# Analysis of AVR Transients induced by Transformer Inrush Currents


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*Abstract*: - **When large transformers are energised, the transformer will draw an inrush current from the supply. On isolated power systems, such as those found on oil and gas installations, large transformers may be directly connected to synchronous machines. In such systems, the resistance available to damp out the inrush current is very small and the inrush transient can be sustained for many seconds. It is the interaction between a large transformer and a synchronous machine automatic voltage regulator (AVR) which will be discussed in this paper. Site measurements as well as computer simulation will be used to describe this complex interaction.**



**Keywords**: Transformer inrush currents, offshore systems, time domain simulation, AVR, magnetic saturation.


## I. INTRODUCTION

This paper describes a series of measurements and computer simulations of inrush currents taken on an isolated offshore power system. The system studied is unusual as the transformer MVA rating approaches one third of the spinning generation capacity when only one generator is running.

After briefly discussing the generation of inrush currents, site measurements are presented. The phenomena of "sympathetic inrush" in power transformers has been reported previously and is known as a source of nuisance differential tripping of other on-line transformers.

A detailed time domain computer model is used to investigate the interaction between the transformer inrush and the generator AVR. It is shown that the AVR response modifies the inrush transient and can send other on-line transformers into magnetic saturation. It is the AVR response and not "sympathetic inrush" as reported in previous studies which is responsible for nuisance tripping of other online transformers on offshore systems.

## II. TRANSFORMER INRUSH CURRENTS

When a transformer is energised it is well known that it may draw an inrush from the supply [1,2]. The generation of the inrush current is easiest to explain using Fig. 1 [3]. Fig 1(a) shows that if a single phase transformer is energised at the peak of the supply voltage $V_m$, the transformer flux $\Phi$ starts to rise in the positive direction. The normal, steady state conditions are established as the core flux $\Phi$ lags the applied voltage V by 90 degrees. The magnetizing current drawn from the supply is in-phase with the flux $\Phi$ and the transformer cycles around the normal hysteresis loop Fig. 1(d,1). If the transformer is energised when the voltage is passing through zero Fig. 1(b), the voltage is positive during the whole of the first half-cycle. Throughout this period $\Phi$ must increase, the peak flux and hence the peak flux density reaching twice the normal steady state value. The magnetizing current required to reach this flux density is large as the transformer is now operating in the saturated region of the B-H curve; Fig 1(d,2). Remnant flux within the magnetic core of the transformer can make the situation worse. If the voltage is applied at a zero voltage instant and in such a direction that the rising field adds to the existing remnant flux $\Phi_r$, the sinusoidal variation of the flux has amplitude $2\Phi_m$, but is offset from zero and rises to a peak value of $2\Phi_m + \Phi_r$. In this case the increase in flux requires a massive magnetizing current as the transformer is now operating at very high saturation levels corresponding to the hysteresis loop of Fig 1(d,3). The magnetizing current drawn from the supply is now unidirectional with a large dc component and takes many cycles to decay to symmetry about the time axis as shown in Fig. 1(e).

