# Inrush Currents: One Less Thing to Worry About

## An innovative solution

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***Abstract* — Power transformers are essential parts of the electrical infrastructure, but they are subject to an important drawback: inrush current (IC). The phenomenon occurs at the instant of the energisation, when it can draw a high current that usually reaches 5 to 10 times the transformer's rated current and lasts for up to a few seconds. This current leads to undesirable voltage dips and other power quality issues. As wind energy converters increase in rating year after year, they need more powerful unit transformers, which means that the challenge of high ICs appears more frequently.**

**"Smart Energise" is an innovative solution that has been developed in order to minimize the transformer's IC, in a simple and cost-effective way. The present paper aims to raise the awareness regarding the increasing frequency of the issue and explains how these can be mitigated. It begins by reviewing existing grid codes that have relevant connection conditions. Afterwards, it summarizes the theory of how a transformer provokes IC and presents briefly the existing solutions to mitigate it. Finally, it explains the "Smart Energise" concept and shows results from field tests.**

***Keywords - inrush current, transformers, power quality, voltage dip***

## I. INTRODUCTION

The challenge of inrush currents (ICs) is well known, probably since the first transformers have been connected in AC power systems. In the case of substations at HV or EHV level this phenomenon is known and managed through specific mitigation measures, such as point-on-wave switching. For the grid connection of individual Wind Energy Converters (WECs) this was not a relevant problem in the early years of wind energy. Nowadays, WECs increase in rating, whilst the points at which they connect to the grid become more remote and thus weaker. These factors combined can lead to an increasing importance of IC considerations. State-of-the-art WECs can easily reach more than 3MW in rated power and also have a built-in capability to exchange reactive power with the grid. As a result, the rating of the unit transformer of WECs can easily exceed 4MVA. When such a unit is connected at a distribution feeder, it may cause a voltage dip, which might not always be acceptable for nearby users. Fig. 1 shows a measurement of a voltage at WEC level. The voltage dip is of about 4% in phase U. It has a nadir and a recovery time that depend on the following: firstly, the instant of switching and, secondly, the relationship between R and X of the grid impedance at the Point of Common Coupling (PCC) [1].

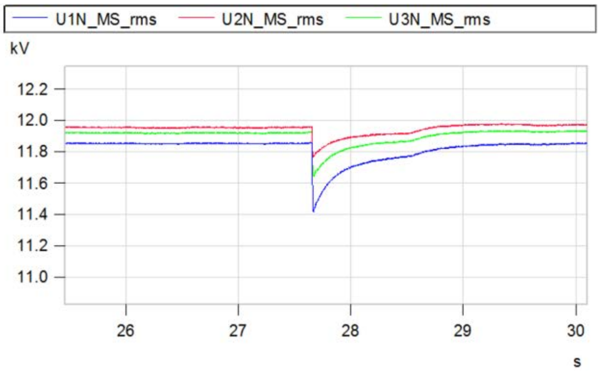


Figure 1: Typical voltage dip when energising a WEC ($P_{rated}$=3MW, $S_{Trafo}$=3.8MVA, $S_{PCC}$=250MVA, $U_{PCC}$=20kV)

It should be noted that the energisation of the unit transformer of a WEC is a rather seldom event. Even under no-wind conditions, the collector system normally stays connected to the grid and thus energised. Nevertheless, even seldom switching operations, e.g. during maintenance, may violate limits defined by the local grid operator. If the wind farm consists of multiple WECs, it is common practice to introduce a delay between the energisation of the unit transformers, so that at PCC never is seen more than one unit causing an IC.

Grid codes usually impose specific requirements dedicated to restrain the inrush. The authors expect that especially in Europe those requirements will be updated very soon due to the imminent implementation by each country of the European Network Code Requirements for Generators (RfG, [2]). Even if in reality this European code does not address the aspects of power quality[1] and therefore the inrush, system operators may see here the opportunity to revise and reinforce the requirements related to the inrush.

The German grid code ([3], [4]) specifies the max. permitted ΔU caused by switching operations to 2%$U_n$ at PCC, based on the (minimum) grid short-circuit power for the assessment of system perturbations, i.e. regular and planned switching operations, of either the entire plant or individual generating units. For example, this could be the regular connection (in the morning) and disconnection (in the

[1] RfG addresses technical aspects of cross-border relevance and not power quality as it is a local phenomenon.

evening) of a LV/MV transformer in a MV-connected PV-plant.

