Measurements on and Modelling of Capacitor-Connecting Transients on a Low-voltage Grid Equipped with Two Wind Turbines

Åke Larsson M.Sc, Torbjörn Thiringer M.Sc
Chalmers University of Technology
Göteborg, Sweden

Abstract - Capacitor connecting transients on a low-voltage grid equipped with two wind turbines are measured and calculated. As the phase-compensating capacitors of the wind turbines are connected, a large current peak, sometimes reaching twice the rated current, occurs. The damping of the transients is strongly influenced by skin and proximity effects.

INTRODUCTION

The majority of the wind energy converters installed today are equipped with an induction generator connected directly to the grid. Phase-compensating capacitors are connected at the wind turbines in order to compensate for the reactive power consumed by the generator. As the capacitors are connected, a transient occurs, which can cause problems to sensitive equipments connected to the same grid. For example, when two wind turbines were installed on the island of Hjärtholmen, close to Göteborg, an old relay indicated grid failure and started an emergency generator at a consumer nearby. An examination of the problem revealed that the reason was the connecting of the phase compensating capacitors.

It is possible to avoid or reduce the connecting transients. One possibility is to first magnetize the generator by capacitors and then synchronize it to the grid [1]. Another possibility is to use power electronic switches to connect the capacitors [2]. However, most wind turbine manufacturers of today use capacitors connected directly to the grid.

The resistance and inductance of cables and transformers vary as a function of the frequency due to the skin and proximity effects. Since the frequency of the connecting transients is usually several times higher than the fundamental grid frequency, the resistance values are substantially increased while the inductance values are somewhat reduced. The skin and proximity effects depend on several parameters, e.g. material and diameter of the conductor, distance between the conductor axes, number of wires and twists of the bundled wires in each conductor [3]. All these parameters make a detailed calculation of the frequency-dependent parameters difficult. The calculation can be made more accurately by using numerical methods, for example the finite element method in three dimensions and in time domain. The computation would, nevertheless, require both a powerful computer and plenty of time.

Knowing the conductor diameter, conductor material and spacing of the conducts it is possible to model the skin and proximity effects by analytical expressions [4–6]. Here, the IEC standard [6] is used.

The purpose of this paper is to study the influence of the skin and proximity effects on the connecting transients when the phase-compensating capacitors of wind turbines are connected to the grid. Another important goal is to compare the calculations with field measurements.

THE WIND TURBINE SITE

A. The site

In Fig. 1 the electrical configuration of the Hjärtholmen wind turbine site is presented together with the points of measuring. The two 225 kW pitch-regulated wind turbines are connected to a 500 kVA transformer by two 4*240 mm^2 aluminium cables each. The ratio between the short-circuit power of the low-voltage grid and the rating of the wind turbines is 20, which is the recommended value for example in Denmark. Phase-compensating capacitors are connected to the wind turbines in two stages, C_1 and C_2.

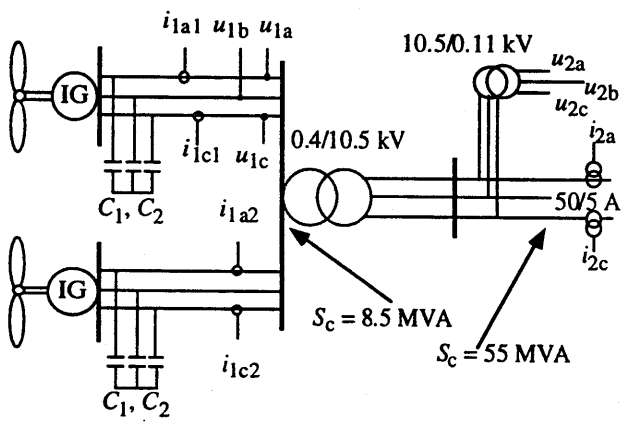

Fig. 1. The wind turbine site and the location of the points of measuring. (IG = induction generator and S_c = short-circuit power)

B. Measuring system

In order to obtain an isolating interface between the grid and the measuring system as well as a high bandwidth, the currents and voltages were measured using LEM-modules [7]. The instantaneous values of the voltages and currents were measured by a data acquisition system having a sampling rate of 7 kHz.

