Virtual Resistance Control for Sequential Green-start of Offshore Wind Power Plants

Jain, Anubhav; Saborio-Romano, Oscar; Sakamuri, Jayachandra N.; Cutululis, Nicolaos A.

Published in:
IEEE Transactions on Sustainable Energy

Link to article, DOI:
10.1109/TSTE.2022.3159620

Publication date:
2022

Document Version
Peer reviewed version

Citation (APA):
Virtual Resistance Control for Sequential Green-start of Offshore Wind Power Plants

Anubhav Jain, Oscar Saborío-Romano, Jayachandra N. Sakamuri, and Nicolaos A. Cutululis

Abstract—The changing energy landscape due to the large-scale integration of renewable energy and shutting down of conventional thermal plants has opened up the potential of alternate sources in the blackstart services market. Grid forming wind turbines can do controlled islanded operation independent of an external grid voltage and thus participate in network restoration from the start. However, it is necessary to study the capability of wind turbines to deal with the demanding energization transients in a controlled and stable manner. This work investigates the feasibility of using virtual resistance in the wind turbine converter control to reduce transients during self-transformer inrush and sympathetic interaction from downstream string transformers. This can eliminate the need for pre-insertion resistors during sequential energization. The sensitivity of the AC current and voltage output along with DC link transient to the virtual resistance parameters has also been analyzed using PSCAD simulations. Finally the effectiveness of the proposed method for offshore network energization by a grid forming wind power plant has been tested by comparing to results for a pre-insertion resistor.

Index Terms—Wind, HVDC, Grid forming, Energization, Transformer, Inrush, Virtual, Resistance.

I. INTRODUCTION

One of the major strategies for sustainable development is the large-scale integration of renewable energy sources in the electrical power system. The global installed capacity of coal-fired plants is set to peak in 2022 before starting to decline in the following years and be overtaken by solar and wind energy by 13% in 2025 [1]. However as traditional synchronous generators are being replaced with power-electronics interfaced variable generation (like wind and solar), maintaining stable and reliable grid operation becomes more complex due to the changing power system dynamics [2], [3]. This has increased the risk of wide-area blackouts — for example most recently in South Australia (2016) and UK (2019) — both initiated by a rapid unexpected decrease in wind power plant generation [4], [5]. Given the changing energy landscape, cost of warming-up large thermal plants and consequently, of blackstart services is increasing. Thus, considerable changes are required to facilitate the participation of alternate sources including aggregated units like large offshore wind power plants (WPP) in the blackstart market [6], [7].

Many studies have been done on power system restoration with WPPs — a comprehensive review is presented in [8].

This work is part of the InMoDC project that has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 765585.

A. Jain, O. S.-Romano and N. A. Cutululis are with Department of Wind Energy, Technical University of Denmark, 4000 Roskilde, Denmark.

J. N. Sakamuri is with Vattenfall Vindkraft A/S, 6000 Kolding, Denmark.

which highlights a change in control philosophy from conventional grid-following to grid-forming (GFM) as essential in facilitating early stage participation of WPPs in bottom-up network energization. Such GFM wind turbines (WT) can operate — albeit with changes to the turbine and converter control [9]—[11] — as a controlled AC voltage source without relying on an external grid and supply load in a power island [8], [12]. This also enables them to provide short term defense against imminent instabilities preceding a blackout by switching to trip-to-houseload (TTH) and ensuring stable controlled islanded operation (CIO) — potential strategies for restoration procedures in the future decentralized converter-rich power system [13]. TTH refers to the capability of power generating modules to supply their local in-house loads in the event of network failures that results in them being disconnected from the grid and tripped onto their auxiliary supplies. This is similar to islanded operation but more local in its scope.

In addition to reducing the blackout impact, GFM WT producing power to sustain themselves can avoid health risks when offline (due to icing up of electronics, bearing deformation during standstill and vibrations due to unfavourable yaw-axis orientation), reduce cost of warming (from complete shutdown) by minimizing the dependence on backup diesel generator for auxiliary power. This can potentially yield economic benefits, save offshore space, reduce downtime, increase reliability and result in a greener footprint (due to CO₂ displacement) — especially during unscheduled events like long duration grid outages or loss of connection due to cable failures [13], [14].