Different to the previous, seldom and random switching operations are not considered, and system operators in practice accept that such seldom events cause $\Delta U > 2\%\ U_n$. The exact meaning of the terms "regular, planned" and "seldom, random" is not entirely clear at the time of writing this paper, with the relevant authorities in Germany working on distinguishing these terms in an additional document.[2]

Part of the grid code in Germany is also a complex certification process for the generating unit and the power plant. In the unit certificate the impact of the transformer inrush is typically disregarded. The relevant voltage change factor $k_u(\psi)$ is given by WEC manufacturers at the LV terminals of the generating unit. It has to be determined in accordance with [5] and documented in the unit certificate.

For the plant certificate the compliance with the 2% limit has to be proven at PCC. In the case of wind farms, the MV grid inside a wind farm is only re-energized very rarely, e.g. after MV maintenance activities in the substation. So it falls under the category "seldom and random" and the resulting voltage dip is usually accepted. The voltage drop caused at PCC by the energization of an individual generating unit has to be checked for the plant certificate too. Whether this can be critical depends mainly on the ratio of the rated apparent power of the individual power generating unit to the (minimum) grid short-circuit power used for the assessment of system perturbations at the PCC.

Another example is the French distribution grid code which defines a maximum limit of 5% for the voltage dip at the PCC of the complete power plant (e.g. wind farm), under the assumption that the minimum short circuit power is at least 40MVA[3] [6], [7]. In practice, this means that special consideration should be given to unit transformers with a rated power higher than 2.8MVA.

A different approach is used in Belgium where the technical requirements are given in chapter 2.7 of the distribution grid code [8]. These requirements are amongst the most demanding known to the authors; the IC has to be limited to 1.0 p.u (based on rated current) for:

- transformers 2600 kVA connected to MV
- transformers 4600 kVA connected to HV

According to the typical size of today's WECs, most of them are concerned and consequently a technical solution is inevitable.

Ideally, system operators should anticipate via grid codes the increasing penetration of distributed generation and try to find reasonable limits that suit the needs of the power system in question. This exercise has to take into consideration the grid's short circuit power at the specific PCC, as well as the equipment-specific switching characteristics. It is expected that isolated networks, like geographical islands, with rather limited short circuit power from the grid side will probably establish more stringent requirements than bulk power systems. The requirements regarding the impact of the IC on the voltage have also to consider other critical conditions, for instance during system restoration.

## II. Inrush Current: The Theory

To gain a better understanding of the IC physics, one must consider: (please refer to Fig. 2) the relationship between the induced voltage $e$ and the flux $\varphi$, between the flux $\varphi$ and the magnetic properties of the transformer core, and between the magnetic field and the current flow $i$.

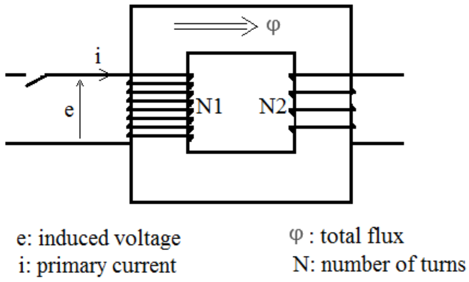


Figure 2: Simple transformer circuit

When a transformer is submitted to a sinusoidal voltage as per equation (1):

$$e = \hat{E} * sin(\omega * t) \qquad (1)$$

*with:* $\hat{E}$*: maximum voltage* ($E*\sqrt{2}$)
$\omega$*: angular frequency* ($2*\pi*f$)

a magnetic flux in quadrature with the voltage is developed according to (2), equation derived from the Faraday law of induction:

$$e = N_1 * \frac{d\varphi}{dt} \qquad (2)$$

*with:* $e$*: induced voltage*
$N_1$*: number of turns*
$\varphi$*: total flux*

From (2) and (1) the flux can be expressed as per:

$$\varphi = \varphi_{RES} + \varphi_M * [\cos(\omega * Te) - \cos(\omega * t)] \qquad (3)$$

*with:* $\varphi_{RES}$*: residual flux before energisation*
$\varphi_M = \frac{\hat{E}}{N1*\omega}$*: flux peak value*
$Te$*: instant of energisation*

$\varphi_{RES}$ is always resulting from a previous energisation state and is due to the hysteresis characteristics of a ferromagnetic element, for instance the iron of the transformer core. Apart from exceptional circumstances[4], the residual flux remains very stable over time, until the core is again submitted to another magnetic field.