The three phase voltages and two phase currents from each wind turbine were measured on the low-voltage side of the transformer. There is only need to measure the currents in two of the phases since the neutral line is not connected. As a reference, the voltage and the current on the high-voltage side were measured by using voltage and current transformers. According to the manufacturer, the voltage transformers used on the high-voltage side can measure voltages up to a frequency of 1 000 Hz.

CONNECTING OF THE FIRST TURBINE

The wind turbines are connected to the grid when the wind speed exceeds 3 - 4 m/s. During the connecting sequence, the speed of the turbine is raised until the generator speed is close to the synchronous one. The generator is then connected to the grid. In order to avoid a large inrush current, a soft starter is used for limiting the current during the starting sequence.

A. Measurements

The measured connecting current of one wind turbine is presented in Fig. 2 as the other wind turbine is not operating. The induction generator is connected shortly after the measurement is started at the time $t = 0$, and the soft starter operates until $t = 2$ s and is then short-circuited. During this time, the current is kept well below the rated current of one turbine (peak value of 566 A). The first stage of capacitors C_2 is connected at $t = 3.3$ s and the second stage C_1 is connected at $t = 4.2$ s. The connection of the capacitors does not pass without problems.

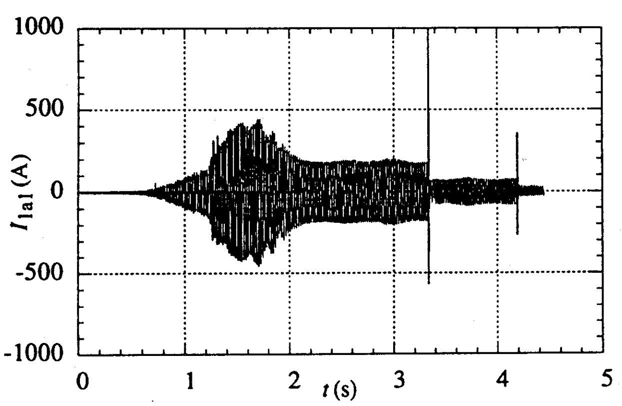

Fig. 2. Measured connecting current.

As can be seen in Fig. 2, there is a large current peak of 1000 A when the first stage of capacitors is connected, presented in detail in Fig. 3. Also the voltage of the 400 V grid is strongly affected by the connecting of the capacitors. As Fig. 4 shows, an oscillating component with a peak amplitude of 160 V is added to the phase voltages, which can cause problems to sensitive equipments connected to the 400 V grid. The voltage on the high-voltage side of the transformer is hardly affected at all by the connecting of the capacitors, as Fig. 5 shows. Also the connecting of the second capacitor stage gives rise to a current peak, presented in detail in Fig. 6.

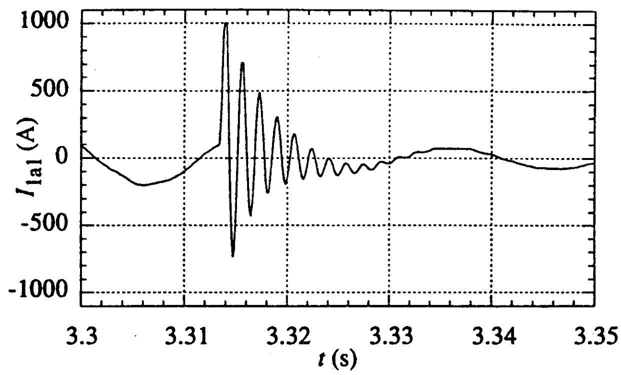

Fig. 3. Measured oscillating current caused by connecting the first stage of capacitors.

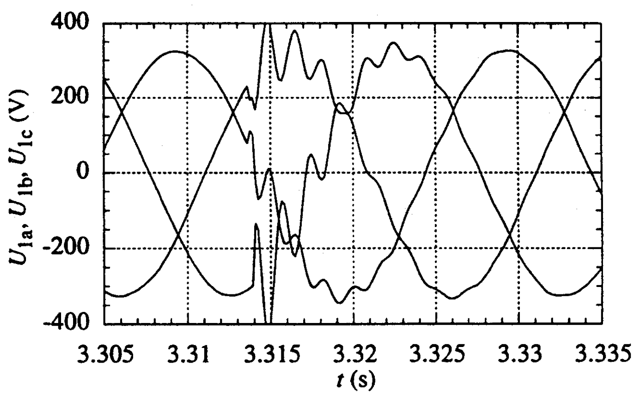

Fig. 4. Measured phase voltages on the low-voltage side when the first stage of capacitors is connected.

