Three-phase five-limb unified magnetic equivalent circuit transformer models for PSCAD V3.

Wade Enright Neville Watson
Electrical and Electronic Engineering Department
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
enrightw@elec.canterbury.ac.nz

Om Nayak
Manitoba HVDC Research Centre
400-1619 Pembina Highway
Winnipeg, Manitoba
Canada R3T 3Y6
nayak@hvdc.ca

Abstract - **This paper describes a three-phase five-limb unified magnetic equivalent circuit (umec) based transformer model for ElectroMagnetic Transient (EMT) analysis. The new model is incorporated in the Power Systems Computer Aided Design (PSCAD) Version 3 computer program. The application of a normalised core (nc) concept to three-limb transformer models is briefly revised, and extended to the five-limb core type. A methodology is explained for the derivation of nc magnetic permeability. Results from several test cases are compared with field measurements.**

Keywords: Power transformer, umec, three-phase five-limb, normalised core, EMT.

I. INTRODUCTION

Recently it was demonstrated that umec EMT transformer models derived from transformer design parameters are exactly equivalent to models derived from name-plate data, if a nc concept is applied. [1] This is fortuitous because the transformer design parameters of: winding turns number, core dimensions and flux density/magnetisation force characteristics may often be available to the transformer manufacturer only. The power system engineer may only have access to the transformer name-plate data.

The application of the umec concept to EMT transformer modelling is now available in the published literature. [2, 3, 4] However, all such applications have been of the umec single-phase or three-phase three-limb transformers. There is potential to apply the umec concept to three-phase five-limb transformers.

Five-limb transformer models for EMT studies have been proposed [5]. In a similar fashion to Stuehm [6], Arturi applies the duality principle to create a three-phase five-limb transformer model. In this paper the umec principle is applied to the three-phase five-limb transformer modelling problem.

II. THE NORMALISED CORE CONCEPT

One of the input parameters to the umec formulation is the number of turns in each transformer winding. Application of a nc to the umec avoids this input. The nc winding number of turns is set equal to the winding voltage, that is for a three-phase transformer $N_{1,3,5} = V_1$ and $N_{2,4,6} = V_2$.

Another input to the umec formulation is magnetic circuit branch permeance P. The permeance of the winding-limb, yoke and outer-limb (five-limb only) umec branches are calculated from

$$P = \frac{\mu_o \mu_r A}{L} \tag{1}$$

The parameters of 1 are not commonly available. The nc umec sets winding-limb length L_{1-6} and cross-sectional area A_{1-6} to unity. It should be noted that the nc concept is not a per-unit (pu) system. In a pu system parameters are dimensionless, this is not the case for all the nc parameters.

A. Core aspect ratios

It is reasonable to expect users have access to scale drawings of power transformer cores. Such information is often located in the transformer maintenance/operating manual. Application of the nc umec to three and five-limb transformers requires the user to input core aspect ratios.

Fig. 1(a) displays the parameter conventions used to derive the ratios for the three-limb core type. Application of the nc umec requires the user to calculate: the yoke to winding-limb length aspect ratio

$$r_{lyw} = \frac{d_y}{d_w} \tag{2}$$

and the yoke to winding-limb cross-sectional area aspect ratio

$$r_{ayw} = \frac{s_y}{s_w} \tag{3}$$

To normalise the core, the transformer length dimensions are scaled by a factor

$$k_d = \frac{2}{d_w} \tag{4}$$

and the cross-sectional area dimensions are scaled by a factor

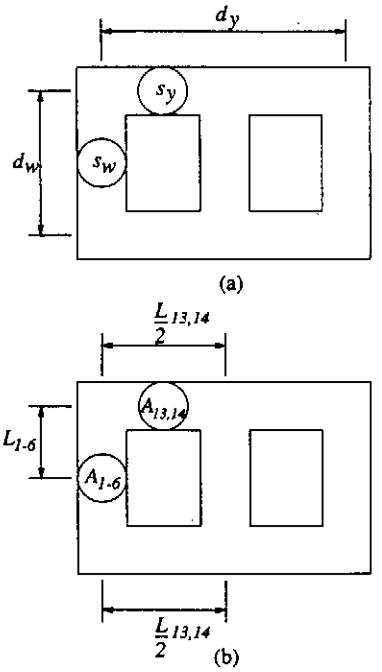


Figure 1: Three-limb core dimensions: (a) user inputs, (b) nc umec parameters.

