Transformer Inrush Studies for Wind farm Grid Connections

K.S. Smith, C.Eng., MIEE, MIEEE

Abstract: When transformers are energised they may draw high magnitude transient inrush currents from the electrical system, which cause a system voltage drop. For larger transformers or on systems with relatively low fault levels, this dip may exceed the limits allowed in national standards. A recent innovation in electrical power systems is the connection of many wind turbine generators (WTGs) forming large wind farms. This paper describes the use of the PSCAD-EMTDC program to determine the voltage dip experienced at the point of common coupling (PCC) with the utility when different numbers of WTG transformers are energised simultaneously. Two different wind farms will be considered, one with 15 WTGs connected to a rural 33kV distribution substation, and a second larger wind farm with 52 WTGs connected to a 132kV substation. For the larger installation, the sympathetic inrush between incoming and on-line transformers is also investigated.

Keywords: Inrush current, modelling, saturation, transformers.

I. Introduction

In the UK a large number of wind farm installations are being designed and commissioned. In a typical wind farm a series of radial 33kV collector circuits run from the main switchboard and link together individual wind turbine generator (WTG) transformers. At the design stage it is necessary to determine the maximum number of WTG transformers that can be energised simultaneously from the 33kV system. This establishes the number of sectionalising switches required along the length of each 33kV collector. One of the factors to be considered is the voltage dip experienced at the point of common coupling (PCC) between the electrical system of the wind farm and the utility company. In the UK the standard applied is P28 [1]. The voltage dip at the PCC depends upon the impedance of the circuit which links the main 33kV wind farm switchboard back to the utility, and also the voltage and fault level at which this connection is made, i.e. 33kV, 66kV or 132kV. This paper describes how the PSCAD-EMTDC program can be used to investigate these and other issues associated with energising WTG transformers.

II. Transformer Inrush

When a transformer is energised, it may draw a high magnitude transient current from the supply. This current, which is characterised as being almost entirely unidirectional, rises abruptly to its maximum value in the first half-cycle after the transformer is energised and henceforth decays until the normal steady-state magnetizing conditions in the transformer are reached. In a three-phase unit, the peak magnitude of this asymmetric current can be as large as thirteen times the rated line current for the winding being energised [2]. In practice, the magnitude and duration of such a transient inrush current depends upon four factors [3]:

- the point on the voltage wave at the instant the transformer is energised (i.e. switching angle);
- the impedance of the circuit supplying the transformer;
- the value and sign of the residual flux linkage in the transformer core;
- the non-linear magnetic saturation characteristics of the transformer core.

The first two factors depend on the electric circuit to which the transformer is connected. The others depend upon the characteristics of the magnetic circuit of the transformer core, and the distribution of the residual magnetic flux in the core. Residual magnetic flux is determined by the instant when the transformer was previously de-energised. Whist the characteristics of the electrical circuits are normally known; details of the magnetic circuit are rarely available and so lumped reluctance models based on core geometry [4] cannot always be utilised. Simplifying assumptions must be made.

III. PSCAD-EMTDC Transformer Model

The PSCAD-EMTDC transformer model used for these studies, is the "classical" model in which each phase of the transformer is represented by a separate single-phase transformer model with no coupling between phases. Magnetic core saturation is represented by a current source [5]. The modelling process is shown in block diagram format in Fig. 1.

The flux linkage is the integral of the winding voltage, i.e. $\Phi_S(t) = \int V_L(t) \cdot dt$. Saturation is modelled on the LV winding as this is closest to the transformer core. The magnetizing current represented by the current source $I_S(t)$, is related to the flux linkage through the non-linear $\Phi_S - I_S$ characteristic which can be derived from the voltage and current measurements taken during a no-load (open circuit) test. At higher values of flux linkage, the slope of the $\Phi_S - I_S$ curve tends towards the saturated core inductance of the transformer winding. This asymptotic function is

K. S. Smith is with Mott MacDonald, Power Systems Division, 1 Atlantic Quay, Glasgow, G2 8YD, UK. (e-mail: Kenneth.Smith@mottmac.com)

Presented at the International Conference on Power Systems Transients (IPST'05) in Montreal Canada on June 19-23, 2005, Paper No IPST05 – 026

programmed internally within the PSCAD-EMTDC program, based on the magnetizing current at rated voltage, the air core saturated reactance of the winding, and the position of the knee point on the $\Phi_S - I_S$ characteristic.