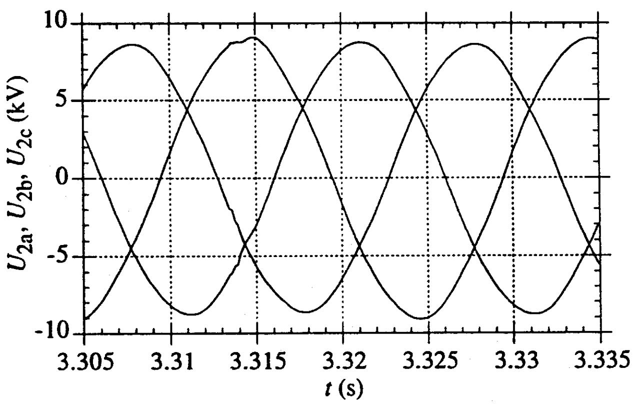

Fig. 5. Measured phase-voltages on the high-voltage side when the first capacitor stage is connected.

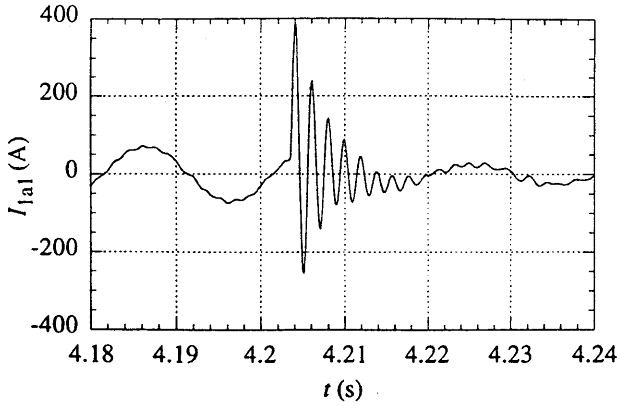

Fig. 6. Measured oscillating current caused by connecting the second stage of capacitors.

B. Calculations

A simplified configuration of the wind turbines is presented in Fig. 7 and the values of the components are given in Table 1. The frequency of the transients can approximately be determined by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{1}$$

if the influence of the induction machine is neglected. When the second wind turbine is not operating and the first stage of capacitors C_2 is to be connected $L = L_{cab} + L_{tr}$ and $C = C_2$ which gives a value of 570 Hz. The measured frequency of the connecting transient occurring when the first stage of capacitors is connected is 590 Hz

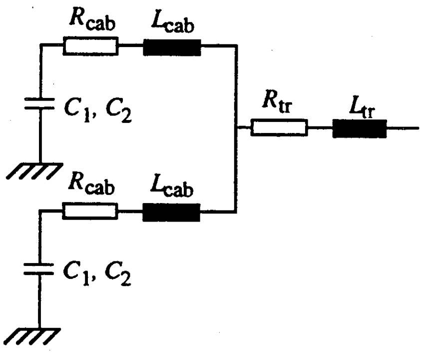

Fig. 7. A simple model of the wind turbine site.

Table 1. Values and description of components.

Description	Symbol	Value
Capacitor	C_1	0.5 mF
Capacitor	C_2	1.2 mF
Cable resistance	R_{cab}	9.4 mΩ
Cable inductance	L_{cab}	17 μH
Transformer resistance	R_{tr}	2.7 mΩ
Transformer inductance	L_{tr}	47 μH

When the second stage of capacitors is connected, $L = L_{cab} + L_{tr}$ and $C = C_1 + C_2$, which gives a frequency of 480 Hz. The measured frequency is in this case 510 Hz.

When the wind turbines had been installed, connecting the capacitors sometimes triggered a relay indicating grid failure, which started an emergency generator at a consumer nearby. The relay was later on replaced and the turbines could operate without interrupting other equipment.

In order to improve the calculations of the connecting current and voltage, a more detailed model than the one presented in Fig. 6 must be used. In this paper the transient course of event has been calculated by means of the Electro Magnetic Transient Program, EMTP. A single-phase diagram of the EMTP-model used is presented in Fig. 8.

