Assessing P28 Guidelines for Renewable Generation Connections

R.A. Turner, K.S. Smith

***Abstract*: This paper reviews the common methodology adopted for assessing the voltage dip when energising renewable generation (RG) transformers. Extensive PSCAD-EMTDC studies have been performed to develop some generic curves relating the system fault level to voltage dip during energisation for some typical RG transformers based on IEC standard ratings and impedances. The curves allow an initial P28 type assessment to be carried out for a proposed RG connection before detailed design information is available. There is good agreement between the generic curves and a detailed calculation performed using design data for a proposed installation. The information presented in this paper provides a useful first step for assessing proposed RG connections against the specified voltage dip limits and identifying if further, more detailed studies are required, such as where the limits will be exceeded.**

***Keywords*: P28 compliance, renewable generation, inrush current, saturation, transformers.**

I. Introduction

NEW sustainable and renewable generation connections are often required to meet the local guidelines concerning voltage fluctuation at the point of common coupling (PCC). Guidelines may be specifically devised by the Distribution Network Operator (DNO), or by a national body responsible for management of the overall grid network. In the UK, a widely adopted standard for new generator connections to the DNO networks is Engineering Recommendation P28 which permits infrequent voltage fluctuations of up to 3% at the PCC [1]. Typical renewable generation (RG) connections including wind turbines and small hydro generators are connected to the medium voltage (MV) distribution network through one or more step-up transformers. When transformers are energised they may draw high magnitude inrush currents from the electrical system which can cause a system voltage dip. Due to the nature of renewable energy sources, new connections are often located in remote or rural areas where the electrical network can often be characterised by relatively low fault levels. For systems with low fault levels, the voltage dip experienced during an energisation may exceed the adopted guidelines.

As part of the generator connection agreement, the applicant may be asked to show that their new generator scheme meets the local DNO guidelines. This paper describes how extensive PSCAD-EMTDC studies have been used to develop some generic curves relating the system fault level to voltage dip during energisation for some typical RG transformers. The information presented in this paper provides a useful first step for assessing proposed RG connections against the DNO guidelines and identifying if further, more detailed studies are required, such as where the P28 requirements will be exceeded. This information may also be used during the detailed design stage to determine the maximum number of transformers that can be energised simultaneously, for example in a typical wind farm radial 33kV collector circuit which runs from the main wind farm switchboard and links together individual wind turbine generator (WTG) transformers. The PSCAD-EMTDC electromagnetic transient simulation program Version X4 produced by the Manitoba Hydro HVDC Research Centre was used for the analysis that led to the development of the generic curves.

R.A. Turner and K.S. Smith are with Mott MacDonald, Transmission and Distribution Division, 1 Atlantic Quay, Glasgow, G2 8JB, UK. (e-mail: Ryan.Turner@mottmac.com and Kenneth.Smith@mottmac.com).

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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 then decays until the normal steady-state magnetising conditions in the transformer are reached. In a three-phase unit, the peak magnitude of this asymmetric current can typically 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 fluxes are due to the remanent magnetization of the core, after a transformer has been de-energised. At the end of a de-energisation transient both the voltages and currents decay to zero, however the flux in the core retains a certain value defined as residual flux [4]. Whilst the characteristics of the electrical circuits are normally known, details of the magnetic circuit are rarely available, especially during the early design stages of a project, and so lumped reluctance models based on core geometry [5] cannot always be utilised.

III. PSCAD-EMTDC TRANSFORMER MODEL

The transformer representation 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 [6] as shown in block diagram format in Fig. 1. Engineering experience has demonstrated that this model is appropriate for modelling inrush currents and calculating the minimum system retained voltage as required for P28 type studies.