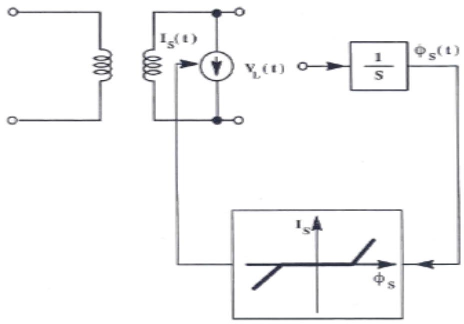

Fig. 1. Modelling of transformer saturation in PSCAD-EMTDC

Residual flux-linkage can be included in the model by inserting a dc current source in parallel with each LV transformer winding; the magnitude of the current is chosen to establish the desired level of residual flux linkage. During normal operation the flux linkage in each phase winding will vary sinusoidally; the magnitude in each phase will be identical, each displaced in time-phase from the next by 120deg. When de-energised, the winding flux linkage will be "frozen" at the instant of disconnection from the supply. To represent this remanance state it is assumed that one phase of the transformer has +80%, the second –80%, and the third zero residual flux linkage. This is generally considered to be the worst case that might be expected upon any random energisation.

IV. WTG TRANSFORMERS

At the initial design stage the only parameters typically available for the WTG transformers are their nominal voltage rating, MVA rating, % impedance and vector group. By itself, this data is insufficient for inrush studies as the magnetizing branch parameters (at rated voltage) and air core saturated reactance Xs are required for studies in which saturation is to be modelled.

There are considerable differences in the values of saturated parameters for transformers suggested in the technical literature. In [6] it is suggested that Xs should be twice the transformer leakage impedance X1, where as in [5] it is observed that Xs can approach the same value as Xl. As the choice of Xs determines the slope of the $\Phi_S - I_S$ characteristic in the saturated region, in the latter case the peak inrush current will be significantly greater.

As the analysis is undertaken to determine the maximum voltage dip that occurs at the PCC with the utility when different numbers of transformers are energised, a lower value of Xs has generally been used in the studies. As a check that the parameters entered into the model are reasonable, the transformer can be energised against an ideal zero impedance source to determine the peak instantaneous inrush current in each phase. Inrush is a function of switching angle, so the simulation must be repeated over a whole ac cycle. For a 1.5MVA, 33/0.69kV, 6.0%, Dy11 transformer, the results are shown in Fig. 2. In this case Xs is assumed to equal 0.06 pu, Imag = 1%, Vknee=1.25 pu and X/R=6.

Inspection of Fig. 2 shows that the peak inrush current can lie anywhere between 0A and 440A. Practically no inrush occurs when the assumed residual flux linkage conditions are close to the instantaneous values that would be present in the core at the switching angular position during normal steady state operation. As the switching angle moves away from this value, the magnitude of the inrush current increases. In the extreme case, the peak inrush current occurs when the switching angle is such that core flux linkage is pushed towards a value approaching 2.8pu, which forces the magnetic core far into saturation. This is readily seen in Fig. 3 where the winding flux linkage and currents for this extreme case are shown.

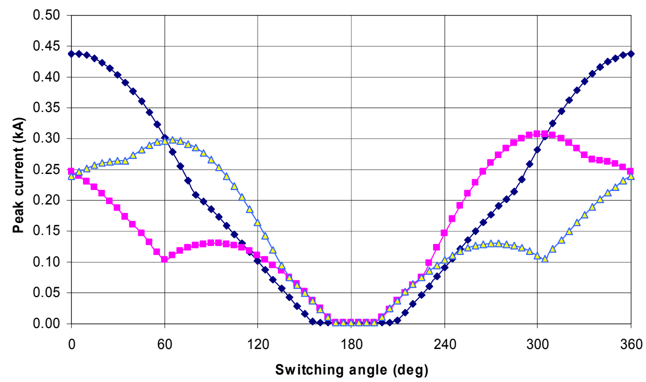

Fig. 2. Variation of peak inrush current 33kV, 1.5MVA transformer.

Another check is to compare the peak inrush current predicted by the simulation, with the tabulated values given for different transformer connections in [2], and revise the value of Xs if considered necessary. In Fig.3 as the transformer is energised from an ideal source the rate of decay depends on the winding resistance that is determined by the X/R ratio. When the ideal source model is replaced by an accurate representation of the utility supply to the wind farm, the source impedance will reduce the magnitude of the 1st cycle peak inrush current and introduce additional resistance that will decrease the time taken to reach the steady state. If available, an inrush decrement curve (for specified source impedance) from the transformer manufacturer is useful to confirm the transient performance of the model and allocate the total per unit winding resistance between the HV and LV windings.