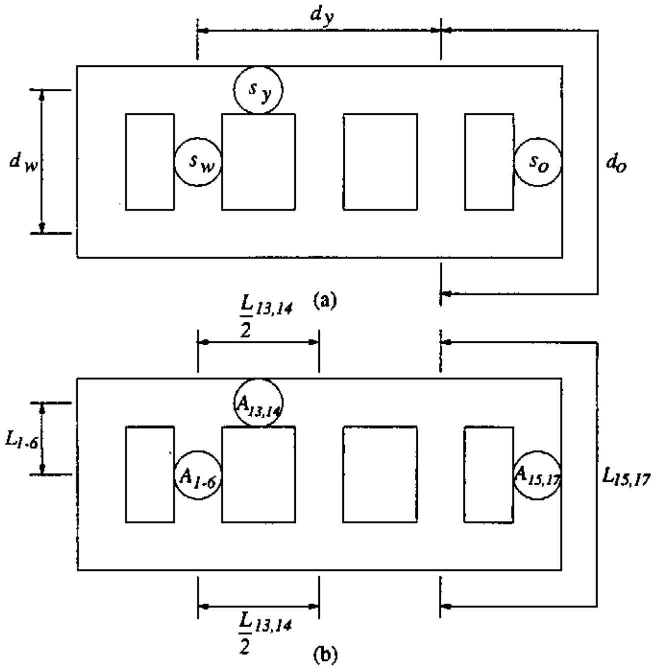


Figure 2: Five-limb core dimensions: (a) user inputs, (b) nc umec parameters.

$$k_s = \frac{1}{s_w} \tag{5}$$

Therefore, the user inputs directly relate to the Fig. 1(b) nc umec parameters as follows:

$$L_{1-6} = \frac{d_w}{2} * k_d = 1.0 \tag{6}$$

$$A_{1-6} = s_w * k_s = 1.0 \tag{7}$$

$$L_{13,14} = d_y * k_d = 2r_{lyw} \tag{8}$$

$$A_{13,14} = s_y * k_s = r_{ayw} \tag{9}$$

Similarly, for the five-limb core type, Fig. 2(a) displays the parameter conventions used to derive core aspect ratios. The five-limb ratios r_{lyw} and r_{ayw} are as per 2 and 3 respectively. The user must also calculate: the yoke to outer-limb length aspect ratio

$$r_{lyo} = \frac{d_y}{d_o} \tag{10}$$

and the yoke to outer-limb cross-sectional area aspect ratio

$$r_{ayo} = \frac{s_y}{s_o} \tag{11}$$

The user inputs directly relate to the Fig. 2(b) nc umec parameters as per 6 to 9, with the addition of

$$L_{15,17} = d_o * k_d = \frac{2r_{lyw}}{r_{lyo}} \tag{12}$$

$$A_{15,17} = s_o * k_s = \frac{r_{ayw}}{r_{ayo}} \tag{13}$$

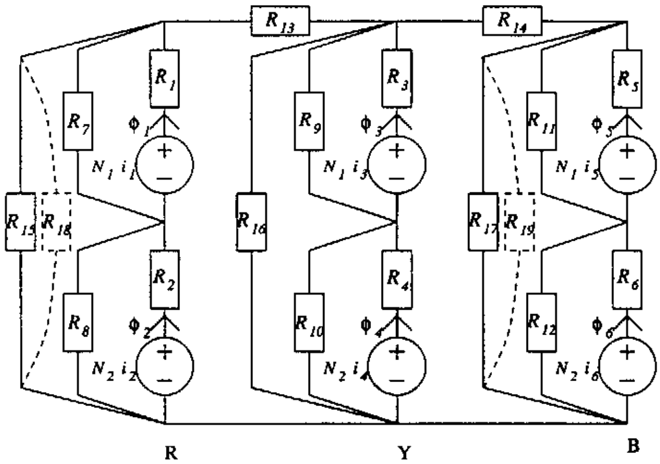


Figure 3: Three-phase umec.