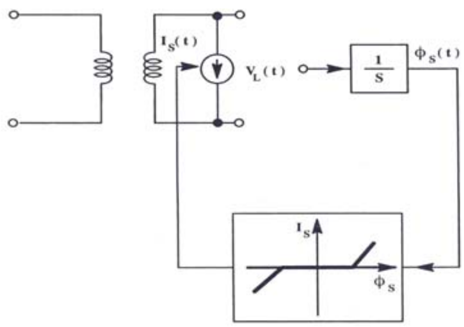

Fig. 1. Modelling of transformer saturation in PSCAD-EMTDC

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 (inductance is flux linkage per ampere of magnetising current) which is represented by the straight line characteristic L_A which bisects the flux axis at Φ_K. The actual saturation characteristic is represented by an asymptotic function that is asymptotic to both Φ_S and L_A which is programmed internally within the PSCAD-EMTDC program, based on the magnetising current at rated voltage, the position of the knee point on the $\Phi_S - I_S$ characteristic and the air core inductance of the winding (see Fig. 2).

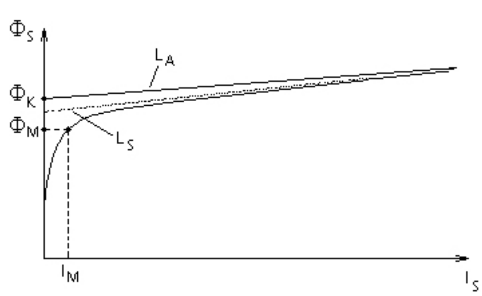

Fig. 2. Core saturation characteristic of the classical transformer

The PSCAD-EMTDC representation of saturation is based on the mean dc magnetisation curve which does not account for hysteresis. A consequence of using this model is that at zero magnetising current there will be zero flux; in reality this will not be true as there will be some residual flux due to hysteresis. The use of a true hysteretic model is required to be able to predict residual fluxes in the core and enable initialisation of the model by a disconnection transient. The Jiles-Atherton model implemented in ATP is capable of representing the hysteresis loops, although it is often difficult to obtain the open circuit test results and relative core dimensions needed to fit the model [7]. A detailed hysteresis model is not usually required for studies which involve high levels of magnetic saturation such as inrush. The most recent publication of the IEEE Working Group on modelling transformers [8] states that with the exception of very specific applications, a very accurate hysteresis model is not required.

Residual flux-linkage can be included in the PSCAD-EMTDC model by inserting a dc current source in parallel with each transformer winding on which saturation is modelled; the current is chosen to establish the desired level of residual flux linkage. During normal operation the flux in each limb of the transformer core will vary sinusoidally; the magnitude in each limb will be similar, each displaced in time-phase from the others by 120 deg. When de-energised, the winding flux linkage will be "frozen" at the instant of disconnection from the supply. To represent this remanence state it is typically assumed that one limb of the transformer has +80%, the second –80%, and the third zero residual flux. Actual measurements of residual fluxes following random transformer de-energisations give worst case residual flux linkages ranging from 40% to 90% [4].

IV. RG TRANSFORMERS

At the initial design stage the only parameters typically available for the RG transformers are their nominal voltage rating, MVA rating, % impedance and vector group. Due to the requirement for voltage fluctuation studies such as those defined in P28 for new RG connections, often the RG transformer inrush current magnitude is also provided by the manufacturer. For EMTP type inrush studies, the magnetising branch parameters (at rated voltage) and air core saturated reactance Xs are required when saturation is to be modelled using the methodology shown in Fig. 1.

The saturated core inductance of the transformer winding and the peak inrush current when the transformer winding is energised can be calculated if sufficient data is available [9]. Where the saturated parameters for transformers have not been provided or cannot be calculated, the parameters may be assumed or derived. There are considerable differences in the values of saturated parameters for transformers suggested in the technical literature. In [10] it is suggested that Xs should be twice the transformer leakage impedance X_l, where as in [6] it is observed that Xs can approach the same value as X_l. 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. For individual transformer models that will be subjected to inrush studies, this approach is not recommended due to the variation in the per unit inrush current magnitudes for different transformer models.