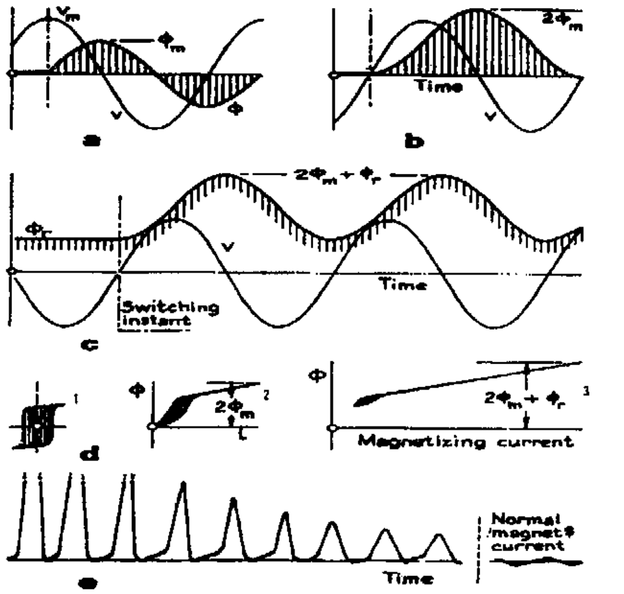



**Fig. 1. Derivation of transformer magnetizing current from B-H characteristics** [3].

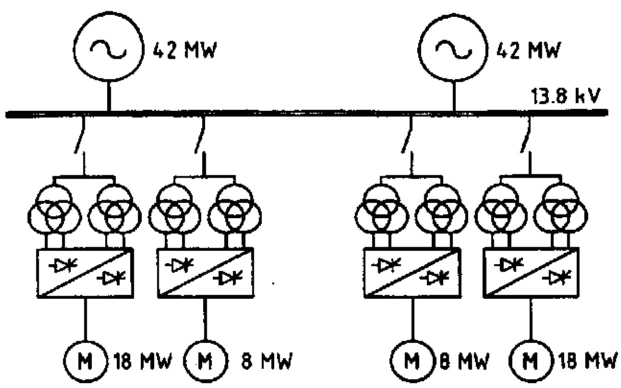



**Fig 2 Simplified representation of power system showing generators and transformers**

## III. SITE MEASUREMENTS

A simplified single line diagram of the isolated power system considered is shown in Fig 2. The system has two 47 MW (0.7 pf) generators, with the largest transformers supplying two 18 MW drives and two smaller 8 MW drives. These drives feature thyristor rectifiers supplying current to thyristor inverters which allow variable frequency operation of the synchronous motors. To limit the harmonics injected into the power system each drive has a 24 pulse thyristor rectifier achieved by using two input transformers (see Appendix for connections).

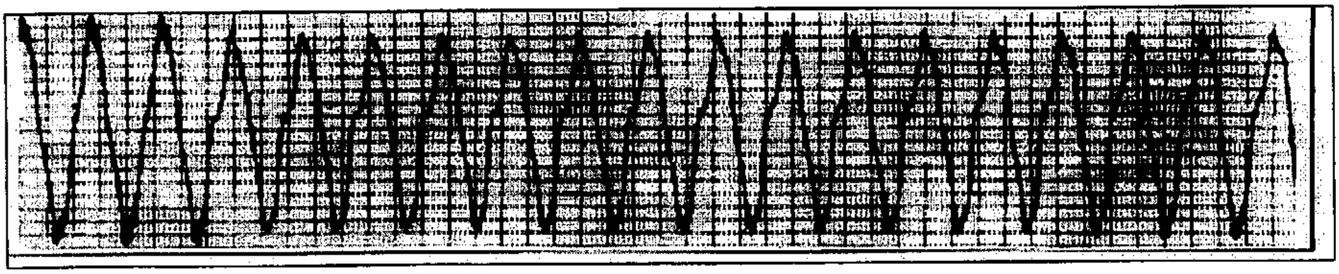
A typical inrush transient current measured when energising two of the 10.256 MVA transformers supplying one of the 18 MW drives is shown in Figure 3(a). These waveshapes were recorded using the secondaries of the protection CTs on the transformer circuit breaker. This recording does not show that classical unidirectional current normally associated with inrush shown in Fig 1(e). This is due to the ac coupling provided by the CTs which removes the dc component of current. It should be noted however that the ac peak to peak value is still in excess of 2000 A. This current is much higher than the normal full load current. In other tests currents in excess of 3200 A were measured, which operated the transformer differential protection after 7 cycles.

The voltage drop on the generator busbar is shown in Fig 3(b). There is clearly a voltage dip in the system which is sustained for a long period of time. The time constant associated with the decay of the transient inrush current is long, typically it takes 2 to 3 sec for this waveshape to become symmetrical about the time axis: this implies that in an offshore power system very little damping is present and other loads may be affected by the initial voltage dip and/or the response of the generator automatic voltage regulator (AVR).

The operators experience with the power system of Fig 2 was that when energising one of the 18 MW drives, there was a strong possibility of tripping another on-line transformer such as that for the 8 MW drives. This was often a trip initiated by the transformers differential protection, suggesting a large current imbalance between the primary and secondary of the transformer. Inspection of the transformer revealed this to be a nuisance tripping of the unit.

The phenomena of "sympathetic inrush" in power transformers has been reported previously [4] and is known as a source of nuisance differential tripping of other on-line transformers [5]. The "sympathetic inrush" is due to the dc component of the inrush current developing a dc voltage drop across the supply resistance which in turn forces the on-line transformer into magnetic saturation. This is not applicable here as the system resistance is very small as shown by the long time it takes the inrush current to decay to zero. This suggests that another mechanism is responsible for the differential tripping.