However before a GFM WPP can pickup onshore block load for grid restoration, there are different stages and associated demanding transients like under/over-voltages associated with magnetization of transformers, charging of cables and potential resonances, that it must deal with while maintaining stable voltage and frequency. These target states are of more concern to the WPP operator and stable CIO of the aggregated asset must be ensured before providing any onshore blackstart service. They include auxiliary load startup by backup supply and self-sustained houseload operation, followed by energization of offshore network and stable islanded operation with synchronized WT in parallel, ultimately ending with the export link energization before connecting to the onshore grid, as explained in detail in [14]. Thus, the sequence of energization constituting the aforementioned target states up to the onshore terminal as shown in Fig. 1 is defined as greenstart to differentiate from the traditionally used ‘blackstart’ of the main grid that is only a kickstarting initial step for the larger
Fig. 1: Target states in the greenstart energization sequence of an HVDC-connected offshore WPP, reproduced from [14]. It starts with initial energization of auxiliary load by backup supply (TS-1) followed by houseload operation when rotor is oriented to the wind (TS-2). Then multiple GFM and GFL WTs must synchronize for operating in parallel (TS-3) to emulate a voltage source strong enough to energize the offshore network (TS-4) while ensuring stable and robust islanded operation of the HVDC link (TS-5) before finally connecting to the onshore grid for block load pickup (TS-6).

The most straightforward method to limit inrush currents during DOL energization is a controlled reduction in generator voltage as demonstrated in [19]. Alternatively, a pre-insertion resistor (PIR) is also commonly used for larger HVDC transmissions. During DOL energization is a controlled reduction in generator voltage. Since voltage dips and over-currents and damage transformers and reactors due to over-heating and rich 13 pu virtual resistance can similarly be modified to emulate a virtual impedance loop to achieve controlled power injection by the distributed generator when it initiates its energy generation [20], [21]. The GFM control of the WT converter can similarly be modified to emulate a virtual resistance ($R_v$) at start-up/energization to reduce the terminal voltage during the transformer connection, mimicking the presence of a real PIR and thus limiting inrush effects. However, the DC link of the WT converter interface takes the brunt of the transient and needs to be controlled to maintain converter controllability as described in Sec. III-A.

The main contribution of this paper is to investigate the techno-economic benefits of augmenting WT GFM control with the virtual resistance concept for application in offshore wind farm blackstart scenario. The potential benefits are significant, since energising the transformer is more challenging offshore than onshore due to a weaker grid in the former case and lack of space constraints in the latter which makes the use of a PIR onshore cost-effective. Since virtual resistance is just a software setting in the WT controller, it allows to deal with different scenarios like energization and faults flexibly without the need for an extra device. This is beneficial for offshore WPPs due to their higher voltage and power levels compared to microgrids, which demands lower switching frequencies and controller bandwidths resulting in potentially reduced stability margins. Moreover unlike microgrids, the presence of a large number of assets located very far from each other limits the dependence on communication links. To the authors’ knowledge, such a study has not been done before as previous literature relies on using a diesel generator offshore and PIR for startup [22].

The next section introduces the concept of virtual resistance in converter control followed by a description of the WT model with the control that has been used in this study. After that the transformer energization of a single islanded GFM WT is shown in Sec. IV-A and comparison has been made between DOL, PIR and $R_v$ methods. Then the sensitivity of the inrush
transients to the $R_v$ parameters is analysed through PSCAD simulations in Sec. [IV-B]. The impact of $R_v$ on inrush and sympathetic interaction from downstream transformers during string energization has also been studied in Sec. [IV-C]. Finally the feasibility of using $R_v$ for offshore network energization by a GFM WPP is investigated and compared to results for a PIR in Sec. [IV-D] before the concluding remarks.

II. VIRTUAL RESISTANCE

A significant amount of research has been done in tackling the challenges of integrating different technologies of power-electronics, telecommunications, generation and energy storage into microgrids. State-of-art hierarchical multilevel control as proposed in [20] endows flexibility and smartness to microgrid operation by using converters as active thinking and data-processing components with cutting edge functionalities like fault-tolerance, load-sharing, soft-start, island-detection, and smooth mode-switching [21].