An alternative approach, used by the authors for modelling purposes, is to assume a maximum peak inrush current for the least favourable switching angle and residual flux linkage conditions, and to select the air core saturated inductance to replicate this current when energised against an ideal, zero impedance source. Where available, the actual RG transformer inrush current magnitude provided by the manufacturer should be used to determine the transformer saturation parameters. Alternatively, Blume's classic 1944 paper [2] tabulates maximum per unit inrush current magnitudes for various transformer winding connections which may be used as a conservative estimate for the maximum inrush current magnitude.

For the modelling methodology adopted in this paper, the actual value chosen for the worst case residual flux linkage may not be critical. For a chosen worst case residual flux linkage, the saturated air core reactance Xs is varied to give the required maximum inrush current when energised against an ideal, zero impedance source. Choosing a lower value of residual flux linkage for a given inrush current requires a larger saturated air core inductance. Specifying too high a value for the saturated air core inductance may result in too steep a slope for the asymptotic function L_A, shown in Figure 2. This may limit the ability of the transformer to saturate sufficiently and draw the specified inrush current. The converse of this situation, i.e. specifying too low a value for the saturated air core reactance, produces a shallow slope for L_A and a sharply defined knee point. A transformer modelled with this characteristic will go into deep saturation and draw a large magnetising current for a very small change in flux and this may cause a numerical instability in the simulation. The authors have found that using a worst case residual flux linkage equal to ± 80% gives acceptable results using our methodology..

The inrush results obtained for a typical 2.1 MVA, 33/0.69kV, 8.67%, Dy11 wind turbine generator (WTG) transformer energised against an ideal zero impedance source are presented in Figure 3 as a function of switching angle. In this case Xs has been selected to give a maximum peak inrush current of 11 pu for I_{mag} = 1%, V_{knee} = 1.15 pu and X/R = 11.

Inspection of Figure 3 shows that the peak inrush current can lie anywhere between 0 A and 409 A. Practically no inrush occurs when the assumed residual flux linkage conditions are close to the instantaneous values that would be present in the core during normal steady state operation at 180 deg after voltage zero in phase A. If the distribution of the residual flux in the limbs of the transformer was changed, the minimum inrush current would occur at a different switching angle but the general shape of Fig. 3 would be unchanged. 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 2.8 pu which forces the magnetic core far into saturation. This is apparent in Fig. 4 where the winding flux linkage and currents for this extreme case are shown.