The procedure above describes the development of a single WTG transformer model. To reduce modelling development and simulation effort when performing wind farm system studies, all incoming transformers are lumped together into a single unit, i.e. scale the base unit MVA rating whilst maintaining per unit parameters and assumed residual flux linkages. With this approach the predicted inrush currents will tend to be large as the beneficial impact of the 33kV collector network impedance is not represented in the model.

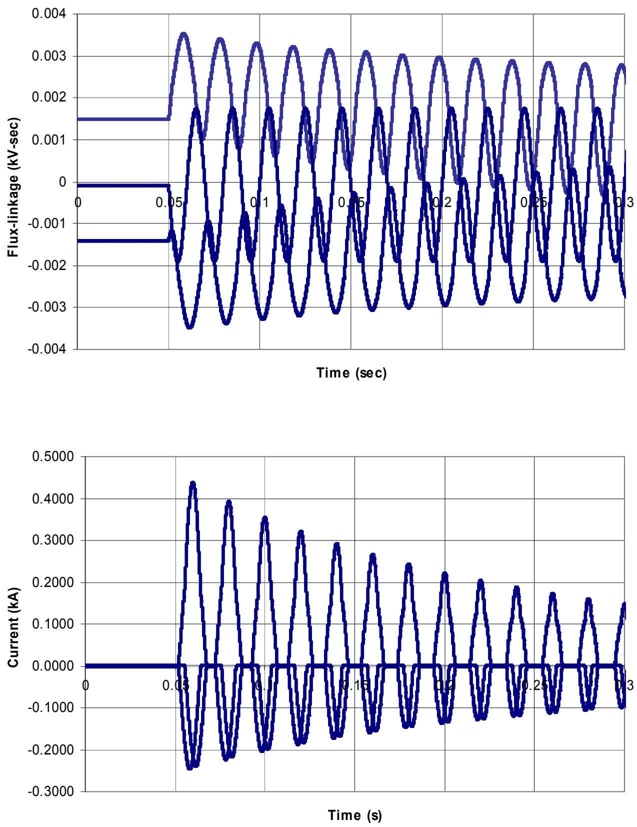

Fig. 3. 33/0.69kV, 1.5 MVA unit energised against an ideal source
Upper trace: winding flux linkage
Lower trace: inrush currents

V. System Descriptions

The results obtained from two different case studies are presented. Each study differs in the rating of the individual WTG transformers, the total generating capacity of the wind farm, and the voltage at which the connection to the utility is made. In both studies the WTG transformers have been modelled using the methodology described above. The wind farm electrical connections are shown in Fig. 4.

Case Study 1: 33 kV grid connection
The Artfield Fell wind farm comprises of 15 wind turbines connected via a 33kV collector network to the main wind farm 33kV switchboard. The individual WTG transformers are 33/0.69kV, 1.5MVA, 6.0% units. The PCC with the utility system at 33kV is 10km distant via an overhead line. The fault levels (rms break) at the PCC are: three-phase 6.81kA and line-ground 2.22kA. Positive- and zero-sequence source X/R ratios are included in the model.

Case Study 2: 132 kV grid connection
The Hadyard Hill wind farm comprises of 52 wind turbines connected via eight radial collector circuits back to the main wind farm 33kV switchboard. The individual WTG transformers are 33/0.69kV, 2.6MVA, 8.28% units. The number of WTGs per collector circuit varies between 1 and 9. In total there is 50 km of 33kV cable in the collector network. The PCC with the utility system is at 132kV, 15km distant via a 132kV single circuit overhead line. Two 90MVA, 0.25pu impedance transformers link the 132kV and 33kV networks at the wind farm site. The central bus section on the main 33 kV switchboard is normally open when both incoming 90 MVA transformers are in service. The fault levels (rms break) at the PCC are: three-phase 6.92kA and line-ground 7.59kA.