The primary level in microgrid hierarchical control is droop based and mainly used to mimic communication-free power sharing in synchronous generators. This also ensures a stable and damped system with energy balance between generation units and energy storage elements [20]. However, resistive line impedance at low voltage applications and inner loop dependent output impedance of converters can negatively affect power sharing. Thus, a virtual output impedance loop characterized by Eq. [1] is typically added to emulate synchronous generator’s physical inductive behaviour as shown in Fig. [2]

$$v_o = G(s)v_{ref} - i_o Z_v$$  \[1\]

The generated output voltage $v_o$ is modified from its original value based on the closed-loop voltage gain transfer function by subtracting the drop across the virtual impedance $Z_v$ due to the output current $i_o$. Additionally, the virtual impedance loop provides features like reactive-current sharing, harmonic-load compensation and hot-swap operation, without any loss in efficiency [20]. [21].

The virtual impedance loop can also be used when the distributed generation unit is connected to the microgrid as small differences in voltage phase and/or amplitude can result in overcurrent spikes that can potentially damage the unit [20]. Moreover when the generator begins injecting power, unfavourable transient disturbances can result if the start-up procedure is improper [21] or if the device being energised draws large currents like an induction motor [23].

Large fixed speed wind turbines used external resistors and thyristors to temporarily increase the output impedance of the generator and smoothly reduce inrush transients [20]. Since the virtual impedance can be chosen arbitrarily, it is possible to mimic such a physical soft-starter by setting a high initial value $R_t$ at the start and gradually reducing it to a final value of $R_i$ with a time constant $T$. Such virtual resistance $R_v$, as characterized by Eq. [2] [21] can reduce the transformer energization inrush transient during DOL connection at $t_o$ and by virtue of it being programmed into the GFM converter, help eliminate the need of a physical (fixed value) PIR.

$$R_v = \begin{cases} 0 & \text{if } t < t_o \\ R_t - (R_t - R_i) e^{-\frac{t-t_o}{T}} & \text{if } t \geq t_o \\ R_i e^{-\frac{t-t_o}{T}} & \text{for } R_t, t_o = 0 \end{cases}$$  \[2\]

In absence of any resistance in the circuit, the (first cycle) peak inrush current $I_{pk}$ for energization of a transformer’s single phase by a sinusoidal AC voltage source (of amplitude $V_m$ and frequency $\omega$) can be estimated using Eq. [3a] [18], where $B_n$ is the nominal peak core flux density and $B_{r/n}$ are the residual/saturated core flux densities, respectively. This is calculated based on the peak instantaneous flux passing through the air-gap (with reactance $L_{air}$) between the iron core (with cross-section $A_c$) and transformer winding (with $N$ turns). Since by definition transformer flux is the integral of the impressed voltage, the nominal maximum flux $\Phi_m (= N B_n A_c) = \frac{V_m}{\omega}$ which results in Eq. [3b]

$$I_{pk} = \frac{N(2B_n + B_r - B_s)A_c}{L_{air}}$$  \[3a\]

$$= \frac{V_m}{\omega L_{air}} \frac{(2B_n + B_r - B_s)}{B_n}$$  \[3b\]

At this point, the only thing that limits the exciting current is $L_{air}$ which is several orders of magnitude smaller than the normal magnetizing reactance. Without resistance in the circuit each successive inrush peak has the same value and would go on indefinitely but in practice this is damped slowly due to parasitic resistance of transformer windings and any internal resistance of the energizing source. However with an external resistance $R_v$ that is sufficiently larger, a significant voltage drop occurs reducing the impressed voltage on transformer and its integral represents a net decrease in the flux required to support the applied voltage [24]. This effectively reduces the inrush current whose peak can now be estimated by Eq. [4] where $R$ is the total line resistance and $L$ represents in addition to $L_{air}$ any line reactance (for example filter) present between the source and transformer.

$$I_{pk} = \frac{V_m}{\sqrt{\omega L + R^2}} \frac{(2B_n + B_r - B_s)}{B_n}$$  \[4\]

Additionally, the DC component of the sinusoidal and offset transformer flux that includes the effect of residual flux and switching instant on the voltage wave now decays at a faster rate [24]. Thus the respective component of the exciting inrush current, the analytical equation of which is out of scope of this paper, has an approximate decay time constant of $\frac{1}{R}$ [25].
Fig. 3: Model of the islanded open-circuit GFM WT used in this study consisting of: RSC average model with DC voltage control, DC link chopper, GSC switching model with GFM control, PIR bypassed after PIT using coordinated breakers (MB, AB), and transformer with inrush and saturation.