Using (3), we can now consider different scenarios depending on the residual flux value and the instant of energisation.

In a first scenario, we consider that there is no residual flux ($\varphi_{RES} = 0$, for instance in the case of the first ever energisation of a transformer) and that the energisation of the transformer occurs at the peak value of the voltage

[2] The terms use here have been translated as close as possible to meaning of the German grid code documents, but they will probably not appear identically in the final wording.

[3] The 5% limit is adjusted for lower short circuit levels

[4] Core submitted to an external intense magnetic field or by reaching the 'Curie point' due to overheating.

considering (1). This is shown in Fig. 3 and can be regarded as an ideal scenario, as the resulting instantaneous flux imposed by the voltage corresponds to the theorical steady state flux value. It is noteworthy that in this context the maximum value of the flux is $\varphi_M$.

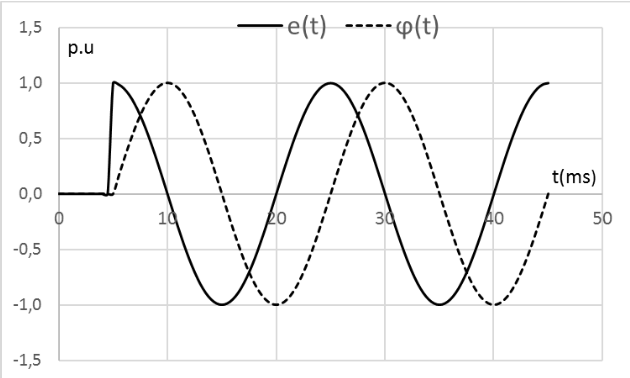


Figure 3: Energisation at the maximum voltage value of a transformer without residual flux

The second scenario considers again a situation with no residual flux ($\varphi_{RES}=0$), but with an energisation at the zero crossing of the voltage (Te = 20 ms [5]). According to (3), the flux expresses a DC component $\varphi_M * \cos(\omega * Te)$ and reaches a peak value of 2*$\varphi_M$ at t= 30ms, as shown in Fig. 4.

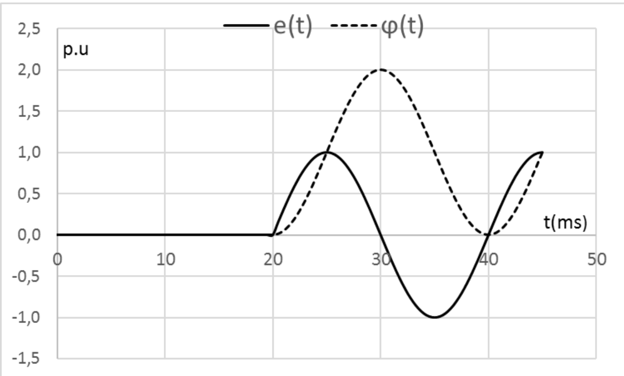


Figure 4: Energisation at zero crossing without a residual flux

In the last scenario shown Fig. 5, the energisation occurs again at the zero crossing of the voltage, whereas a residual flux $\varphi_{RES}= \varphi_M$ now exists. In such a case, according to (3), the flux reaches a peak value of 3*$\varphi_M$ when t = 30ms.

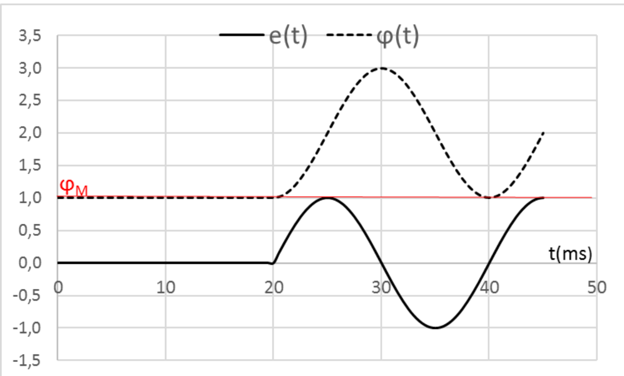


Figure 5: Energisation at zero crossing with a positive residual flux

Hence, depending on the instant of energisation and its residual value, the flux can reach a value between $\varphi_M$ and 3*$\varphi_M$. In practice, the residual flux resulting from a previous energisation is always below $\varphi_M$ due to the magnetic properties of the core.