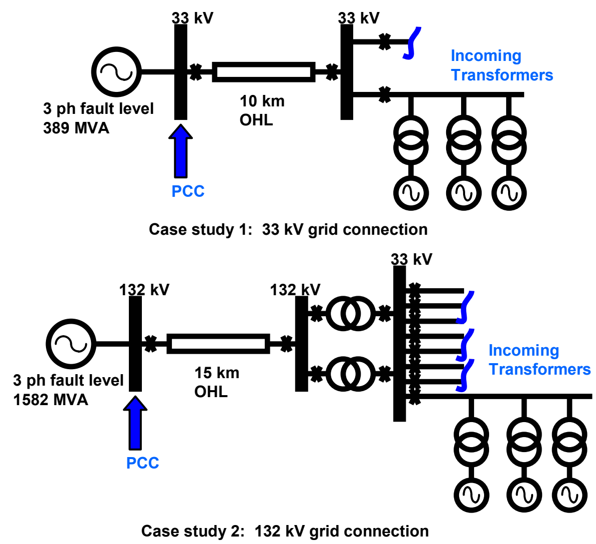

Fig. 4. Case study single line diagrams

VI. Results of P28 Analysis

Wind farm transformer energisation and re-energisation is not anticipated to be a very frequent event. Therefore it is considered appropriate to use the maximum voltage dip permitted by the standards prevailing in the UK, i.e. P28 [1] as the criteria with which to assess the results of the studies. P28 allows a maximum 3.00% change in voltage at the PCC for switching events which occur with a period exceeding 750sec.

The voltage dip has been determined from the instantaneous voltages predicted at the PCC using the rms voltmeter function available in PSCAD-EMTDC. For the studies considered and discussed below the worst case residual flux linkage and least favourable switching angle conditions were analysed, i.e. zero degrees switching angle and 0.8 per unit residual flux linkage as shown previously in Figures 2 and 3. The results for both studies are summarised in Table 1.

Case 1: 33kV grid connection
The variation of the minimum three phase rms per unit voltage at the 33kV PCC with the number of 1.5 MVA WTG transformers energised simultaneously is shown in Table 1. When a single 1.5 MVA transformer is energised the peak current is 407 A. This is less than the 440A predicted for this rating of transformer when energised against an ideal source as shown in Fig. 2 above. For this wind farm configuration no more than three WTG transformers should be energised simultaneously to ensure that the 3% limit imposed at the PCC by P28 is never exceeded. If four units are energised simultaneously, an analysis with different switching angles

shows that there is a 44% probability of the voltage dip at the PCC exceeding the 3% limit.

Case 2: 132kV grid connection
The variation of minimum three phase rms per unit voltage at the 132kV PCC are shown in Table 1. Energising nine WTG transformers will produce a voltage dip of 13.5% at the main wind farm 33kV switchboard, however at the 132kV PCC where P28 applies, the dip is only 2.6% which is within the 3% limit.

The simulation studies show that as far as compliance with the P28 requirements is required, fewer transformers can be energised simultaneously at the smaller capacity wind farm with a 33kV grid connection. This has a direct impact on the number and placement of the sectionalising switches necessary on the 33kV wind farm collector network

TABLE 1
RESULTS OBTAINED FROM INRUSH STUDIES

No of units	Case 1 Artfield Fell 33 kV connection 1.5 MVA WTG transformers		Case 2 Hadyard Hill 132 kV connection 2.8 MVA WTG transformers		
	Peak current at 33kV (A)	Min voltage at PCC (33kV) (pu)	Peak current at 33kV (A)	Min voltage at 33 kV (pu)	Min Voltage at PCC (132kV) (pu)
1	407	0.988	528	0.997	0.993
2	745	0.979	995	0.971	0.990
3	1036	0.972	1410	0.950	0.987
4	1297	0.965	1780	0.931	0.984
5	1532	0.960	2113	0.915	0.982
6	1748	0.956	2413	0.900	0.979
7	1945	0.951	2686	0.887	0.977
8	2098	0.948	2935	0.875	0.975
9	2266	0.945	3160	0.865	0.974

VII. ASSESSMENT OF SYMPATHETIC INRUSH

When an incoming transformer is energised, the dc component of current in the inrush current drawn by the transformer flows through the resistive component of the system impedance, which produces a dc component of voltage. This dc voltage is seen by all other on-line transformers which are then forced into magnetic saturation as their flux linkage (which is the time integral of voltage) develops an offset. As the on-line transformers are driven into saturation, their magnetizing currents increase and they are said to develop a sympathetic inrush current [7]. The interaction that takes place between the incoming and the on-line transformers does not significantly increase the magnitude of the initial inrush current, as it takes some time for the on-line transformers to be driven into saturation. One concern, is that the interaction does result in the inrush current being prolonged, and in extreme cases can cause incorrect operation of protection devices [8] or lead to excessive temporary over voltages [9].

