

A study on the identification of major harmonic sources in power systems

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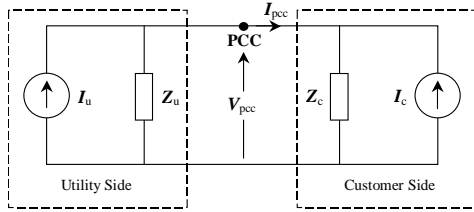
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Abstract

Power system transmission and distribution utilities strive to ensure that the voltage harmonic distortion planning levels are maintained by limiting the harmonic currents injected by the loads. With large customers assessment of the harmonics contributed is carried out at the point of common coupling (PCC). Determination of the contribution to the overall harmonic distortion at the PCC by the major customer is a complex task as it is dependant on aspects such as supply system configuration, associated loads and background harmonics for which the supply authority is responsible. This paper reviews some of the methods that have been proposed to identify the harmonic contribution by a load and reports on a preliminary simulation study in relation to a highly simplified practical situation.

1. INTRODUCTION

One of the commonly employed concepts used to analyse the situation where both the supply system and the major customer load contain harmonics is the Norton equivalent circuit at each harmonic frequency, as shown in Figure 1.



I_u, Z_u - supply side harmonic voltage and harmonic impedance

I_c, Z_c - customer side harmonic voltage and harmonic impedance

Figure 1 Norton equivalent circuit representation of supply system and customer for a given harmonic

One commonly used method for identification of the dominant harmonic source involves monitoring of the direction of the harmonic power flow at the PCC. By measuring the h^{th} harmonic voltage V_h and current I_h at the PCC and their respective phase angles θ_{Vh} and θ_{Ih} , the active harmonic power can be calculated using the equation [1]

$$P_h = V_h I_h \cos(\theta_{Vh} - \theta_{Ih}) \quad (1)$$

In this method, if $P_h > 0$, the utility side is said to cause more harmonic distortion and is the dominant source. Conversely, if $P_h < 0$, the customer side is said to cause more harmonic distortion and is the dominant source.

If Superposition principle is applied to the circuit of Figure 1, the harmonic current contribution at the PCC by the supply and the customer can be individually expressed by the phasor equations [1-3]

$$I_{U-pcc} = \frac{Z_c}{Z_u + Z_c} I_u \quad (2)$$

$$I_{C-pcc} = \frac{Z_u}{Z_u + Z_c} I_c \quad (3)$$

The equation representing the net current at the PCC is

$$I_{pcc} = I_{U-pcc} + (-I_{C-pcc}) \quad (4)$$

As (4) is a phasor equation the contribution to the total PCC current is ambiguous and a better approach [1,2] is to evaluate the component currents of both I_{U-pcc} and I_{C-pcc} that are in phase with I_{pcc} (I_{cf} and I_{uf}) as illustrated by Figure 2.

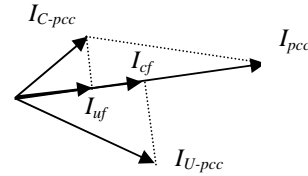


Figure 2 Harmonic current components

Hence

$$|I_{pcc}| = I_{cf} + I_{uf} \quad (5)$$

The component currents I_{cf} and I_{if} are scalars and can have the same or opposite signs leading increase or decrease of net PCC harmonic current once the supply is connected to the customer.

The work presented in [1] indicate that the harmonic power flow method and the current components derived by above by applying Superposition principle do not always give consistent results. For example while I_{cf} is greater than I_{if} the harmonic power flow can in fact change sign depending on the relative phase angle between the supply Norton current and customer Norton current. There are increasing arguments against the harmonic power flow method although it is a feature that is being incorporated into power quality monitors [1].

There are also other techniques [4] suggested which involve measurements made at the PCC with and without the customer connected but such invasive techniques are not normally practical.

The work presented in this paper covers application of the above described techniques to a highly simplified practical system. This was done with a view to develop useful insight to the problems in hand, and especially to make some preliminary investigations on the validity of the existing methods and to examine alternative techniques for identification of harmonic sources. The results obtained through a number of simulations using PSCAD®/EMTDC™ [5] are presented.

Section 2 gives a description on the study network. Section 3.1 covers simulation results in relation to PCC measurements covering net harmonic voltage levels, harmonic real and reactive power flows and their sensitivity to various critical parameters. The simulation results in relation to the development of Norton equivalent circuits are covered in Section 3.2. Concluding remarks are given in Section 4.