For the relationship between the flux φ and the current density I, the magnetisation curve of the transformer should be considered; this so-called "induction curve" shows the relationship between the magnetic field B and the excitation H. For demonstration, a typical induction curve is shown below in Fig. 6.

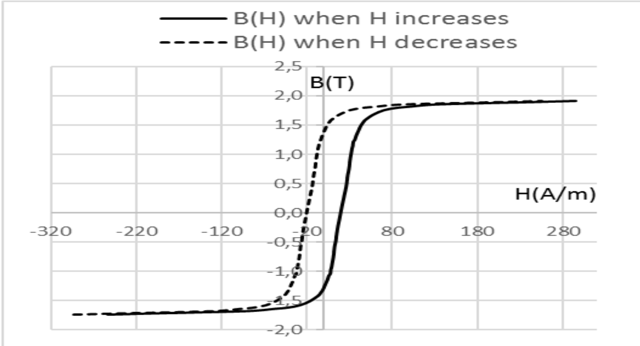


Figure 6: Typical transformer induction curve

Now, assuming that the flux B is strictly proportional to φ according to (5), and that H is strictly proportional to the magnetisation current I according to (6), we can then consider that the induction curve B(H) shown in Fig. 6 is like $\varphi(I)$.

$\varphi = N1 * B * S$ (Lenz-Faraday law) (5)

$H = N1 * I/L$ (Amperes law) (6)

*with:* *S: cross section of the core*

*L: length of the magnetic path*

Hence, by simply projecting $\varphi(t)$ (Fig. 7a) into $\varphi(I)$ (Fig. 7b ) one can find the current I(t) (Fig. 7c and Fig. 8).

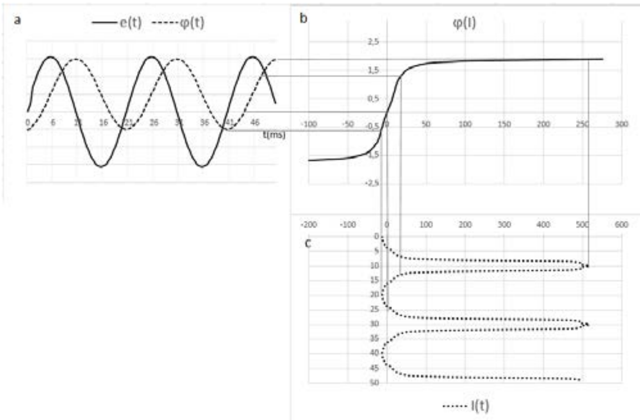


Figure 7: Image of the inrush current by projection

Fig. 7c and Fig. 8 illustrate that the current is asymmetrical, reaches a high peak, has a high RMS value, contains a DC component and significant harmonics. Consequently, it causes power quality issues and leads to mechanical and electrical stress on the electrical material (windings of the transformer but switchgears as well).

[5] A 50Hz nominal frequency is considered

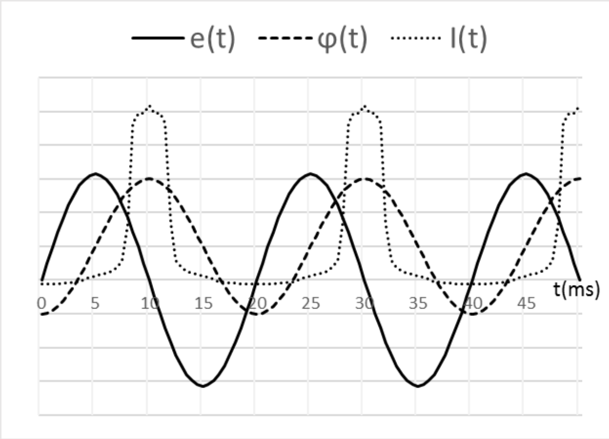


Figure 8: voltage, flux and current waveforms during energisation

According to [1], the maximum peak value of the IC is limited only by the impedance of the system (i.e. of the grid and the other electrical equipment until the PCC), and then tends to decrease exponentially with a time constant of R/L (R and L, being the total resistance and inductance, respectively, of the system). Additionally, in all power plants with several transformers in parallel, the phenomenon of sympathetic ICs can occur [9].

To summarize, according to the previous description, the IC is dependent of several factors:

- the characteristics of the magnetic core
- the impedance of the grid connected to the transformer
- the instant of energisation
- the instant of de-energisation which affects the residual flux.