The PSCAD-EMTDC model of the 52 turbine wind farm was used to investigate the phenomena in wind farm type installations. The scenario considered was the case where nine 2.6MVA transformers are energised simultaneously with one 132/33kV, 90MVA incoming transformer in service and the 33kV bus section closed. All other 2.6MVA wind turbine transformers are assumed to be on-line. For each collector circuit with N individual transformers, a single equivalent transformer of rating N x 2.86MVA is used. This configuration is that most likely to display the strongest sympathetic interaction between transformers. Generation on the LV side of the 2.6MVA transformers is not represented; as this load component of current would mask changes to the transformer's magnetizing currents which are the main concern of this study.

The winding flux linkage and total inrush current of the nine incoming transformers are shown in Fig 5 and 6. For clarity only traces associated with one phase of the transformer are presented. The assumed residual flux linkage and choice of switching angle are identical to those used above to ensure that the incoming transformers are pushed far into magnetic saturation i.e. zero degrees switching angle and 0.8 per unit residual flux linkage. The peak inrush current of 3138A is practically unchanged from the Case 2 studies discussed above (with nine incoming units).

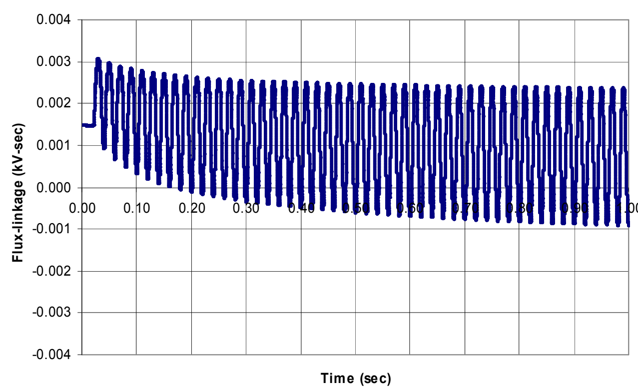

Fig. 5. Incoming transformer flux-linkage

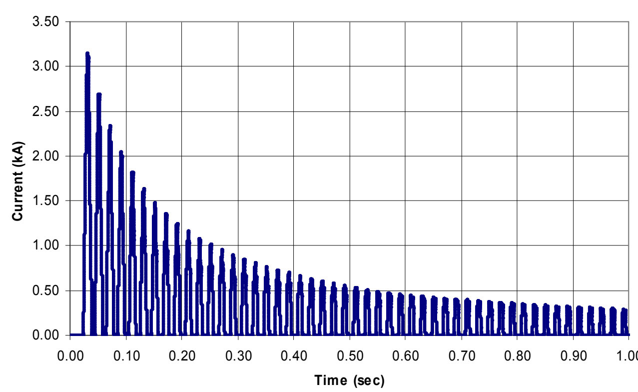

Fig. 6. Incoming transformer inrush current

The flux linkages of the on-line transformers clearly develop a dc offset as shown in Fig. 7 which in turn increases their magnetizing current shown in Fig. 8. The peak flux linkage increases by some 35% while the magnetizing current increases to a peak of 94A some 12 cycles after the incoming transformers are energised. This predicted peak current corresponds to a lumped transformer representing nine individual 2.6MVA units. The increase in the magnetizing current for an individual 2.6MVA unit therefore results in a peak current of 10.4A. As this peak current is only 22% of rated and will be wholly reactive, at full load and unity power factor, the transformer total current will only momentary exceed 1.02 times full load current. It is therefore anticipated that sympathetic inrush current will not be problematic when energising groups of up to nine 2.6MVA wind farm transformers.