(a) Three phase inrush currents when energising transformers for 18 MW drive (12.8ms/div, 125 A/div)



(b) Generator line to line voltage during inrush transient (12.8ms/div. 2150 V/div)

**Fig. 3 Site measured inrush currents and system voltage dip**

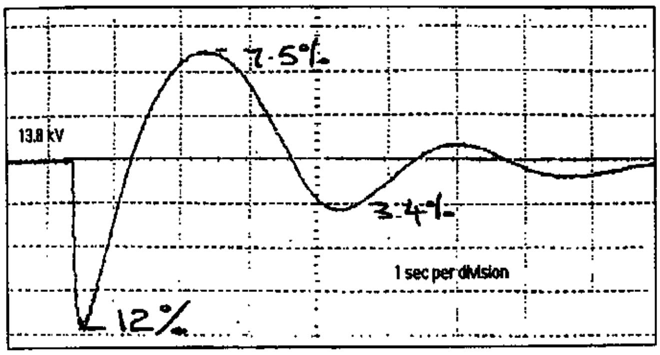



**Fig. 4 Site measured system RMS voltage**

A different set of measurements taken to assess the transient response of the generator AVR showed that a voltage dip as large as 12% could occur when the largest transformers were energised. The response of the AVR is lightly damped resulting in a 7.5% overshoot in system voltage which takes about 10 s to return to normal steady state conditions as shown in Fig. 4. This lightly damped system voltage response will modify the transient inrush current as well as affecting other on-line transformers which see sudden voltage dip followed by a system overvoltage.

## IV. COMPUTER MODELLING OF TRANSFORMERS, SYNCHRONOUS MACHINES AND AVRS

In an attempt to understand the impact of the AVR response a computer model was developed using the time domain capabilities of the SABER program [6]. The electric and magnetic circuits of the transformers were modelled within a single, coupled circuit simulation [7]. A given current flowing in one of the transformer windings produces a known mmf, a magnetic equivalent circuit of the transformer can be developed in which the main iron paths are represented as variable reluctances and the leakage air paths are constant reluctances. For example, Figure 5(a) shows the structure of the magnetic circuit for a three-phase, three-limb transformer showing the main iron and air leakage paths. The corresponding magnetic circuit is shown in Figure 5(b) [7]. The reluctance of the iron path is dependant on the B-H characteristic of the core material. For the analysis of inrush currents a two-slope representation of the B-H curve is sufficient. The air path leakage reluctances can be estimated from the geometry of the transformer [8].

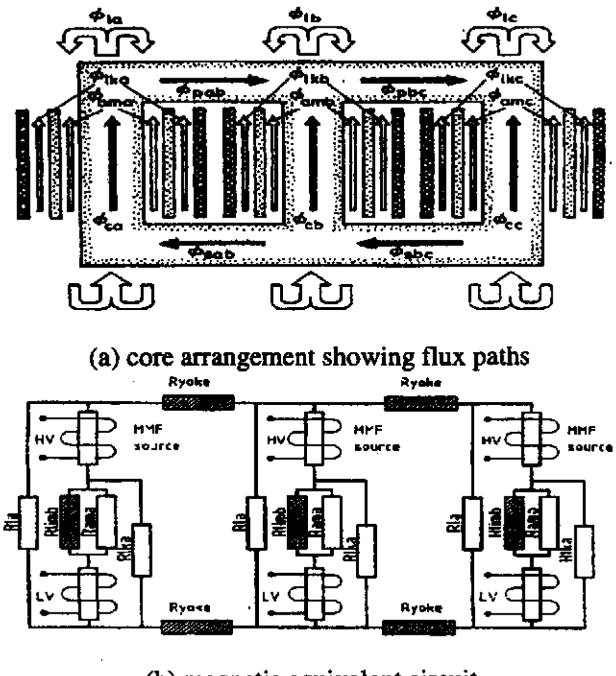
The voltage equation for the transformer windings are represented in matrix format as:

$$[v] = [r]\cdot[i] + [N]\cdot\left[{}^{d\phi}\!/_{dt}\right]$$

where [v] and [i] are the winding voltage and current vectors, [$\phi$] is the winding flux vector, and [r] and [N] denote the winding resistance and number of turns. The flux $\phi$ is excited by the magnetomotive force [F] which is produced by the winding currents:

$$[F] = [N]\cdot[i]$$

The core flux and its mmf requirement are linked through the B-H curve of the core material.