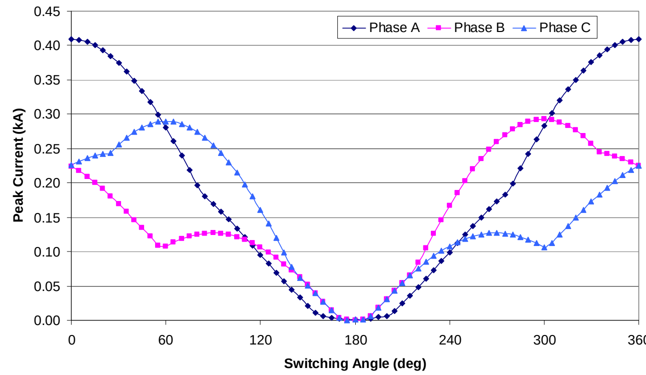

Fig. 3. Variation of peak inrush current 33 kV, 2.1 MVA transformer

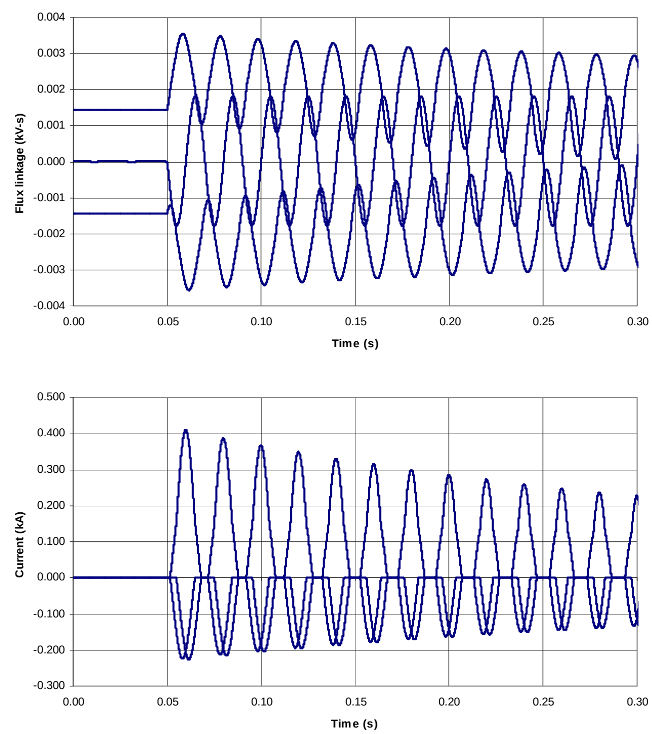

Fig. 4. 33/0.69kV, 2.1 MVA unit energised against an ideal source
Upper trace: winding flux linkage
Lower trace: inrush currents

The methodology described above was used to develop two winding transformer models for standard transformer ratings that may be found in a typical RG scheme. The transformer ratings have been selected from the R10 series of ISO 3:1973 [11] based on the preferred transformer ratings given in Clause 4.3 of IEC 60076-1 [12] in the range from 1 MVA to 5 MVA. Minimum values of short circuit impedances have been specified for each transformer based on Table 1 of IEC 60076-5 [13] with typical X/R ratios. A summary of the transformer parameters used in the PSCAD-EMTDC studies is presented in Table 1.

TABLE 1
RG TRANSFORMER PARAMETERS

Rating [MVA]	V1 [kV]	V2 [kV]	Z1 [%]	X/R	Vector Group
1.00	11	0.69	5	6	Dyn11
1.25	11	0.69	5	6	Dyn11
1.60	11	0.69	6	7	Dyn11
2.00	11	0.69	6	8	Dyn11
2.50	11	0.69	6	8	Dyn11
3.15	11	0.69	7	10	Dyn11
4.00	11	0.69	7	11	Dyn11
5.00	11	0.69	7	12	Dyn11

V. Generic RG Transformer Inrush Curves

The multirun component within PSCAD-EMTDC was used to generate data relating the system fault level to voltage dip when energising the RG transformers with the standardised IEC parameters listed in Table 1. A series of figures were produced for nominal inrush current magnitudes ranging from 5 pu to 11 pu (when energised against a zero impedance source). For each case, the source fault level was varied from 10 MVA up to 1000 MVA and the transformer was energised from its HV delta connected winding. The source impedance was calculated for each case assuming a constant X/R ratio equal to 15. For the curves 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 Fig. 3 and 4. The voltage dip has been determined from the instantaneous voltages predicted at the PCC, which is assumed to be the HV transformer winding terminals for these studies. The generic curves produced by this analysis are shown in Fig. 5 to Fig. 8. The curves have been produced assuming a primary HV winding voltage of 11 kV for each transformer. This need not preclude the use of these figures for higher voltage windings (e.g. 33 kV) as the voltage dip is expressed as a function of fault level in MVA. If the methodology outlined in this paper was adopted to develop curves for transformers with the same rated apparent power but different voltage ratings (e.g. 33/0.69 kV or similar), the results would be the same.