ICs occur whenever the flux imposed at the instant of energisation does not match to the theoretical steady state flux.

## III. Existing Mitigation Solutions

The factors listed above are the target of the existing different mitigation solutions, which are the object of this section.

Firstly, one method uses the magnetic properties of the transformer core. According to (5), for a given flux φ, the magnetic field B can be reduced by increasing the section S of the core; hence the saturation is reached for a higher level of flux. The drawback of this method is that it increases the volume and the price of the transformer, hence its use is limited to cases where the IC issue is moderate. This method has been used in some French windfarms for cases where voltage dips generated by ICs were slightly above the limits.

Secondly, one attractive method consists on artificially increasing the impedance of the source feeding the transformer, as shown per Fig. 9. This method is known as the pre-insertion resistor method.

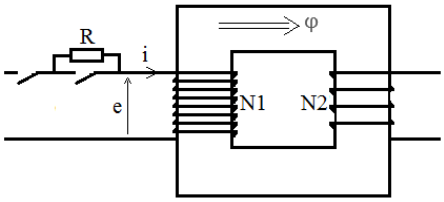


Figure 9: Limitation of inrush with pre-insertion resistor

Even if this mitigation method is in theory very efficient, it is rarely used in the case of wind farms, because such resistances must be integrated at the grid's side, most commonly in the grid connection substation. This can lead to significant investment costs and the need for dedicated space.

Thirdly, the most advanced methods to mitigate high ICs consist on the so-called "point-on-wave switching"; it takes into consideration the instant of previous de-energisation, and then calculates and controls the proper instant of energisation. According to (3), in order to minimise φ, the minimisation of the term $\varphi res + \varphi_M * [\cos(\omega * Te)]$ is necessary. Hence, by monitoring the instant of de-energisation, a dedicated controller calculates $\varphi res$ and then decides on the proper moment of energisation Te. This is shown with Fig. 10 where Te' or Te" are two possible ideal instants of energisation. In this case, the transformer is energised at Te", instant at which the theoretical steady state flux matches perfectly with the residual flux value ($\varphi res = 0{,}5 * \varphi_M$ in this case).

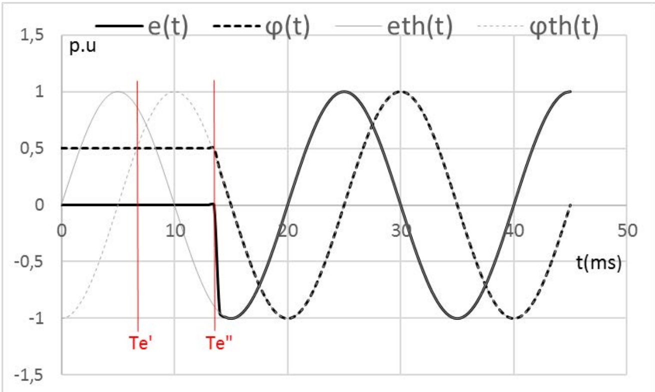


Figure 10: Optimal energisation of a single-phase transformer showing a residual flux (Two optimal energisation times (Te' and Te"); energised at Te" in this case)

The previous explanation was for single-phase transformers. Now coming to three-phases transformers, the method stills partially also suitable. In the "delayed closing strategy", the transformer is treated like a single-phase transformer in the first place. By knowing the residual flux of a single phase, it is connected at an optimal energisation time. The other two phases stay disconnected for a few cycles. Due to electrical correlation, the flux of the remaining two phases both converge to half of the connected phase flux. Now the optimal point of energising the remaining two phases matches with the maximum flux of the connected phase. By doing so, the transformer gets connected without any saturation, leading to no inrush. This is well shown by Fig. 11, which is extracted from [10].

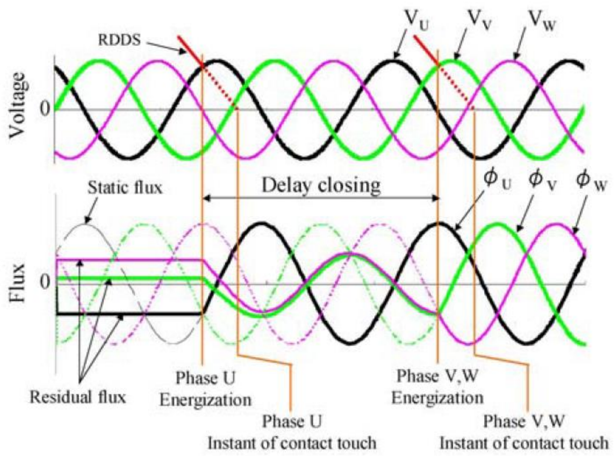


Figure 11: Delayed closing strategy on a three phase transformer: Phase U is energised at an optimal time, after a short delay phase V and W have settled and closed at maximum flux of phase U. [10]

This method became a well-known solution for HV transformers, where the impact of ICs can be significant. Besides the demanding calculations and switching operations, it is mandatory to connect the transformer with a single-pole circuit breaker, which leads to higher investment costs.