(a) core arrangement showing flux paths

(b) magnetic equivalent circuit

**Fig. 5 Three-phase, three-limb transformer** [7]

The equivalent circuit of the transformers used in this study are more complex than the three-phase three-limb arragement shown in Fig. 5. The coupled electric and magnetic circuits for one of the transformers analysed is shown in the Appendix.

The standard seven-winding model is used to simulate the synchronous generator [9] whilst in this simulation an AVR with PID control is utilised. Complete details of the computer models of the transformer, synchronous machines and AVRs can be found in another paper [10].

## V. COMPUTER SIMULATION RESULTS

As a first attempt to assess the impact of the time variation in the system line to line voltage during an inrush transient, the line to line voltage amplitude was modulated to follow the trace in Fig 4. The predicted current drawn by one phase of a three-phase unloaded transformer is shown in Fig. 6.

The envelope of the line current shows a significant increase in the transformer magnetizing current. The current waveshape shows that the steady state magnetizing current of 7.1 A peak increases to about 300 A peak, i.e. a 42 p.u. increase. There is a strong possibility of saturation due to this over-voltage tripping the transformers differential protection as this increase in magnetizing current produces a 24% imbalance between the transformer primary and secondary currents.

Another source of saturation in this on-line transformer is the sudden change in the line to line voltage amplitude. Since the transformer flux is the time integral of voltage (Faraday's Law) any sudden change in the voltage amplitude during a single supply cycle will mean that the integral of voltage over that cycle is no-longer zero, i.e. a d.c flux component has been introduced. This explains why in Fig. 6 there is an increase in the magnetizing