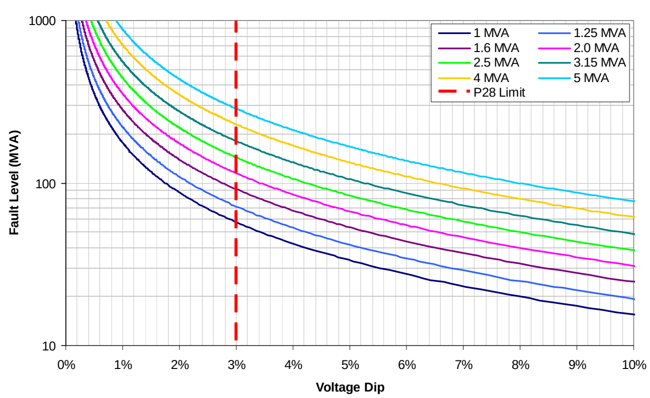

Fig. 5. Variation of voltage dip with fault level for typical RG transformers (5 pu inrush current)

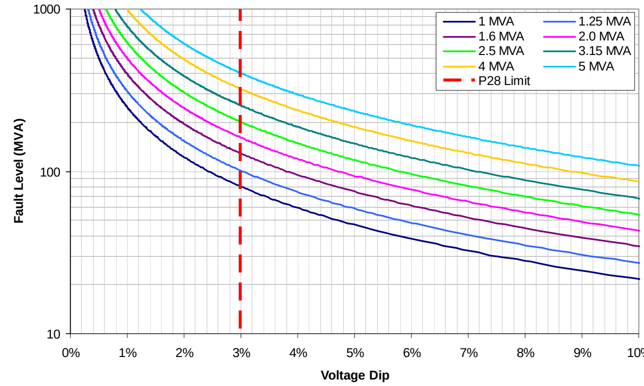

Fig. 6. Variation of voltage dip with fault level for typical RG transformers (7 pu inrush current)

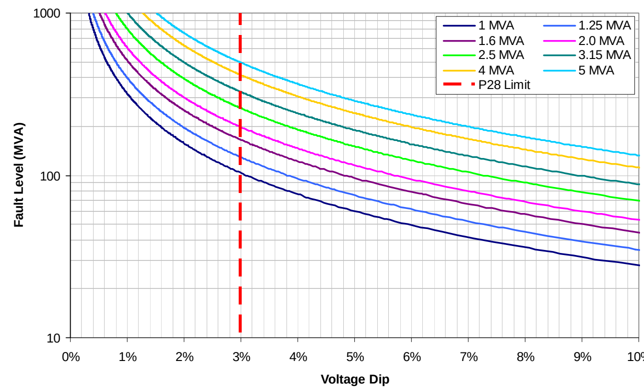

Fig. 7. Variation of voltage dip with fault level for typical RG transformers (9 pu inrush current)

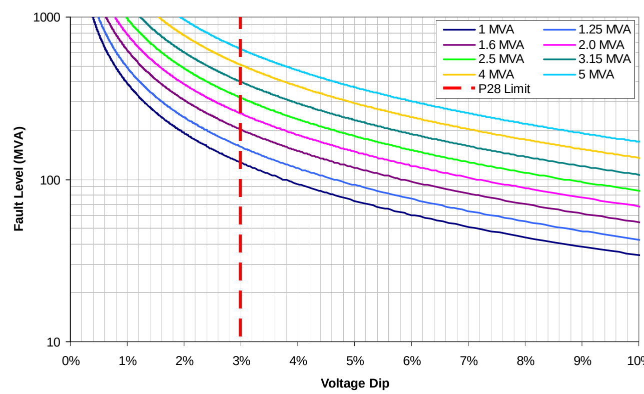

Fig. 8. Variation of voltage dip with fault level for typical RG transformers (11 pu inrush current)