The calculated transient determined using the 50-Hz values of the resistances and inductances is presented in Fig. 9. The calculated frequency of 600 Hz agrees well with the measured one while the calculated transient is less damped than the measured one. The main reason for this is that the resistances of the cable and transformer are frequency-dependent. This is due to two phenomena known as skin effect and proximity effect.

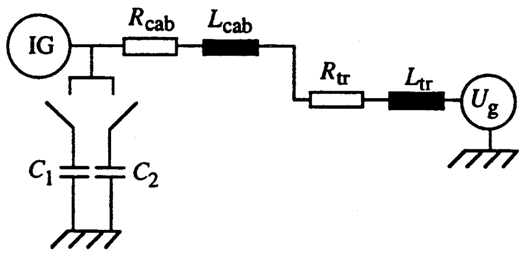

Fig. 8. Single-phase representation of one generator with the grid. (Ug is the grid voltage)

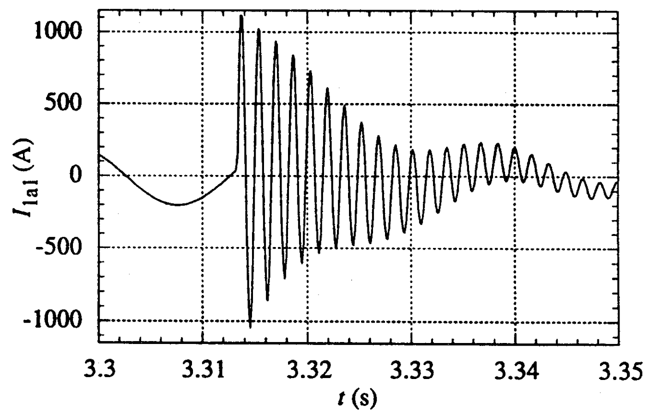

Fig. 9. Calculated current without skin and proximity effects taken into account.

The main influence of the skin and proximity effects is that the resistance increases for currents having a higher frequency. Another feature of these two phenomena is that the inductance is somewhat lowered as the frequency is increased. The skin effect increases the resistance of a conductor due to a current in the conductor while the proximity effect increases the resistance in a conductor due to a current in an adjacent conductor. [4–6] presents three different analytical methods to determine the increase of the resistance due to these effects. In Fig. 10 the resistance values predicted by the three methods are compared. As can be noted from Fig. 10, the methods predict similar resistance values. The values used are the ones predicted by the IEC standard which is represented by the solid curve.

Compared to the cable, the transformer is a much more complicated component. As a first step the transformer resistance is regarded to be constant. Moreover, the inductance of the transformer and cable is also considered to be constant.

The currents calculated taking the skin and proximity effects of the cable into account are presented in Figs. 11 and 12 . Fig. 11 presents the measured transient occurring as the first stage of capacitors is connected. Fig. 12 presents the measured connecting current when the second capacitor stage is connected. The results have been substantially improved compared to those reached when only using the 50 Hz value of the cable resistance. However, the damping of the oscillating current is still somewhat too low, as can be seen if the calculated transients presented in Figs. 11 and 12 are compared with the measured ones presented in Figs. 3 and 6. Still, the resistance increase in the transformer has not been taken into account. In [8] the resistance of a 263 MVA transformer was measured at different frequencies. The measurements indicated the effective resistance at 600 Hz to be 10 times the DC resistance. In [9] a similar resistance increase was calculated for 20, 100 and 500 MVA transformers. The inductance was considered to be constant.

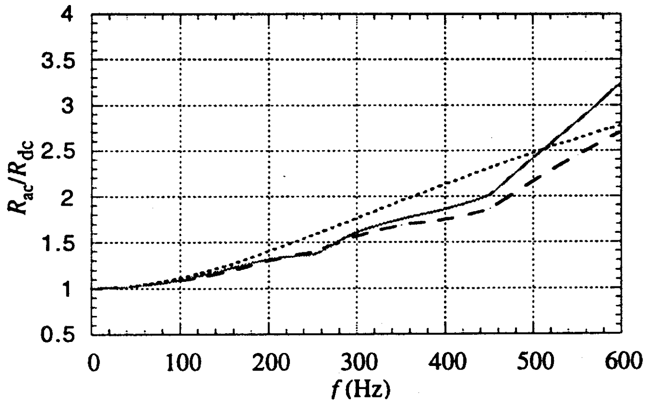

Fig 10. Calculated cable resistances. Solid curve according to IEC 287 [6], dashed curve according to [4] and dotted curve according to [5].