III. SYSTEM MODEL AND CONTROL

The schematic of the 8 MW GFM WT under study is shown in Fig. [3]. The EMT model developed in PSCAD consists of average model of rotor-side-converter (RSC) and detailed switching model of the grid-side-converter (GSC) with a chopper at the DC link. The GSC terminal is connected to the WT transformer (WTTr) through the main breaker (MB) for DOL energization. A PIR is also present for inrush limitation that is bypassed by closing the auxiliary breaker (AB) after a certain PIT. There is no load connected at the WT terminal (WTT) i.e. the GFM WT operates in islanded mode open circuit as this study focuses on the transients during no-load transformer energization. The WTTr is modelled with inrush and saturation characteristics as shown in Fig. [12] in Appendix [A]. The values of all the circuit parameters are based on [8], [15] and tabulated in Table [I] in the Appendix.

A. Control and tuning

The GSC is a 2-level voltage-sourced-converter (VSC) switching at 2 kHz with GFM strategy based on improved Direct Power Control (DPC) [26], as shown in Fig. [4a] and similar to the implementation in [8]. The controller is tuned for natural frequency of 4 Hz and damping ratio of 0.74 based on its structure identical to standard Vector Current Controller obtained by integrating Instantaneous Power Theory, as described in detail in [8].

The DPC-GFM control implemented in this paper has been chosen based on the results from previous published work where the authors tested 4 of the most common schemes and compare their transient characteristics in the energization sequence of an HVDC-connected wind farm [8]. The main advantage of the chosen DPC scheme is its stiff voltage and frequency control along with ease of tuning compared to the other GFM schemes, which are more vulnerable to instabilities especially in a multi-machine system. Since DPC-GFM lacks current saturation like the inner current control loops of the other control strategies, a virtual impedance loop has been added in the GFM control structure based on Eq. [1] for dealing with the energization transient using virtual resistance as shown in Fig. [4b] The virtual impedance can be activated above a certain current threshold. Another possibility is to set limits in the power loops by back calculating from the current, which may indirectly achieve current saturation.

Since the GSC controls the terminal AC voltage of the WT, the RSC is tasked with controlling the WT DC link voltage. This is modelled with a current source that receives its reference from a DC link voltage controller as shown in Fig. [4b]. The control loop is tuned for 3 Hz bandwidth [9] and 55° phase margin for stable operation. Although optimal control to maximize generator output power ramp rate has been proposed in [9], a conservative limit of 0.1 pu/s has been used here as a faster ramp-up can lead to vibrations in the shaft and excite tower/blade oscillatory modes. The tuned values of the control loops are tabulated in Table [II] in the Appendix.

B. Assumptions

Contrary to grid-following WT, GSC cannot control the DC link in GFM mode by ensuring power balance as the power flow is now set by the AC load and not the turbine controller, which conventionally extracts maximum power from the wind. However, now it has to regulate the speed — especially avoid over-speeding during low AC load and high winds. Thus, RSC is required to maintain constant DC link voltage by ensuring that the generator output power tracks the load power demand. This can be achieved by optimally controlling the generator speed based on the WT power-speed characteristics [9]. Such a DC link control has much lower bandwidth (maximum 5 Hz [9]) than the inner speed and torque/current control loops, and has been shown to perform well with changing wind speeds and for seamless transition between weak and
strong grid connection modes. Thus, it has been adapted with some simplification as shown in Fig. 4b since the mechanical dynamics are not in the scope of this study.

Moreover, the redesign of the turbine speed controller as discussed in [11] allows for stable operation over an extended operational range (including strongly de-rated and negative power values), cope with sudden changes in generator torque during large load steps, and prevent transient over-speeding of the WT during load disconnections in weak grid conditions.