B. Umec core-steel permeability

Once the nc winding turns number and core dimensions are set, the core steel permeability must be fixed to give rated magnetising current at rated voltage. Due to the magnetic asymmetry of the three-limb core type, the permeability is set so that, at rated voltage, rated magnetising current flows in the outer-limb windings.

Fig. 3 displays the three-phase umec. When this model is applied to a three-limb transformer magnetic branches R_{15} to R_{17} are air flux paths. Calculation of the nc permeability is simplified by the fact that during an open circuit test the flux: in branches 1,2 and 13 is dominated by the red-phase flux ϕ_1, in branches 3 and 4 is dominated by the yellow-phase flux ϕ_3, and in branches 5,6 and 14 is dominated by the blue-phase flux ϕ_5. For the purpose of permeability calculation the

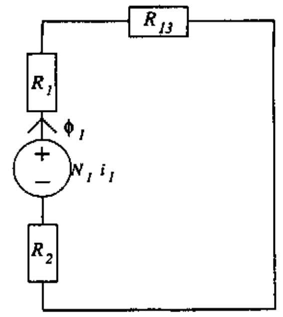


Figure 4: Open-circuit flux path.

open-circuit test red-phase flux path can be simplified to that shown in Fig. 4.

The umec nc relative permeability μ is calculated from

$$Ni_m = \phi_1 R = \phi_1 \frac{L}{\mu A} \tag{14}$$

which when rearranged for μ gives

$$\mu = \frac{\phi_1 \frac{L}{A}}{Ni_m} \tag{15}$$

At rated voltage, and frequency, the rated flux is

$$\phi_1 = \frac{V_1}{\omega_0 N_1} \tag{16}$$

and the rated magnetising current is

$$i_m = i_m^{pu} I_b \tag{17}$$

Furthermore,

$$\frac{L}{A} = \frac{2L_{1-6}}{A_{1-6}} + \frac{L_{13,14}}{A_{13,14}} \tag{18}$$

Substituting 16 and 17 into 15 gives

$$\mu = \frac{V_1}{\omega_0 N_1^2 i_m^{pu} I_b}\left(\frac{2L_{1-6}}{A_{1-6}} + \frac{L_{13,14}}{A_{13,14}}\right) \tag{19}$$

Calculation of the five-limb transformer permeability is not as simple as the three-limb case. For a five-limb transformer magnetic branches R_{15} and R_{17} are the outer-limb core-steel flux paths, branch R_{16} is an air flux path. Two extra air flux paths are added to the five-limb umec. These paths are shown with the dashed lines in Fig. 3, they are umec branches 18 and 19. With the addition of the extra branches each phase has a path for zero-sequence flux.

Under open-circuit conditions the resultant fluxes within the core-steel branches of the five-limb umec are not all in-phase with either ϕ_1, ϕ_3 or ϕ_5. Moreover, the red and blue-phase winding-limb flux is not in-phase with the respective red and blue-phase magnetising currents.

It is fortunate that, due to the symmetry of the five-limb core type, the yellow-phase winding-limb flux is in phase with the yellow-phase magnetising current. The five-limb umec nc relative permeability μ is set so that, at rated voltage, rated magnetising current flows in the centre winding or the yellow-phase.

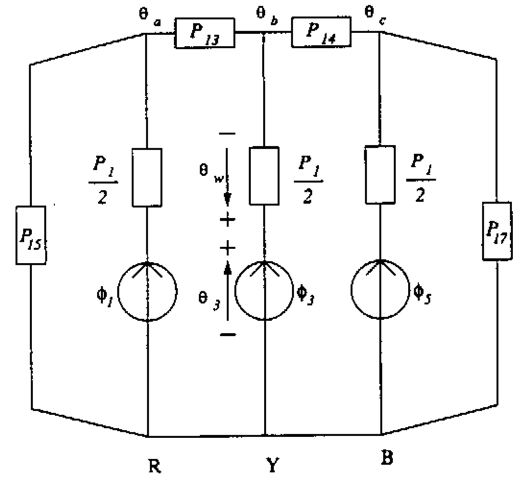


Figure 5: Five-limb open-circuit umec.