Due to their high cost and the limited space in the WEC tower, it is not practical to use single-pole circuit breakers for the unit transformers of WECs. The circuit breaker used typically operate all three phases at the same time. However it still possible to have a significant influence on the IC, but with some compromise since not all phases can be closed according to their optimal energisation time.

A good way to visualize this dilemma is to apply the dq transformation to the three fluxes.

$$\begin{bmatrix}\varphi_{re}\\ \varphi_{im}\end{bmatrix} = \frac{1}{3} * \begin{bmatrix}2 & -1 & -1\\ 0 & \sqrt{3} & \sqrt{3}\end{bmatrix} * \begin{bmatrix}\varphi_u\\ \varphi_v\\ \varphi_w\end{bmatrix} \quad (7)$$

With this formula, the three fluxes of the transformer core are translated to a complex value, a single rotating vector: its magnitude represents the height of the flux, its phase angle is rotating counter-clockwise. The phase angle of the flux is directly linked to the phase angle of the voltage; this is helpful when applied to the flux of a transformer being shut down, which is shown in Fig. 12. The flux starts with a circular motion (e.g. 50Hz) and with an amplitude of the rated flux (1 p.u). When disconnected, the flux decreases and remains at a random amplitude and phase angle. In this example, the residual flux stays at 60% of the rated flux and has a phase angle of 220° with reference to phase u.

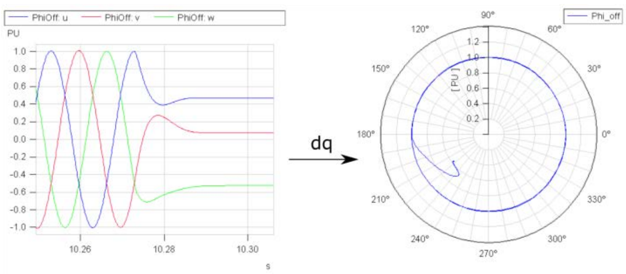


Figure 12: Fluxes of a transformer that is de-energised, left: single phase values, right: complex flux

This is already enough information for a controlled switching device to energise the transformer again with minimum inrush. In this case, the optimal energisation time is related to the phase angle of 220° of the residual flux. If reconnected at this instant, and if the flux magnitude would not drop after transformer de-energisation, the flux would perfectly continue its movement on the original line, resulting in no saturation and no IC. Since the flux usually decreases after disconnection, and therefore can not match any steady state value, it will exceed the rated flux at some point and cause an inrush as already explained in part II of this paper. But this unavoidable saturation will be kept at a minimum when energised with the matching phase angle. In general, a higher flux leads to a lower inrush. Depending on the core design, ICs from 0 p.u. to 2 p.u. are possible.

Besides the optimal energisation point, the phase angle can also be used to determine the energisation time that results in the highest possible saturation. In the example above, this would be at 40°. Energising at this point would lead to the highest possible IC, which can reach in some cases 10 p.u. The IC value is provided generally with the transformer datasheet and is used in simulations to estimate the worst-case impact of the transformer energisation for a given grid.

In practice, however, measuring the fluxes is fairly complex. The transformer needs to be monitored 24/7 to capture the moment of de-energisation. Also, during de-energisation, transients can influence the measurement and thus the resulting calculations. Although computing power has increased and became cheaper, flux calculation can still be complex to handle.

## IV. THE "SMART ENERGISE"

A simpler way to determine the residual flux is not to measure it, but rather to set it. Transformers come with beneficial properties that make pre-magnetisation easy. Firstly, their no load current is a fraction of the rated current. Furthermore, they are sensitive to DC components:

- The transformer cores have no air gap and can hold high residual flux
- Their low voltage side is easily accessible, especially in the case of a WEC

Therefore, the flux of a transformer can easily be changed with a DC voltage source of 5V. In most cases, a current of less than 20A is sufficient to saturate the core of a transformer.