VI. P28 Study Assessment

RG transformer energisation and re-energisation is not anticipated to be a very frequent event. The majority of DNOs in the UK require the new RG connection to meet Engineering Recommendation P28 which allows a maximum 3.0% transient change in voltage at the PCC for switching events which occur with a period exceeding 750 s. The minimum time interval between switching events may be reduced depending on the size of the voltage change as per Figure 4 in [1]. For cases where simple RG schemes will be connected to the rural distribution network and switching events are expected to be very rare, the DNO may agree to more relaxed limits for the permitted voltage dip during energisation. The case for relaxed limits can be made particularly when consideration is given to the probability of any random switching event resulting in the worst case residual flux linkage in the transformer core and the worst case switching angle on the ac voltage wave. For example, the authors are aware of a small capacity hydro generation connection to a rural 11 kV feeder where the DNO agreed to a 10% voltage dip limit due to the very rare requirement for switching. In such cases, it would be preferable to have the RG transformer remain connected to the feeder during outages as the transformer could be energised simultaneously with the other step-down distribution transformers connected to the line. Of course, this scenario would not be applicable to WTG transformers.

For a single RG transformer connection closely connected to the PCC, Fig. 5 to Fig. 8 can be used to estimate the voltage dip for the worst case switching event. The charts derived from the PSCAD studies for the standardised transformers in Table 1 may also be used to perform a preliminary P28 assessment for a wind farm and to estimate the number of WTG transformers that can be switched in simultaneously while meeting the permitted voltage dip limits before detailed design information is available. For example, two case studies are presented based on the 2.1 MVA WTG transformer discussed in Section IV which belongs to a 56 MW wind farm consisting of 28 WTGs. The WTGs are connected via three radial collector circuits back to the main wind farm 33 kV switchboard which supplies a single 33/275kV grid transformer. The two cases consider the PCC at the 33 kV switchboard and at the 275 kV grid connection, as shown in Fig. 9.

Case Study 1: 33 kV PCC

For Case Study 1, the 33 kV switchboard was considered the PCC for this system with a corresponding three-phase fault level equal to 7.9 kA, or approximately 450 MVA as shown in Fig. 9(a). For this case we will assume the impedance between the 33 kV switchboard and the WTG transformers is negligible. This will provide a more conservative estimate of the voltage dip as the additional series impedance between the switchboard and the transformer would effectively reduce the magnitude of the inrush current resulting in a lower magnitude of voltage dip seen at the PCC. Inspection of Fig. 8 for a similarly rated 2.0 MVA transformer with an inrush current corresponding to 11 pu shows the voltage dip is approximately 1.7% when switching in a single transformer against a fault level of 450 MVA. Therefore, a maximum of 2 WTG transformers could be switched simultaneously while still maintaining the 33 kV voltage within the P28 limits. The results obtained from a comprehensive PSCAD-EMTDC model of this system using the design transformer parameters yields a voltage dip equal to 1.3% at the 33 kV PCC. This demonstrates good agreement between using the actual system data and the generic curves that are based on the standardised transformer parameters for performing an initial assessment of P28 compliance.

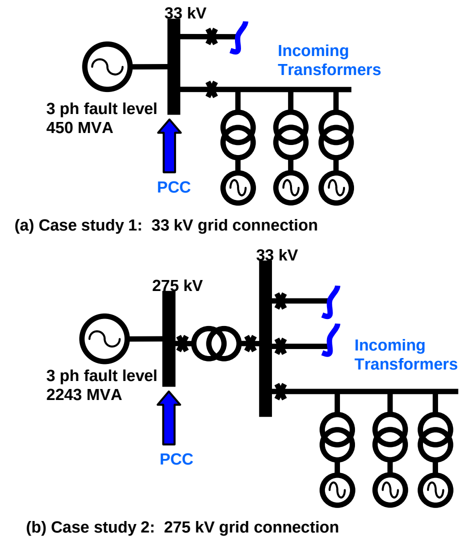

Fig. 9. Case study single line diagrams

Case Study 2: 275 kV PCC

If we were to consider the PCC at 275 kV as per Fig. 9(b), the three-phase fault level would be equal to 4.71 kA, or 2243 MVA. For this case we cannot assume the WTG transformers are directly connected to the PCC as there is the significant impedance of the 33/275 kV transformer to be considered. Given the fault levels at 275 kV and 33 kV, we can calculate the approximate voltage dip at 275 kV based on the results from Case Study 1. This calculation yields a voltage dip of 450/2243 x 1.7% = 0.34% at the 275 kV PCC for a single WTG transformer energisation. Based on these results, an estimated maximum of 8 WTG transformers could be energised simultaneously to ensure that the 3% limit imposed at the PCC by P28 is never exceeded. This compares well with the actual voltage dip of 0.31% obtained from a comprehensive PSCAD-EMTDC model of this system.