Consider the simplified five-limb umec shown in Fig. 5; this circuit represents the transformer on open-circuit. For the purpose of core steel permeability calculation the leakage flux paths are ignored. Applying nodal analysis to the magnetic circuit of Fig. 5 gives

$$\begin{bmatrix}\phi_1\\ \phi_3\\ \phi_5\end{bmatrix} = \begin{bmatrix}P_{13}+P_{15} & -P_{13} & 0\\ -P_{13} & 2P_{13} & -P_{13}\\ 0 & -P_{13} & P_{14}+P_{17}\end{bmatrix}\begin{bmatrix}\theta_a\\ \theta_b\\ \theta_c\end{bmatrix} \tag{20}$$

For the linear five-limb umec P_{13}=P_{14} and P_{15}=P_{17}, this allows 20 to be rewritten as

$$\begin{bmatrix}\phi_1\\ \phi_3\\ \phi_5\end{bmatrix} = \begin{bmatrix}a & -b & 0\\ -b & 2b & -b\\ 0 & -b & a\end{bmatrix}\begin{bmatrix}\theta_a\\ \theta_b\\ \theta_c\end{bmatrix} \tag{21}$$

where

$$a = P_{13} + P_{15},\ b = P_{13} \tag{22}$$

Solving 21 for $\tilde{\theta}$ gives

$$\begin{bmatrix}\theta_a\\ \theta_b\\ \theta_c\end{bmatrix} = \begin{bmatrix}B & A & C\\ A & D & A\\ C & A & B\end{bmatrix}\begin{bmatrix}\phi_1\\ \phi_3\\ \phi_5\end{bmatrix} \tag{23}$$

where

$$A = \frac{-1}{2(b-a)},\ B = \frac{b-2a}{2a(b-a)} \tag{24}$$

and

$$C = \frac{-b}{2a(b-a)},\ D = \frac{-a}{2b(b-a)} \tag{25}$$

Concentrating only on the yellow-phase mmf θ_b gives

$$\theta_b = A(\phi_1 + \phi_5) + D\phi_3 \tag{26}$$

now

$$\phi_1 + \phi_5 = -\phi_3 \tag{27}$$

and substituting 27 into 26 gives

$$\theta_b = (D - A)\phi_3 \tag{28}$$

Finally, substituting 24, 25 and 22 into 28 gives

$$\theta_b = \frac{1}{2P_{13}}\phi_3 \tag{29}$$

Equation 29 gives the mmf across the centre winding-limb of the five-limb nc. In order to calculate the mmf produced by the centre winding the permeance of the winding-limb must be taken into account. For the linear umec the winding-limb permeances P_{1-6} are equal and set to P_1. Fig. 5 shows that

$$\theta_3 = \theta_w + \theta_b \tag{30}$$

and

$$\theta_w = \frac{2}{P_1}\phi_3 \tag{31}$$

Substituting 31 and 29 into 30 gives

$$\theta_b = (\frac{2}{P_1} + \frac{1}{2P_{13}})\phi_3 \tag{32}$$

and placing 1 into 32 gives

$$\theta_b = \frac{1}{\mu}(\frac{2L_{1-6}}{A_{1-6}} + \frac{L_{13}}{2A_{13}})\phi_3 \tag{33}$$

For the open-circuit three-phase transformer

$$\theta_b = N_1 i_m = i_m^{pu} I_b \tag{34}$$

and

$$\phi_3 = \frac{V_3}{\omega_o N_1} \tag{35}$$

Substituting 34 and 35 into 33 gives

$$\mu = \frac{V_3}{\omega_0 N_1^2 i_m^{pu} I_b}(\frac{2L_{1-6}}{A_{1-6}} + \frac{L_{13}}{2A_{13}}) \tag{36}$$

III. SIMULATION RESULTS

New umec three-phase bank, three-limb and five-limb models have been tested under open-circuit, over-voltage and short-circuit conditions. In each simulation scenario, the transformer parameters have been derived from a 61MVA 11/220kV three-phase five-limb hydro-electric power station transformer which operates in the New Zealand ac system. The transformer parameters are summarised in Table 1

In each case the windings have been represented in a star-star configuration. Although the field transformer 11kV winding is connected in delta, removal of the delta winding helps identify the magnetising currents. For the single-phase bank and three-limb transformer simulations the core aspect ratios have been set arbitrarily as follows: r_{lyw}=1.08, r_{ayw}=1.00. For the five-limb simulations the ratios have been calculated from the manufacturer drawings of the field transformer five-limb core, they are: r_{lyw}=1.08, r_{ayw}=0.683, r_{lyo}=0.836 and r_{ayo}=1.74.