Fig. 13 presents the connecting current as the first stage of capacitors is connected using the assumption that the resistance is 10 times greater at 600 Hz compared to the DC-resistance value. As can be observed from Fig. 13, the calculated current now agrees very well with the measured one.

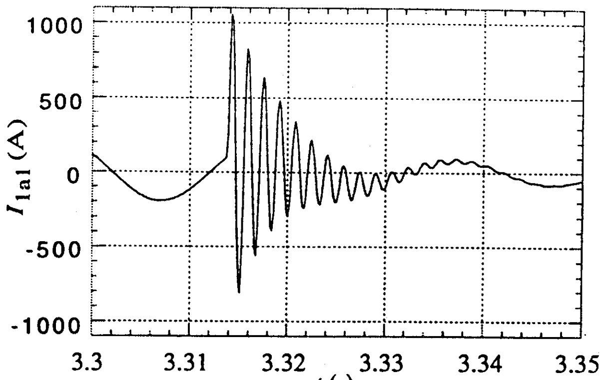

Fig. 11. Calculated current when connecting the first capacitor stage, taking the skin and proximity effects into account.

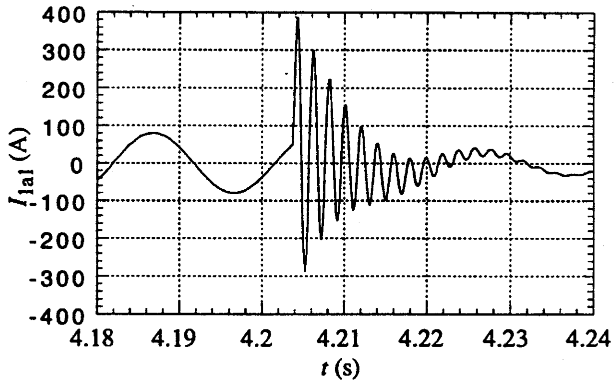

Fig. 12. Calculated current when connecting the second capacitor stage, taking the skin and proximity effects into account.

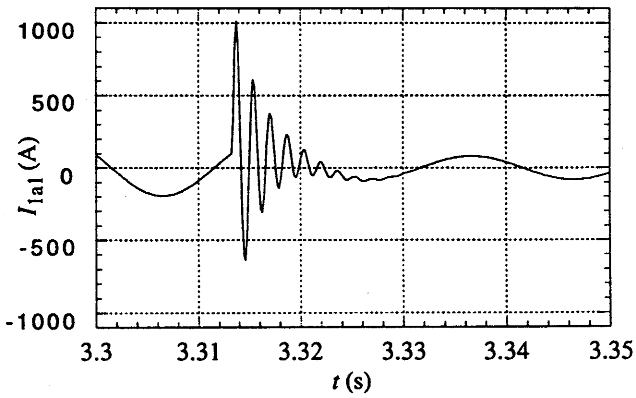

Fig. 13. Calculated current with skin and proximity effects both in cable and transformer taken into account.

CONNECTING OF THE SECOND TURBINE

The connecting of the first stage of capacitors of the second wind turbine causes two transients at different frequencies. One at a higher frequency which takes place between the two turbines and one at a lower frequency taking place between the two turbines and the grid. The frequency of the oscillations can be determined by using (1). In the first case $L = 2L_{cab}$ and $C = C_2//(C_1 + C_2)$ giving a frequency value of 1000 Hz. In the second case $L = L_{cab}/2 + L_{tr}$ and $C = C_1 + 2C_2$ giving an oscillating frequency of 400 Hz. The two oscillating modes are illustrated in Fig. 14.

In Fig. 15 the measured current from the first wind turbine is presented as the second one connects the first stage of capacitors. Although the sampling rate of the data acquisition system is not high enough to catch the rapid transient accurately, the two oscillation modes are clearly visible.