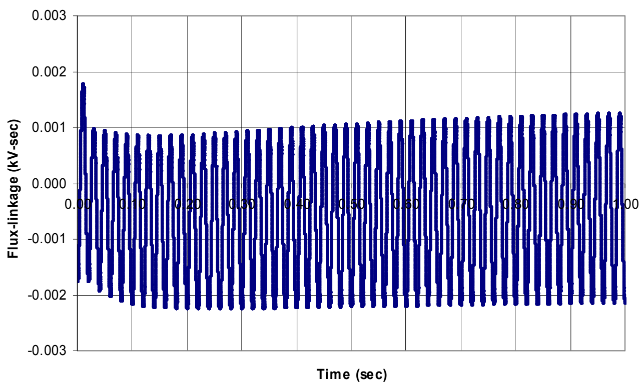

Fig. 7 On-line transformer flux-linkage

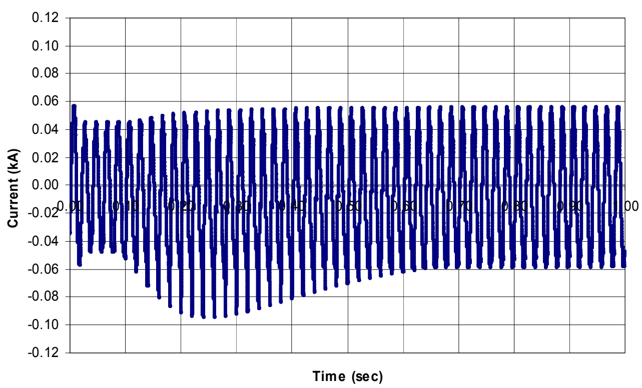

Fig. 8 Sympathetic magnetizing inrush current in on-line transformers

VIII. Conclusions

This paper has described how the PSCAD-EMTDC program can be used to determine the transient inrush current and system voltage drop caused when energising WTG transformers. The paper provides guidance on the choice of parameters required to represent the saturated parameters of the WTG transformers and suggests simple tests which can be used to confirm the veracity of the transformer model. It has been demonstrated that the effects of point on wave switching and residual flux linkage can be included in the model.

The results of two different inrush studies have been presented. It has been shown that for a smaller wind farm with a rural 33kV grid connection voltage, fewer WTG transformers should be energised simultaneously to ensure that the voltage dip at the PCC with the utility does not exceed the maximum 3% value imposed by P28. For a larger wind farm with a 132 kV grid connection many more WTG transformers can be energised simultaneously. This has a direct impact on the number and placement of sectionalising switches required on the wind farm 33kV collector network. Studies for the larger wind farm show that "sympathetic inrush", i.e. the interaction between incoming and online transformers is not a significant concern for this installation.

IX. References

[1] Engineering Recommendation P28, "Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the UK", The Electricity Council, September 1989.

[2] Blume L.F., Camilli G., Farnham S.B., Peterson H.A., "Transformer Magnetizing Inrush Currents and its Influence on System Operation", AIEE Trans, Vol 63, pp 366-375, 1944.

[3] Hudson A.A., "Transformer Magnetising Inrush Current – A Resume of Published Information", Electrical Research Association, Report No 5152, 1966.

[4] Smith K.S., Ran, L., Docherty, J., "Analysis of AVR Transients induced by Transformer Inrush Currents", Proceedings International Conference on Power Systems Transients, June 20-24, 1999, Budapest, Hungary, pp 445-450

[5] Dommel, H.W., "Transformer Models in the Simulation of Electromagnetic Transients", Proc 5th Power Systems Computing Conference, Cambridge England, September 1-5, 1975, Paper 3 ¼.

[6] Woodford, D., "Introduction to PSCAD V3", Manitoba HVDC Research Centre, Rev 1.4, Jan 2001.

[7] Bronzeado, H., Yacamini, R., "Phenomenon of sympathetic interaction between transformers caused by inrush currents", IEE Proc – Science, Measurement and Technology, Vol 142, No 4, July 1995, pp 323-329.

[8] Hayward, C.D., "Prolonged Inrush Currents with Parallel Transformers Affect Differential Relaying", AIEE Transactions, Dec 1941, Vol 60, pp 1096-1101 and pp 1305-1308.

[9] Bronzeado, H., Brogan, P.B., Yacamini, R., "Harmonic analysis of transient currents during sympathetic interaction", IEEE Trans on Power Systems, Vol 11, No 4, Nov 1996, pp 2051 – 2056.

X. Acknowledgement

The author gratefully acknowledges the permission obtained from Scottish and Southern Energy to disclose the results presented in this paper.

XI. Biography

Kenneth S Smith was born in Perth, Scotland in 1966. He graduated with 1st class honours in Engineering Science from the University of Aberdeen in 1988, and after a period as a research student was awarded his Ph.D. in 1992 for work on the time domain modelling of marine electrical propulsion systems. Dr Smith was a member of the academic staff at the University of Aberdeen, Aberdeen, UK between 1991 and 1996 and thereafter at Heriot-Watt University, Edinburgh, UK. During this period he directed two major Engineering and Physical Sciences Research Council funded projects and completed numerous consultancies. He joined the Analysis Section of Mott MacDonald's Power Systems division in Glasgow, UK in April 2002 where his work is principally focused on power system harmonic and transient measurements and analysis. Dr Smith is a Corporate Member of the IEE, a Chartered Electrical Engineer (UK), and a Member of the IEEE.