Table 1: Five-limb field transformer data.

Rating	61 MVA
Primary winding voltage	11 kV
Secondary winding voltage	220 kV
Base operating frequency	50 Hz
Leakage reactance	10.27

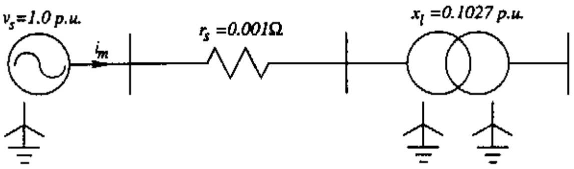


Figure 6: Transformer open-circuit test system.

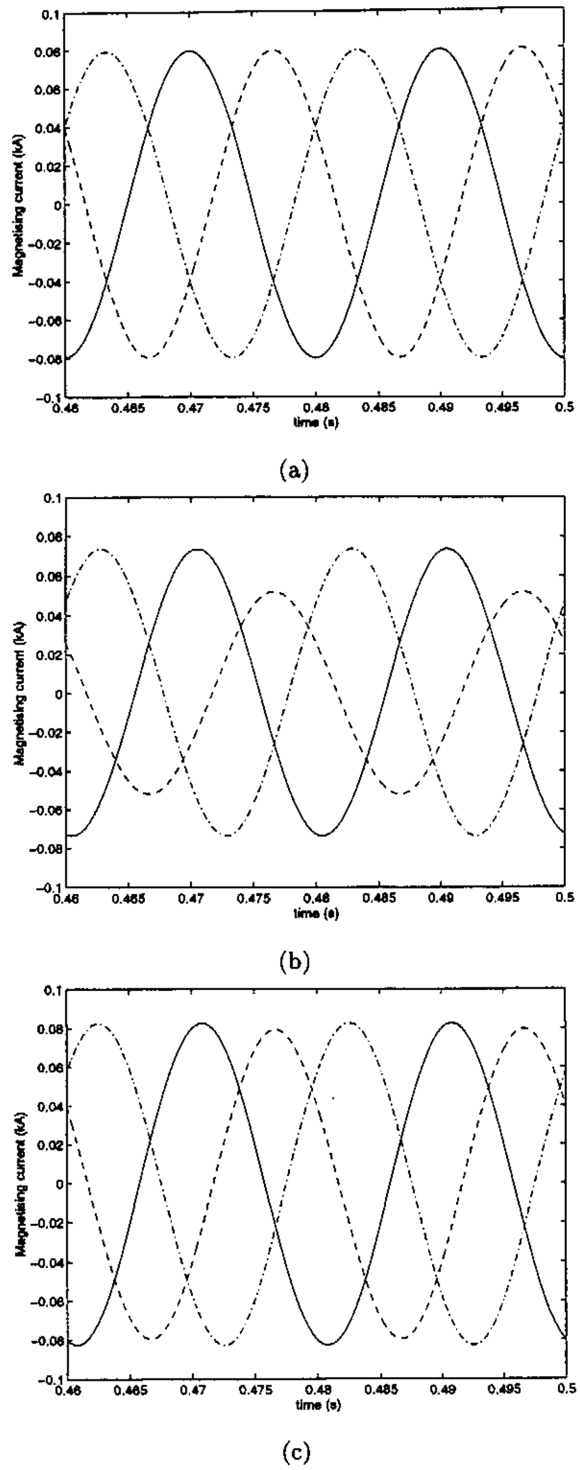
A. Open-circuit tests

Recently open-circuit measurements were taken from the 61MVA field transformer. The measured magnetising current on the centre phase was 1.76%. At 1.76% magnetising current the peak open-circuit winding current is calculated using

$$i_{mag}^{peak} = \frac{\sqrt{2}}{\sqrt{3}}\frac{S_b}{V_b}I_m^{pu} = 0.080(kA) \tag{37}$$