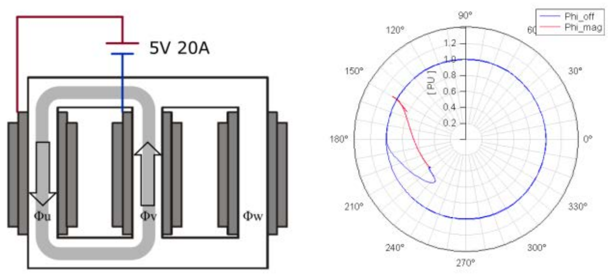


Figure 13: Pre magnetisation of a Dyn5 transformer, left: DC-voltage source connected to phase u and v, right: complex flux

Fig. 13 shows a DC source connected between phase u and v. The star connection allows the DC current to flow from phase u to phase v. This leads to a complete change of the flux. The flux in phase u becomes maximum positive and the flux in phase v becomes maximum negative. Due to the core design, the flux in phase w will become close to 0. This pre-magnetisation process can again be visualised by the dq transformation. It shows that the former flux angle of 220° has now changed to 150°. In addition, the amplitude has changed significantly: it has increased from 60% to 80% of the nominal flux, which results in a better inrush performance when it comes to energisation.

Most importantly, however, this process will always end in a fixed flux angle despite the usually random flux distribution. Hence, the measurement and calculation of the fluxes become obsolete, which drastically simplifies the process of IC reduction into a few steps:

- Apply dc voltage for short time
- Synchronize with the grid
- Connect the transformer at a fixed angle

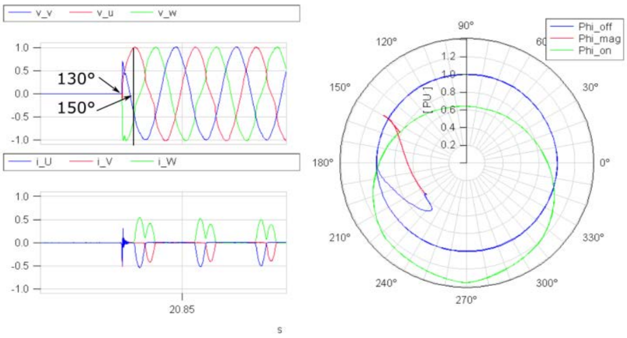


Figure 14: Transformer being energised: left: measurement data (voltage on LV side, current on MV side), right: complex fluxes

Applied on a transformer, this will lead to very small ICs. In the example above (Fig. 14), the transformer absorbed a current of only 0.5 p.u. Although the target of 150° was slightly missed, the performance was still good. Due to core design reserve[6], saturation often starts above 100% of the rated flux, which is beneficial for this method.

## V. Prototype Testing

Besides remote-controlled circuit breakers, which are often standard in modern WECs, the needed hardware for "Smart Energise" is rather simple. The key component is a micro processing unit that controls the pre-magnetisation and the synchronized switching of the circuit breaker. Due to the highly optimized design, only few additional components are needed, e.g. a contactor and fuses. Another big advantage of the simple process and the highly specialised device is the opportunity of automation. Indeed, the biggest remaining challenge is the specific closing time of the individual circuit breaker.

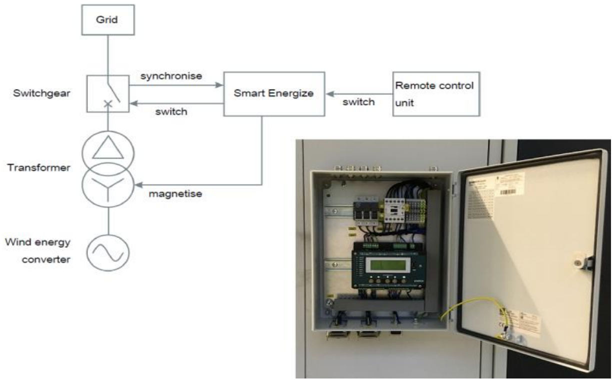


Figure 15: schematic implementation of ENERCON "Smart Energise" in a remote-controlled switchgear, bottom-right: View inside the prototype box

By allowing only once an uncontrolled initial energisation, it is possible to automatically measure this specific closing time and save it as a parameter. After this, the "Smart Energise" is fully functional for operation. Therefore, the commissioning process is drastically simplified, with the downside of a possible initial high IC.