2. STUDY SYSTEM

The test network shown in Figure 3 was developed after making several simplifications to the actual plant load containing multipulse rectifier systems, linear loads and the actual supply system configuration.

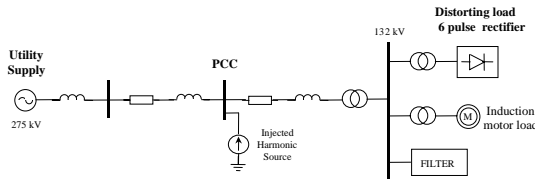


Figure 3 Test network

In this investigation the studies were restricted to

5th harmonic only as it is the most dominant harmonic current drawn by a 6-pulse rectifier system.

The layout that represents the distorting load and the supply system (of Figure 3) is given in detail in Figure 4 (excluding the induction motor load and the filter). Note that this is a circuit with all quantities referred to the rectifier side. The injected harmonic current at the PCC (of Figure 3) represents the background harmonic voltage (V_5/ϕ) originating from within the supply system. As the 5th harmonic is a negative sequence harmonic the phase angle ϕ shown in Figure 4 requires a phase rotation opposite to that of the supply source (V_{source}).

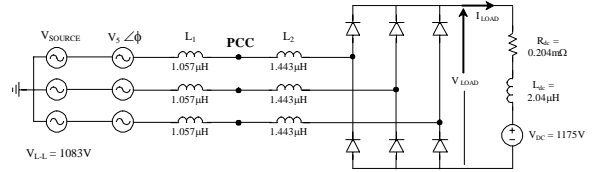


Figure 4 Distorting load and the supply system

3. SIMULATION RESULTS

3.1 PCC measurements

To examine the sensitivity of harmonics at the PCC to the supply voltage (V_{source}) it was varied between 95% and 105% of the nominal value (without the background harmonic source) where a proportional variation in the rectifier ac side current was observed. This represented an equally proportional increase in the harmonic current and harmonic voltage at the PCC.

When the utility side supply inductance (L_1) is increased the voltage harmonics measured at the PCC increased in a linear fashion. In both these simulations it was ensured that the DC side current is kept constant with the help of a control loop.

To investigate the effect on measurements at the PCC due to harmonic distortion being caused by both sides of the PCC, the 5th harmonic voltage distortion (V_5) was injected in series with the utility supply. In order to achieve a practical level of voltage distortion, the level of voltage distortion measured at the PCC was set such that maximum level of total voltage distortion of the 5th harmonic at the PCC is limited to 1%. As the harmonic voltage distortion measured at the PCC due to the rectifier alone (without any harmonic filters) was in the order of 8%, the dc side R-L load had to be adjusted to achieve the 1% limit. In this simulation both the rectifier load and injected 5th harmonic

voltage (on their own) were set to produce equal 0.5% distortion at the PCC. The phase angle of the injected harmonic voltage was rotated through 360 degrees to monitor the situation at the PCC. Assuming that the superposition of the harmonic voltages is valid it is possible to calculate an expected value for the net 5th harmonic voltage and compare it with the observed value from the simulations. This comparison is shown in Figure 5.

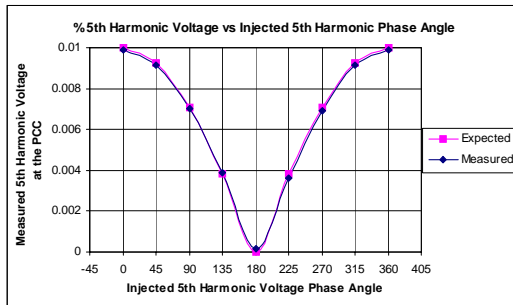


Figure 5 PCC 5th harmonic voltage

The good correlation between the expected and measured values of Figure 5 indicate that the rectifier behaviour is not affected by application of the external harmonic voltages.

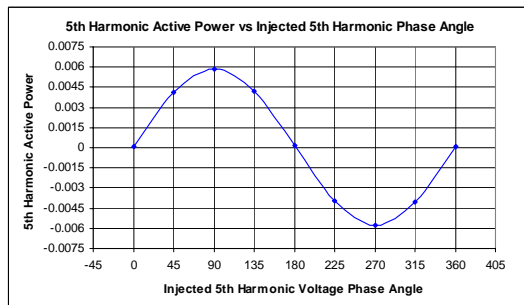


Figure 6 Variation of 5th harmonic active power

The variation of the PCC 5th harmonic active power flow is shown in Figure 6 clearly indicates that the harmonic power flow is very much dependant on the phase angle separation. This further supports the possibility of reaching meaningless results through power flow method as discussed in [2].