IV. SIMULATION STUDY AND RESULTS

Most modern WTs rely on an internal backup UPS for auxiliary power during idling operation to supply house-load [14]. Moreover, energy storage required to handle the transient load variations has been shown to be acceptable with the potential to be reduced further using advanced technologies in future [9]. Additionally, pre-charging control proposed in [10] allows charge retention on the DC bus following a blackout, thus enabling terminal voltage build-up for network energization and load pick-up, if wind energy is available. A synchrophasor-enabled algorithm is also proposed in [10] for autonomous synchronization and ‘hot-swap’ operation without resetting of controller dynamic states or requirement of energy storage.

With the above in consideration, the energization sequence for this study consists of the following three steps:

1) Pre-charging – a controlled DC link voltage is necessary for GSC to operate. This is regulated by the RSC as described in Section III-A using the control loop shown in Fig. 4b. The power ramp-rate limit is disabled during this stage as it is assumed that proper control such as that presented in [10] allows charge retention on DC bus after a blackout, or the backup UPS is sufficient to sustain the auxiliary requirements of the WT for a critical period of time. In the worst case the DC voltage would be built up by first spinning the generator up to a minimum voltage and then deblocking the RSC (operating the switches for rectification with backup power from UPS) to charge the DC link capacitor, similar to the AC side pre-charging of the offshore MMC as shown in [15] (Stage 2). This is however out of the scope of this study.

2) Grid forming – once the DC link voltage is controlled, the GSC can be deblocked in GFM mode to control the AC voltage and frequency at the filter output.

3) Connection – after the DC bus initialization by RSC and terminal AC voltage and frequency control by GSC, the WTTr is connected by closing MB. The inrush transients during energization of the WTTr are the main focus of this study.

A. Proof-of-concept

In this section the inrush transient and its associated DC link dynamics along with the impact on AC terminal voltage are compared for three energization methods namely, direct online (DOL), using PIR that is bypassed by closing AB after PIT delay, and implementing a virtual resistance ($R_v$) in the GFM control of GSC. For DOL and $R_v$ methods AB is closed

![Comparison of waveforms during inrush transient for DOL, PIR and $R_v$ energization of WTTr.](image-url)
together with MB to bypass the PIR from start. Figure 5 shows a comparison of the results for DOL, PIR and \( R_c \) methods when WTTr is connected at 2 s.

The DOL energization is shown here as the base case scenario. The values for the PIR case and \( R_c \) methods has been chosen only as an example to demonstrate that the virtual resistance emulation can indeed reduce inrush transient and its associated dynamics. PIR/PIT and \( R_c \) parameter values are chosen to result in approximately similar inrush current peak (about 0.5 pu) as shown in Fig. 5(b). Thus, PIR and \( R_c \) of 0.05 \( \Omega \) (0.8 pu) are selected with \( T \) set to 0.04 s, so that the time when \( R_c \) settles to zero \((= 5 T)\) is equal to the PIR bypass time \((= \text{PIT})\) of 0.2 s.

From Fig. 5(a) it can be seen that \( R_c \) reduces the transient real and reactive power peaks to 0.11 MW and 0.93 MVar compared to 0.42 MW (2.87 MVar) and 0.37 MW (0.7 MVar) for DOL and PIR cases, respectively. This is corroborated by Fig. 5(b) clearly demonstrating that \( R_c \) reduces the inrush current/power transient significantly — both in peak amplitude and settling time — similar to the PIR case. Additionally, the associated DC link voltage drop is lesser for \( R_c \) as it dips to 0.81 pu, 0.86 pu and 0.95 pu for DOL, PIR and \( R_c \) methods respectively, as shown in Fig. 5(a). Moreover while the RMS AC voltage dip is almost identical for DOL and PIR cases (0.87 pu), it is smaller for \( R_c \) (0.94 pu). Lastly it can also be observed from Fig. 5 that while both PIR and \( R_c \) reduce distortion in the 3-phase instantaneous AC voltages, the transient dip recovers faster for \( R_c \). The aim here is not to compare \( R_c \) with PIR, but rather to show that it can achieve a similar (if not better) reduction of the inrush current transients during transformer energization with improvements in AC voltage distortion and power/DC link voltage dips. Hence, it allows hard-switching to be used without the need for an extra physical component viz. PIR which can help save space and cost offshore. Moreover being just a software setting, it is easier to change the value and adapt according to the requirements of different scenarios like energization and faults.