First measurements of the "Smart Energise" were collected at a WEC with 3MW rating and a 3.8MVA transformer. The WEC was connected at a 20kV grid that has a high short circuit power (250MVA). Since the WEC was already equipped with a remote control, the device was easily retrofitted within a few hours.

Overall, more than 26 transformer energisations were performed; only during two events high ICs occurred and both of them were anticipated. The first event was the initial switching, required for the "Smart Energise" to find the switching time of the circuit breaker. The following transformer energisations showed the expected very low ICs, ranging from 0.1 p.u. to 1.0 p.u. (Fig. 17). After the 20th transformer energisation, the device was reseted and repeated this process, hence the high IC experienced in the 21st measurement.

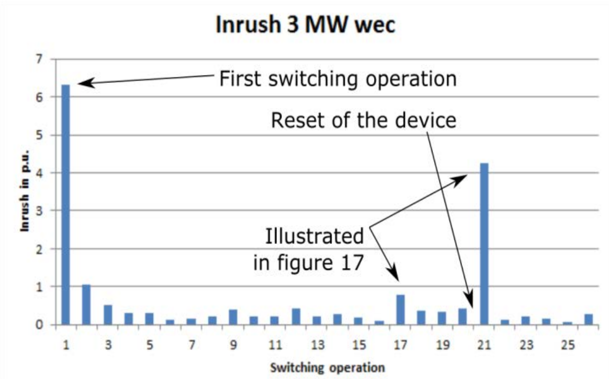


Figure 16: Inrush measurements of a 3 MW WEC equipped with ENERCON "Smart Energise"

Measurements of the grid voltage show that even a grid with a high short circuit power can be affected by a totally uncontrolled IC of a WEC unit transformer (Fig. 1 and Fig. 17 left). With the IC staying below 1 p.u., the voltage dip also stays below 1%, which reduces the impact to nearby grid

[6] Transformer manufacturers usually oversize slightly the core; the saturation point is thus above the rated flux.

users, reduces the stress for the transformer and ensures power quality is kept at a compliant level.

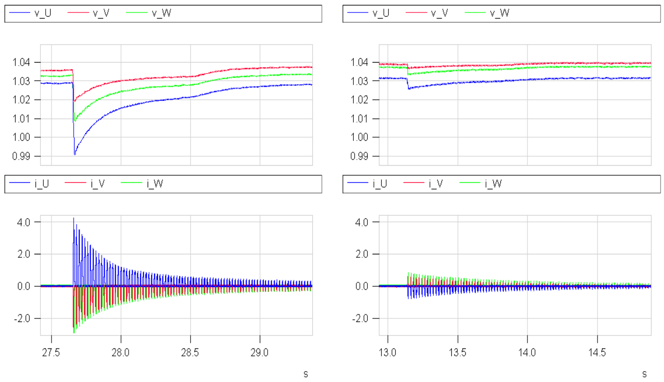


Figure 17: Left: Inrush current of 4.2 p.u. and voltage dip of 3.7%, right: inrush of 0.8 p.u. and voltage dip of 0.5%

## VI. CONCLUSIONS

Inrush currents generated by the energisation of transformers cause transient grid voltage dips. In addition, they inject harmonics and affect protections systems. Besides grid quality issues, they induce some stress in the transformer windings and in the associated switchgear.

WECs are becoming increasingly more powerful, employing larger unit transformers leading inevitably to higher inrush. System operators must gain a greater awareness of this trend as it could lead to negative consequences in the future. Even if today most of the grid codes already express some requirements, it is perhaps time to review and even enforce them. On their side, wind farms developers must have this trend in mind as well, and must anticipate on the early stage of their project design the need of a mitigation measure.

As of today several solutions are commonly used (oversizing of the transformer core, pre-insertion resistor, point-on-wave switching) which are relatively efficient but at a significant investment cost.

An innovative method was presented in this paper. It offers a remarkable combination of simplicity, high efficiency and reliability and at cost well below the most advanced solutions. By using this new method, the inrush current is restrained to 1 p.u whereas it could reach easily 5 to 10 p.u without it.

We are in the early days of the deployment on the field of this “Smart Energise” solution, but it already gives peace of mind for both project developers and system operators.

To finish, it is noteworthy that its application field is by no means restricted to wind energy, as the transformer can be part of a wind energy converter, a photovoltaic plant or any other generation mean.

## ACKNOWLEDGMENT

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