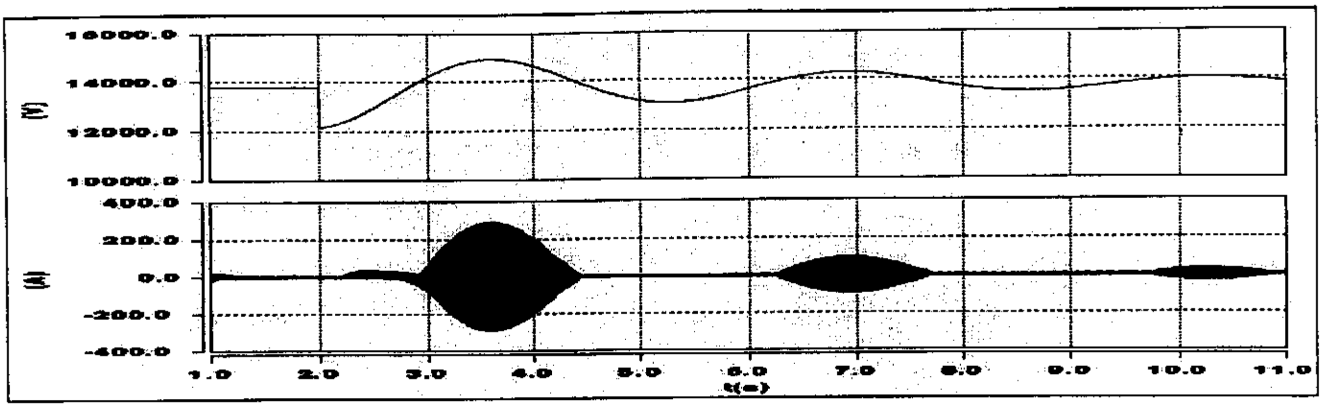



**Fig. 6 Line current with voltage modulation**

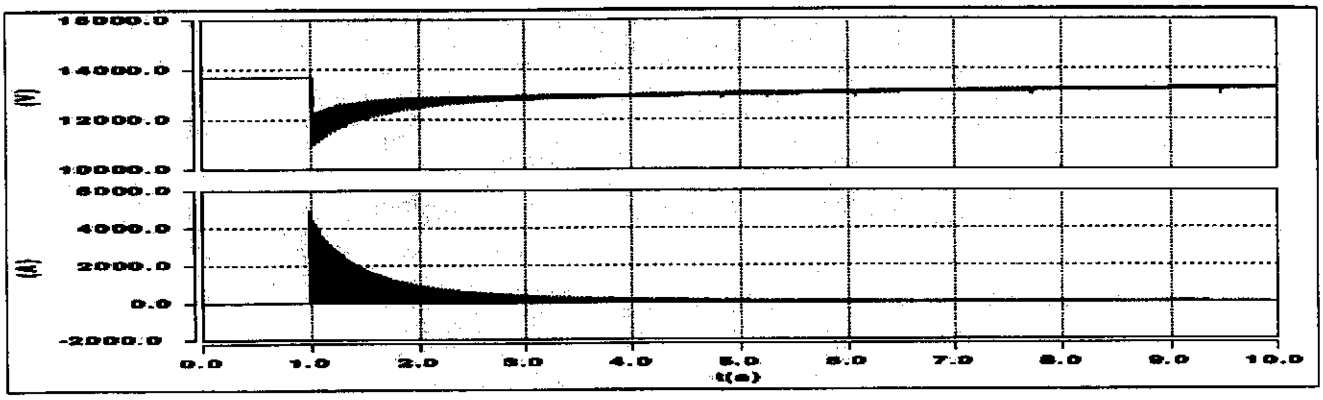



**Fig. 7 Inrush current using synchronous machine and transformer models with no AVR**

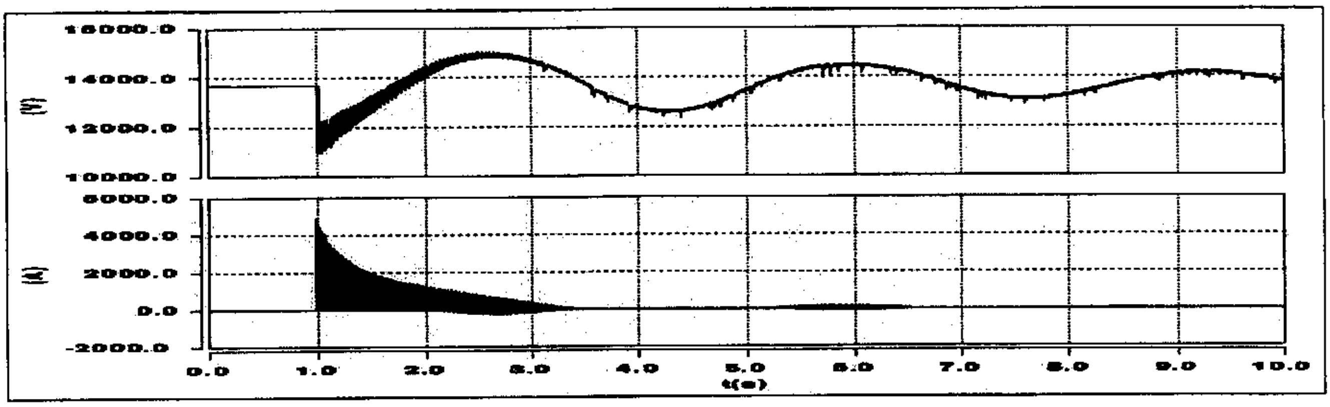



**Fig. 8 Inrush current using full model with AVR, synchronous machine and transformer**

current as soon as the voltage dip occurs and before the 7.5 % increase in voltage.

The modulation of the supply line voltages to an on-line transformer clearly changes the transformer's magnetizing current. The modulation of the terminal voltage of the transformer being energised will also affect the inrush transient itself.

Fig. 7 shows the simulated inrush current when a pair of the 18 MW drive transformers are energised without the corrective action of an AVR. The supply is represented using a full model of the generator. The model has a three-phase representation of the armature windings and a two-axis model of the rotor with damper windings on both the d- and q-axis of the machine. This avoids the problem of choosing an appropriate transient reactance. Figure 8 shows the simulated inrush current for the same transformer at the same switching angle, this time with terminal voltage feedback and an AVR to adjust the generator excitation level.