Further simulations were performed with varying levels of harmonic voltage distortion levels established on either side of the PCC. Magnitudes of the externally injected 5th harmonic voltage and the rectifier 5th harmonic voltage were varied in the range 0.01% to 0.99% covering several combinations but ensuring that the maximum 5th harmonic voltage distortion measured at the PCC for the total system is limited to 1.0% in all simulations. In these simulations the 5th harmonic current magnitude and phase angle measured at the PCC remained relatively constant. A proportional

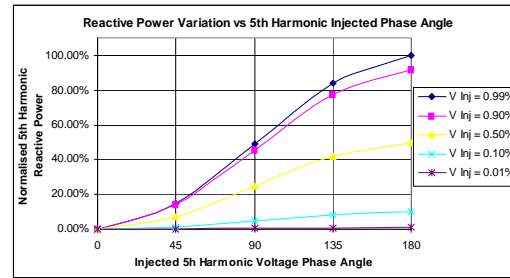


Figure 7 Variation of 5th harmonic reactive power with injected voltage

variation of the injected 5th harmonic voltage phase angle to the level of injected 5th harmonic voltage was also noted. The simulations also indicated a change in the direction of harmonic real power but it was independent of where the harmonics originated from rather dependant on the relative phase angle between the two harmonic sources.

It was also noted that for a chosen phase angle of the 5th harmonic its magnitude had a strong influence on the flow of harmonic reactive power. This is illustrated in Figure 7 where the vertical axis is shown normalised. Results are shown only for phase angle variation from 0 to 180 degrees as the symmetry exists for angles beyond 180 degrees.

During normal operation the phase angle of the injected harmonic with respect to that of the distorting load is not known. However, Figure 7 supports the idea that if the reactive power is positive then the dominant harmonic voltage source resides within the supply system and vice versa.

3.2 Distorting load Norton equivalent circuit representation

Representation of the distorting load by a Norton circuit was further verified by applying unusually large external harmonic voltages while the rectifier on its own produces only 0.5% 5th harmonic distortion at the PCC. In this experiment a linear increase in the current magnitude and phase is illustrated by Figure 8.

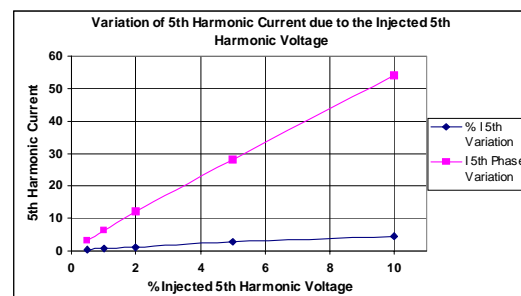


Figure 8 Variation of 5th harmonic current and its phase with injected voltage

The behaviour of Figure 8 tends to support the idea that the rectifier can be represented by a Norton equivalent circuit having a constant current source in parallel with a large impedance.

When an external single harmonic voltage is applied to a rectifier circuit there will be many harmonics generated which have a linear relationship to the applied harmonic. This will result in many interactions occurring between the different frequencies produced by the non-linear load. However, the specific response of a converter to an applied harmonic, at the applied harmonic will remain approximately linear as seen in Figure 8.

To determine the Norton impedance of the rectifier load as shown in Figure 9 equations (6) – (10) can be used.

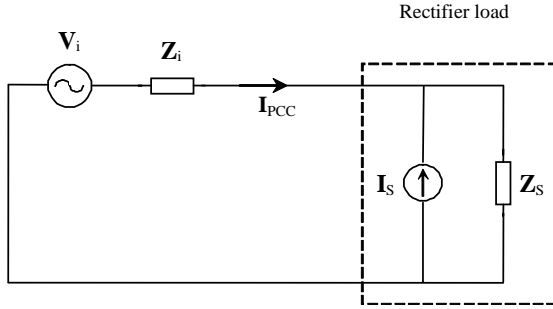


Figure 9 Rectifier Norton harmonic equivalent circuit

Assuming I_s to be constant, variation in the line current for a small variation in V_i can be written as

