the load, which is the half-wave rectified current waveform with a mean value equal to 4 A. Figure 21 shows the output of the DC current sensor (same as the DC current circulating in the transformer secondary) which, due to the action of the DC current eliminating system has come to zero after a brief transient of less than 2 seconds. Figure 22 shows the DC current injected to the load by the power electronic converter which is settled at 4 A after the brief transient. It should be noted that, as stated before, the transient observed in the current sensor output is an initial inrush caused by the sudden application of AC voltage at the sensor input. The transient observed in the DC current injected to the load is partly due to the inrush of the sensor output but its amplitude is much lower due to the action of the current limiter. Figure 23 shows the final current in the transformer secondary, which is the rectified current waveform but without the DC component of 4A.

Figure 20- Half-wave rectified load current waveform

Figure 21- Output of the DC current sensor

Figure 22- DC current injected to the load by the power electronic converter

Figure 23- Final current in the transformer secondary

It can be observed that the waveform in Figure 23 is same as that in Figure 20 but now shifted down by 4 A, indicating the removal of DC component.

b) Case of 10% DC current in the load produced by half-wave rectification of part of the load current

Figure 24 shows the schematic of the system that was simulated. A series combination of 170Ω resistive load and a diode on the transformer secondary created a DC current, approximately 10% of rated rms current of the secondary. The 58Ω resistive load created the AC component of load current, nearly 80% full load.

Figure 24- System schematic for 10% DC current in the load produced by half wave rectification of part of the load current

Figure 25 shows the current waveform in the load, which has a 13 A positive peak and -9.7 A negative peak, with a mean value of 1 A. Figure 26 shows the output of the DC current sensor (i.e. DC current circulating in the transformer secondary) which, due to the action of the DC current eliminating system has come to zero after a brief transient lasting about 1 second. Figure 27 shows the DC current injected to the load by the power electronic converter which is settled at 1 A after the brief transient. Figure 28 shows the final current in the transformer secondary, which is the load current waveform without the DC component of 1A.

Figure 25- Load current waveform with 10% DC on top of 80% AC

Figure 26- Output of DC current sensor

Figure 27- DC current injected to load by the power electronic converter

Figure 28- Final current in the transformer secondary

It can be observed that the current waveform in Figure 28 is same as that in figure 25 but now shifted down by 1 A, indicating the removal of DC component.

c) Case of 1 A step DC current in the load produced by an ideal DC source at the load

Figure 29 shows the schematic of the system that was simulated. The 45Ω resistive load established 90% load current, and the ideal DC current source introduced step 1 A DC current in to the load. Figure 30 shows the current waveform in the load, which has a 13.4 A positive peak and -11.4 A negative peak, with a mean value of 1 A.

Figure 29- System schematic for 1A step DC current in the load produced by an ideal current source

Figure 31 shows the output of the DC current sensor. It can be observed that the sensor response has now gone to -45V at the beginning. Initially, 1A step current passes entirely through

the 45Ω load resistance as the inductive secondary winding acts as an open circuit for the step-change. So, the resulting 45 V DC developed across the load has been detected by the sensor. Soon the DC current starts transferring to the transformer secondary but the current controller cancels the same and hence the sensor output goes to zero fast, within about 0.5 second. It may also be noted here that the actual output of a practical sensor may not exceed about 15 V due to saturation but in any case we have limited the same to $\pm 3V$ making it irrelevant. Figure 32 shows the DC current injected to the load by the power electronic converter which is settled at 1 A after the brief transient. Figure 33 shows the final current in the transformer secondary, which is the load current waveform without the DC component of 1A.

Figure 30- Load current waveform with 1A DC on top of 90% AC current

Figure 31- Output of DC current sensor

Figure 32- DC current injected to load by the power electronic converter

Figure 33- Final current in the transformer secondary

It can be observed that the final transformer current is now the 90% resistive load current (with equal positive and negative half-cycles) without the 1A DC component.

d) Case of -1 A step DC current in the load produced by an ideal DC source at the load

Figure 34 shows the schematic of the system that was simulated. The 45Ω resistive load established 90% load current, and the ideal DC current source introduced -1 A DC current in to the load (notice that the current source is now acts in reverse direction).

Figure 34- System schematic for -1A step DC current in the load produced by an ideal current source

Figure 35 shows the output of the DC current sensor. The sensor response has now gone to 45V at the beginning due to the same reasons given in section (c) above. DC current has then transferred to the transformer secondary but the current controller has canceled the same and the sensor output has gone to zero accordingly, within about 0.5 second. Figure 36 shows the DC current injected to the load by the power electronic converter which is settled at -1 A after the brief transient. Figure 37 shows the final current in the transformer secondary, which is the load current waveform without the DC component of -1A. It can be observed that the final current in the transformer secondary is now the 90% resistive load current (with equal

positive and negative half-cycles) without the -1A DC component.

Figure 35- Load current waveform with -1A DC on top of 90% AC current

Figure 36- Output of DC current sensor

Figure 37- DC current injected to the load by the power electronic converter

Figure 38- Final current in the transformer secondary

In summary, the results of simulation show that the DC current in the transformer secondary has been eliminated completely in all cases of load-injected DC current.

6. Conclusion

This paper has described the development of a very satisfactory DC offset elimination system for a distribution transformer. DC current reaching at the secondary side of the transformer was completely absorbed in to a current controlled converter. Preliminary investigations revealed the severity of the effects due to DC current in a transformer emphasizing the need for elimination. A critical requirement in the development of the system was an accurate current sensor to detect small DC current mixed up with large AC current and the authentic current sensor developed and described in the paper solved the problem. This sensor can be used in many similar other applications. Considering the future growth of non-linear loads, grid-tie inverters and power electronic intensive loads in utility system, the DC current elimination will be an ever pressing need for most of the future distribution transformers.

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