A comparison of Fig 7 and Fig 8 clearly shows that the inrush current is modified by the action of the automatic voltage regulator. In Fig. 7 the inrush current appears to decay at two different rates; at first the decay is relatively fast and this is then reduced as the saturation levels within the transformer drop. At the beginning of the transient, at high saturation levels the magnetizing inductance of the transformer is effectively the air-cored inductance of the winding. As the saturation level decreases, the inductance increases giving a longer L/R time constant, hence the slower rate of decay.

Fig. 8 shows the simulated inrush current with the corrective action of the AVR. It should be noted that in this case the initial surge of current has the same amplitude as before, however the rate at which the inrush decays is increased. The most obvious difference is the presence of an overvoltage induced saturation at around t=6 s corresponding to the 2nd peak of the system rms voltage. A similar effect occurs between t=2 and t=3 s when a negative component of magnetizing current becomes apparent. This bi-directional overvoltage saturation due to the first overshoot in the system voltage is partially masked by the more dominant inrush current.

The following conclusions can be drawn from the results of the computer simulations shown in Figures 6, 7 and 8. When the transformers supplying the large 18 MW drives in Fig 2 are energised, there is clearly a voltage dip on the generator busbar, this voltage dip forces other on-line transformers into magnetic saturation. The response of the generator AVR results in a period of system overvoltage which can also push the transformers further into saturation. This system overvoltage also modifies the inrush current drawn by the incoming transformer. It is the sudden increase in magnetizing current which accounts for the differential tripping of on-line transformers when energising the larger 18 MW drive transformers. This is due to the combined effects of the sudden voltage dip and also the overvoltage caused by the lightly damped AVR. Sympathetic interaction is not the major cause of the differential tripping as the dc resistance of the Thévenin equivalent circuit of an offshore power system is very small.

## VI. CONCLUSIONS

This paper has presented a series of measurements taken on an isolated offshore power system. It is shown that inrush currents on such systems can be sustained for many cycles as little series damping is available to damp out the inrush currents. Energising large transformers may cause the differential tripping of other on-line transformers. This is due to the saturation of the on-line transformer caused by the sudden system voltage dip and also the overvoltage induced by the generator AVR response. In isolated offshore power systems "sympathetic interaction" is not the dominant mechanism for saturation of on-line transformers as the dc resistance of the power system is very small.

This paper clearly demonstrates the advantages of analysing the interactions between different system components using a time-domain computer analysis. When performed at the design stage, such calculations provide a valuable tool for predicting the transient performance of the power system, as well are providing guidance for electrical power system protection engineers, attempting to choose appropriate relay settings.