Open-circuit simulations were performed with the test system of Fig. 6. The transformer model was energised at rated voltage, and in this scenario the umec representation is linear. Fig. 7(a), (b) and (c) show the open-circuit magnetising currents for the three-phase bank, three-limb and five-limb models respectively. The single-phase bank red, yellow and blue magnetising currents all peak at 0.080kA. Asymmetry occurs in the three-limb magnetising currents, with the characteristic yellow-phase below the red and blue-phases. The red and blue-phase outer-limb magnetising currents peak at 0.074 (kA), while the centre-limb yellow-phase magnetising current peaks at 0.052 (kA).

Asymmetry also occurs in the five-limb magnetising currents. In this case the centre yellow-phase is slightly less than the balanced outer red and blue-phases. The red, yellow and blue-phase magnetising current peaks are 0.083, 0.080 and 0.083 (kA) respectfully. The five-limb centre-limb magnetising current can be greater or less than the outer-limb magnetising currents, depending on the value of r_{ayo}. The phase shift between the red-phase voltage and the magnetising current is 104°, and the phase-shift between the blue-phase voltage and magnetising current is 76°.



(a) (b) (c)

Figure 7: Open-circuit current; solid=red-phase, dash-dash=yellow-phase, dash-dot=blue-phase: (a) bank, (b) three-limb, (c) five-limb.

Table 2: Saturation characteristic points.

I_m (%)	V (p.u.)
1.76	1.0
6.0	1.1

Table 3: Short-circuit currents.

	R (kA)	Y (kA)	B (kA)
Three-phase bank	4.41	4.40	4.40
Three-limb	4.41	4.40	4.40
Five-limb	4.41	4.40	4.40

B. Over voltage test results

Over-voltage excitation simulations were performed with the test system of Fig. 6. In this scenario the transformer model was energised at 1.1 p.u. (12.1 kV), and the umec representation is non-linear. The two-slope piecewise saturation characteristic parameters are given in Table 2

The symmetrical three-phase bank magnetising currents are shown in Fig. 8(a). The magnetising currents are a combination of two sinusoidal waveforms, as can be predicted by the piecewise saturation curve. The three-phase bank experiences the deepest saturation.

The three-phase three-limb magnetising currents, shown in Fig. 8(b), are more complex. The magnitude of the yellow-phase magnetising current peaks are less than the red and blue-phases. Symmetry is exhibited by the yellow-phase magnetising current around it's largest peak, this is not the case for the red and blue-phases.

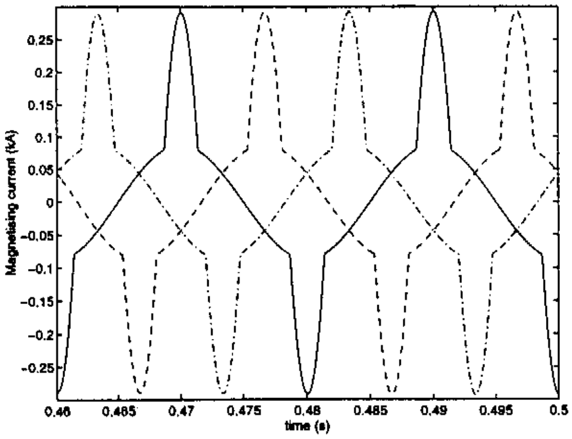
The comments made in the previous paragraph are applicable to the five-limb transformer representation. However, in this case the yellow-phase magnetising current peak is only slightly lower than the red and blue-phases.