These case studies usefully demonstrate that the generic curves based on the IEC preferred ratings and impedance data shown in Fig. 5 to Fig. 8 can be used to estimate the voltage dip and number of RG transformers that may be energised simultaneously, however they do not allow the user to calculate the optimum switching times between energisations of groups of transformers for a wind farm. The rate of decay depends on the winding resistance that is determined by the X/R ratio for the RG transformer and the source impedance. Introducing additional resistance into the circuit will decrease the time taken to reach the steady state. A secondary limitation of using the charts to assess the voltage dip during a transformer energisation is that the phenomenon of sympathetic inrush is not accounted for [14]. This interaction is prevalent in systems where there is significant resistance in the circuit supplying the transformers, and other on-line transformers are slowly driven into magnetic saturation due to the dc component of voltage drop produced by the incoming transformers. For the relatively small transformers considered in this paper, sympathetic inrush is not expected to significantly affect the results and this has been confirmed in an earlier paper [15]. This paper addresses the initial voltage drop when the incoming RG transformer is energised, i.e. during the first cycle of the inrush current. In scenarios where sympathetic inrush is significant, it takes a number of cycles for other online transformers to develop a sympathetic inrush, during which time the initial current peak of the incoming unit has decayed and the system voltage has partially recovered, i.e. the respective time frames for the maximum voltage drop and sympathetic inrush events are different.

In some cases, power factor correction capacitors may be connected to the DNO network. The generic charts can still be used to estimate the voltage dip, however more detailed studies should be performed to ensure that resonances are not excited by the harmonic content of the transformer current leading to potential harmonic overvoltages.

VII. 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 a range of RG transformers as required for sustainable energy generation projects. The methodology described in the paper was applied to the chosen transformer models and the PSCAD-EMTDC program was used to develop a series of generic estimating curves relating the voltage dip magnitude to the grid fault level for RG transformers based on IEC standard ratings and impedances. A series of generic curves were produced for nominal inrush current magnitudes ranging from 5 pu to 11 pu (when energised against a zero impedance source).

The curves permit the user to perform an initial P28 assessment for a proposed RG connection before detailed design information is available. There is good agreement between the generic curves and a detailed calculation that was subsequently performed once design data was made available. This information is presented in a simple, straightforward manner with the intention of being a useful reference for practitioners and applicants engineering new RG connections.

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IX. Biography

Ryan A Turner graduated with a Bachelor of Engineering (Electrical) from the University of Queensland, Brisbane, Australia in 2003. Mr Turner joined the Power Systems Analysis Group at Mott MacDonald’s Transmission and Distribution Division in Glasgow, UK in 2006. Mr Turner is a Chartered Electrical Engineer (UK), a Corporate Member of the IET, and a Member of the IEEE.

Kenneth S Smith graduated with honours in Engineering Science from the University of Aberdeen, UK in 1988, and was awarded his Ph.D. in 1992 for work on the analysis of marine electrical systems. Since April 2002 he has been with the Power Systems Analysis Section of Mott MacDonald’s Transmission and Distribution Division in Glasgow, UK. Dr Smith is a Chartered Electrical Engineer (UK), a Fellow of the IET, a Senior Member of the IEEE, and a Fellow of the Higher Education Academy. He is an Honorary Professor in Electrical Engineering at Heriot Watt University, Edinburgh and Associate Editor of the IEEE Transactions on Industry Applications (Power Systems Committee).