$$\Delta I_{PCC} = \frac{\Delta V_i}{Z_i + Z_s} \quad (6)$$

where

$$\Delta I_{PCC} = (I_{Max} - I_{Min}) / 2 \quad (7)$$

$$\Delta V_i = (V_{i(I_{Max})} - V_{i(I_{Min})}) / 2 \quad (8)$$

The Norton impedance Z_s can be evaluated using

$$Z_s = \frac{\Delta V_i}{\Delta I_{PCC}} - Z_i \quad (9)$$

$$Z_s = \frac{V_{i(I_{Max})} - V_{i(I_{Min})}}{I_{Max} - I_{Min}} - Z_i \quad (10)$$

For variations of V_i from 0.5% to 10% the rectifier Norton impedance remained constant. It was also attempted to examine whether there is a correlation between Z_s and the rectifier dc load components. In this experiment it was found that there is no such correlation.

Instead of subjecting the circuit of Figure 9 to small variations, absolute value of the impedance can be calculated using

$$I_{PCC} = \frac{V_i - Z_s I_s}{Z_i + Z_s} \quad (9)$$

By rearranging Equation (9), Equations (10) and (11) can be established for two different measurements of V_i and I_{PCC}

$$Z_s I_s = V_i - Z_i I_{PCC} - Z_s I_{PCC} \quad (10)$$

$$Z_s I_s = V_i^1 - Z_i I_{PCC}^1 - Z_s I_{PCC}^1 \quad (11)$$

The Norton equivalent impedance (Z_s) can then be solved by combining the simultaneous Equations (10) and (11) and solving for Z_s

$$Z_s = \frac{V_i^1 - V_i - Z_i (I_{PCC}^1 - I_{PCC})}{I_{PCC}^1 - I_{PCC}} \quad (12)$$

Norton current I_s can be obtained by substituting Z_s into equations (10) or (11).

To obtain different operating conditions required for these calculations the phase angle of the 5th harmonic voltage was varied. The subsequent results are shown in Figure 10. The rectifier load itself produced a 5th harmonic distortion level of 0.5%.

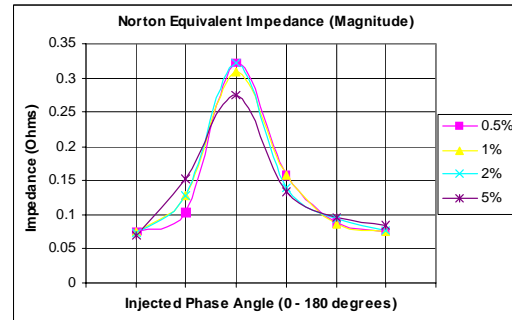


Figure 10 Norton equivalent impedance variation with V_i

Figure 10 indicates that the Norton harmonic impedance of the rectifier load is quite sensitive to the phase of the injected harmonic voltage and no general circuit could be developed to cover all possibilities.

To determine whether a correlation exists between the calculated value of Z_s and the corresponding dc side components of the rectifier values Z_s were calculated for different values of the dc side components. The calculated values of Z_s were found to change significantly for a relative change in L_{dc} or R_{dc} . However, no direct correlation between the values of the dc side components and Z_s could be determined.

The 5th harmonic filter and the induction motor load was also incorporated in further simulations to investigate their effects on the harmonics at the PCC. These simulations provided no definitive conclusions on the harmonic levels at the PCC. This is due to (a) numerous critical components that have an impact on the harmonic measurements at the PCC and (b) the interactions that take place between the critical components.

4. CONCLUSIONS

The resultant voltage distortion at the PCC is very much dependant on the relative phase angle of the external harmonic voltage further supporting the growing support for rejecting the harmonic power flow method. However, the harmonic reactive power flow can provide some indication as to where the dominant source is located.

Norton equivalent circuits although can be developed such circuits representing a complete range of operation of the distorting load cannot be determined. An important reason for this is its high level of dependency on the dc load components and hence the ripple current.

The simulations carried out indicate that without knowing the specific characteristics of the various distorting loads and the supply system no conclusions can be reached on the location of the dominant harmonics even though the distorting load is the considered to be the dominant harmonic producing part of the test system.

Further theoretical, simulation work and experimental work will be undertaken in the near future to investigate the actual system which contains multipulse converter systems.

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