C. Short-circuit test results

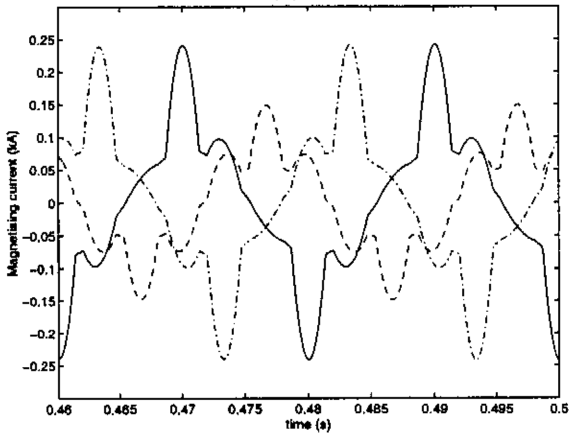
Short-circuit simulations were performed with the test system of Fig. 6. In this scenario the transformer model was energised at 10% rated voltage, the umec representation is linear, and a transformer load resistance introduced at 0.001Ω. At 0.1027 p.u. leakage reactance, the peak short-circuit winding current is calculated using

$$i_{sc}^{peak} = \frac{\sqrt{2} v_s S_b}{\sqrt{3} V_b^2 x_{pu}} = 4.41 \ (kA) \tag{38}$$

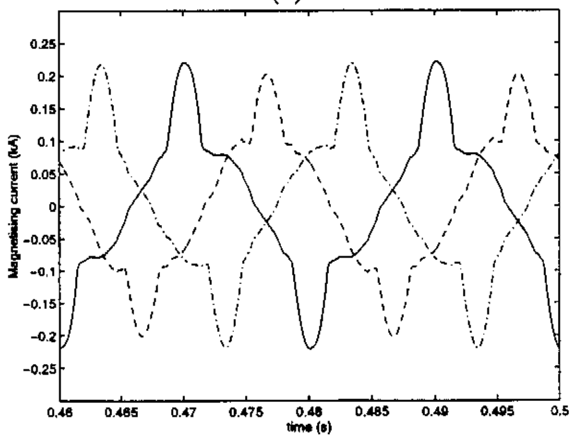
Table 3 summarises the peak values of the simulated short-circuit winding currents. All short-circuit currents were sinusoidal, balanced, lag the excitation voltage by 90°, and acceptably match the current predicted by 38.



(a)



(b)



(c)

Figure 8: Over-voltage current; solid=red-phase, dash-dash=yellow-phase, dash-dot=blue-phase: (a) bank, (b) three-limb, (c) five-limb.

IV. CONCLUSIONS

The nc concept has been described for three-phase three-limb and five-limb umec transformer models. The nc based models require only commonly available name-plate and core aspect ratio data inputs. The relative permeability of the nc steel branches is set so that rated magnetising current flows in the outer-limbs of the three-limb umec, and the centre-limb of the five-limb umec. Calculation of the five-limb core steel permeability is complicated by the fact that the red and blue-phase winding-limb fluxes are not in phase with the red and blue-phase magnetising currents. Transformer core non-linearity has been implemented with a piecewise saturation curve.

Simulation results have been presented to examine the new umec based transformer model under open-circuit, over-voltage and short-circuit conditions. While the winding current waveforms, for each core type, show significant differences under the first two scenarios, they are almost identical under short-circuit.

REFERENCES

[1] W Enright, O B Nayak, G D Irwin, and J Arrillaga. An electromagnetic transients model of multi-limb transformers using normalised core concept. *International conference on Power System Transients (IPST), Seattle, USA*, pages 93–98, June 1997.

[2] J Arrillaga, W Enright, N R Watson, and A R Wood. Improved simulation of hvdc converter transformers in electromagnetic transient programs. *IEE Proceedings-Generation, Transmission and Distribution*, 144(2):100–106, March 1997.

[3] W Enright, J Arrillaga, N R Watson, and J Zavahir. Modelling multi-limb transformers with an electromagnetic transient program. *Mathematics and Computers in Simulation*, 46:213–223, 1998.

[4] W Enright and J Arrillaga. A critique of steinmetz model as a power transformer representation. *Internation Journal of Electrical Engineering Education*, 35:370–375, 1998.

[5] C M Arturi. Transient Simulation and Analysis of a Three-Phase Five—Limb Step—Up Transformer Following Out—Of—Phase Synchronisation. *IEEE Transactions on Power Delivery*, 6(1):196–207, January 1991.

[6] D L Stuehm. Three-phase Transformer Core Modeling. Technical report, North Dakota State University, 1993.

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