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## VIII. ACKNOWLEDGEMENTS


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## IX. APPENDIX

### TRANSFORMER AND GENERATOR DATA

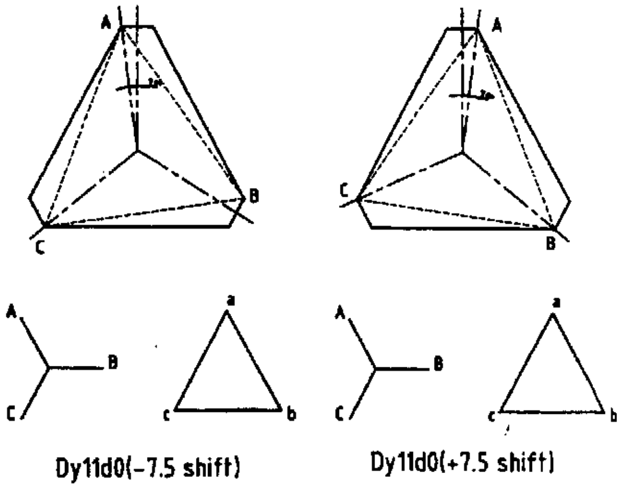



**Fig A.1 24-pulse connection for pair of transformers**

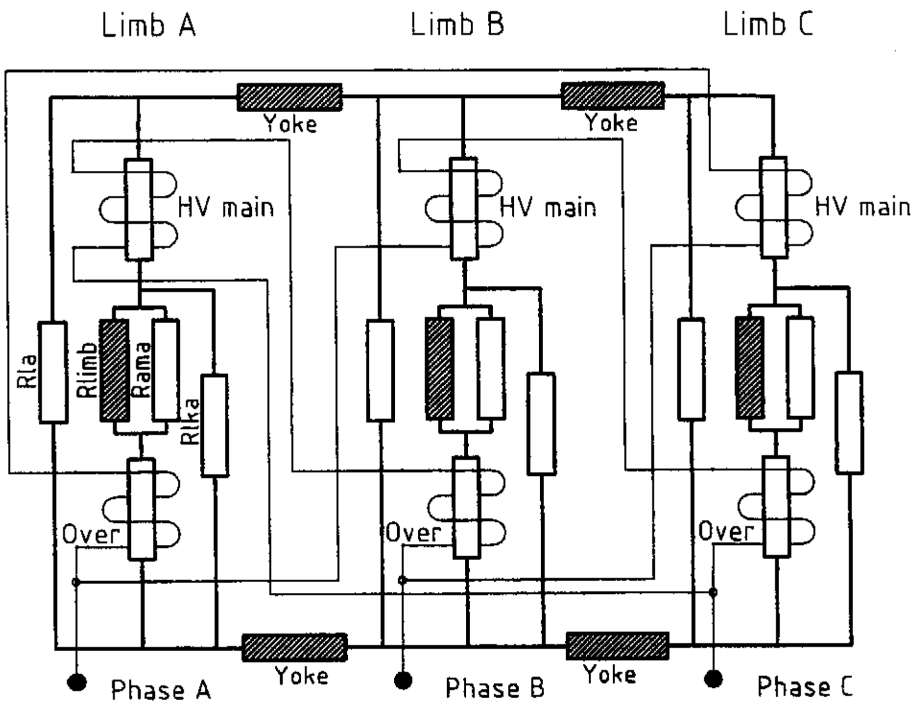
**Transformer Parameters**

| Parameter | Units for 18 MW drives | Units for 8 MW drives |
|---|---|---|
| Net core area | 1220.6 $cm^2$ | 1016.8$cm^2$ |
| Flux density | 1.67 T | 1.60 T |
| Limb length | 120 cm | 109 cm |
| Yoke length | 75 cm | 68 cm |
| HV turns (main) | 232 | 326 |
| HV turns (over) | 38 | - |
| LV turns (delta) | 45 | 27 |
| LV turns (star) | 26 | 16 |
| HV res (main) | 0.112 Ω | 0.139 Ω |
| HV res (over) | 0.017 Ω | - |
| HV main height | 769 mm | 692 mm |
| HV over height | 769 mm | 690 mm |
| HV main in. dia. | 63.9 cm | 57 cm |
| HV main out. dia. | 72.7 cm | 65.5cm |
| HV over in.dia. | 59.6 cm | 54 cm |
| HV over out. dia. | 60.8 cm | 55.2 cm |
| B-H slope (unsaturated) | 5.1 mT/(A-turn/m) | |
| B-H slope (saturated) | 3.1 µT/(A-turn/m) | |

**Generator Parameters**

(All pu values on 60.10 MVA, 13.8 kV)

| | |
|---|---|
| Resistance: Armature | 0.0034 pu |
| Resistance: Neg Sequence | 0.047 pu |
| Resistance: Zero Sequence | 0.013 pu |
| Reactance: Armature | 0.17 pu |
| Reactance: Neg Sequence | 0.26 pu |
| Reactance: Zero Sequence | 0.17 pu |
| Reactance: Potier | 0.36 pu |
| d-axis unsat synch. reactance | 2.98 pu |
| d-axis unsat transient reactance | 0.43 pu |
| d-axis unsat sub-transient reactance | 0.33 pu |
| d-axis sat transient reactance | 0.37 pu |
| d-axis sat sub-transient reactance | 0.26 pu |
| q-axis unsat synch. reactance | 2.73 pu |
| q-axis unsat transient reactance | 0.61 pu |
| q-axis unsat sub-transient reactance | 0.39 pu |
| Armature time const (short circuit) | 0.24 s |
| d-axis transient (open circuit) | 10.8 s |
| d-axis sub-transient (open circuit) | 0.05 s |
| q-axis transient (open circuit) | 3.3 s |
| q-axis sub-transient (open circuit) | 0.05 s |




(Note: Secondary windings not shown in this diagram)

**Figure A.2** **Combined electric and magnetic circuit of Dy11d0 (-7.5 degrees) transformer**

Rla: reluctance corresponding to interphase leakage path

Rama reluctance corresponding to leakage path in parallel with limbs

Rlka reluctance corresponding to leakage path between main and over HV windings