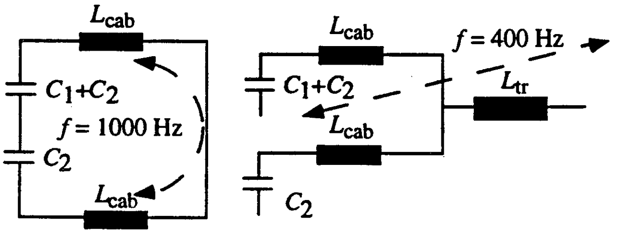

Fig. 14. Oscillating modes as the second wind turbine connects the first stage of capacitors.

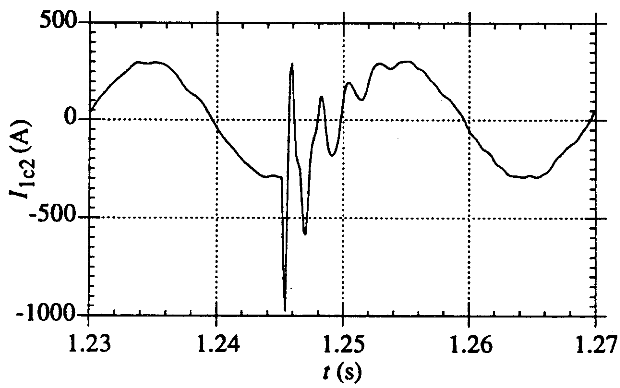

Fig. 15. Measured current from the first wind turbine is presented as the second one connects the first stage of capacitors.

CONCLUSION

As the phase-compensating capacitors are connected, a large current peak occurs. This transient sometimes reaches a value of twice the rated wind turbine current. Also the voltage on the low-voltage grid is substantially affected, which can disturb sensitive equipments connected to the same part of the grid as the wind turbines. The connecting of the second capacitor stage influences the grid less.

If the skin and proximity effects of the cable and transformer are not taken into account, the damping is much underestimated. When the increase of the cable resistance due to skin and proximity effects is taken into account, the calculated transients agree better with the measured ones. The calculations can be further improved by also taking the increase of the transformer resistance due to skin and proximity effects into account.

ACKNOWLEDGEMENT

The financial support given by the Swedish National Board for Industrial and Technical Development and the Göteborg Energy Ltd Foundation for Research and Development is gratefully acknowledged.

REFERENCES

[1] O. Carlson, J. Hylander, "Some Methods to Connect a Wind Power Induction Generator to the Utility Network", International Colloquium on Wind Energy, Brighton, UK, August 1981, pp. 179–184.

[2] G. Oliver, I. Mougharbel, G. Debson-Mack, "Minimal Transient Switching of Capacitors", *IEEE Trans. on Power Delivery*, Vol. 8, No. 4, Oct. 1993, pp. 1988–1994.

[3] A. Sakurai, T. Tsuchiya, Y. Kagawa, "Boundary Element Estimation of Current Density Distribution and Eddy Current Loss in Bundled Multi-Wire Cables", *International Journal of Numerical Modelling*, Vol. 6, 1993, pp. 169–181.

[4] D. E. Rice, "Adjustable Speed Drive and Power Rectifier Harmonics–Their Effect on Power Systems Components", *IEEE Trans. Industry Appl.*, Vol. IA-22, No. 1, Jan/Feb. 1986, pp. 161–177.

[5] A. Hiranandani, "Analysis of cable ampacities in cable systems containing harmonics", Wire Journal International, Sept. 1993, pp. 54–62.

[6] International Electrotechnical Commission, IEC Standard, Publication 287, Calculation of the Continuous Current Rating of Cables, Second edition, 1982.

[7] "The LEM Module: A Perfect Isolating Interface between Power Circuits and Electronic Control", LEM ELMES AG, Switzerland.

[8] S. Benapudi, C. J. Forrest, G. W. Glenn, "Effects of Harmonics on Converter Transformer Load Losses", *IEEE Trans. on Power Delivery*, Vol. 3, No. 3, July 1988, pp. 1059–1066.

[9] CIGRE-Working Group 13.05, "The Calculation of Switching Surges. II. Network Representation for Energization and Re-Energization Studies on Lines Fed by an Inductive Source", Electra 1974, No. 32, pp. 17–42.