B. Sensitivity analysis

Since the parameters in Sec. IV-A were chosen to only demonstrate the concept, a sensitivity analysis has been done to study how the inrush transients vary with different values of the \( R_c \) parameters. This can give some insight into how to choose the virtual resistance parameters. For this study the values of \( R_i \) used are 0.05 pu, 0.5 pu and 1.5 pu, and 0.05 s, 0.2 s and 1.0 s for \( T \). The results of the effect of varying \( R_i \) and \( T \) on the real and reactive power outputs of the WT, DC link voltage and the 3-phase RMS AC voltage output of WT are presented in Fig. 6(a). The effect on the inrush currents is shown in Fig. 6(b).

As expected, Figs. 6(a) and 6(b) show that the transient power and current peaks decrease as \( R_i \) is increased. Moreover, Fig. 6(a) also shows that larger values of \( R_i \) help reduce the AC and DC voltage dips. Additionally, it can be inferred from Fig. 6(a) that the transient settling time and voltage dip recovery time increases for smaller values of \( T \), especially at lower \( R_i \).
This is also corroborated by Fig. 6b which shows that the inrush current transient damps faster for larger values of $T$ — the effect being more visible for smaller $R_i$. The sensitivity analysis shows the effect of higher values in significantly damping the inrush transient compared to a negligibly small value for which the transient is similar to the base case DOL energization when there is no external resistive damping present.

C. String energization

Once the WTTr of the GFM WT has been energised, the next step is to energise the WTTrs of the other WTs connected in the string as shown in Fig. 7. In this section the effect of using virtual resistance to reduce inrush transients of downstream WTTrs in the string has been studied. In the previous energization studies we assume complete WTTr de- energization for best case residual flux ($\psi_{\text{res}} = 0$). However, in this section sympathetic interaction between series and parallel connected WTTrs has also been studied by simulating for worst case residual flux ($70\%$) — setting $\psi_{\text{res},a} = 0.7\pu$, $\psi_{\text{res},b} = 0\pu$ and $\psi_{\text{res},c} = -0.7\pu$ in the WTTr PSCAD model. The aim here is to study the impact of the inrush and sympathetic interaction on the GFM WT when it is used to energise the transformers in the string and supply the auxiliary load of other (conventional grid following) wind turbines, hence modelled as such. The sequence starts with BRK1 closing at $2\,\text{s}$ to energise Tr-1, then BRK2 at $6\,\text{s}$ to energise Tr-2 and finally BRK3 at $10\,\text{s}$ to energise Tr-3. The value of $R_i = 1\pu$ and $T = 0.06\,\text{s}$ has been used for each energization event but need not be same for each WTTr connection.

It is clear from Fig. 8a that virtual resistance helps reduce the transient power peaks and voltage dips for both best and worst case residual flux. Moreover, from the instantaneous current waveforms in Fig. 8b it can be inferred that although $R_v$ helps reduce the Tr-1 inrush significantly both in peak amplitude and duration, only a reduction in peak is seen for the subsequent WTTrs (Tr-2 and Tr-3) with no impact on the duration of decay of the sympathetic inrush, especially for worst case residual flux. Different virtual impedance characteristics may be used to deal with this.

![Fig. 7: Model of the string to study energization of downstream WTTrs by GFM WT.](image)

![Fig. 8: Waveforms during DOL and $R_v$ energization of downstream WTTrs in string for best ($\psi_{\text{res}} = 0$) and worst ($\psi_{\text{res}} = 70\%$) case residual flux.](image)

D. WPP level energization

In this section the virtual resistance has been implemented in the GFM WTs of a $400\,\text{MW}$ HVDC-connected WPP for
the energization of its 400 MVA offshore HVDC transformer (HVDC-Tr), based on that in [15], and with aggregation as shown in Fig. 9. Figure 10 depicts the energization of the offshore HVDC-Tr at 1.3 s by the GFM WPP using a PIR versus $R_v$. The 120 $\Omega$ PIR, bypassed after 0.3 s PIT [15], is used as base case. $R_i = 4$ pu and $T = 0.06$ s have been used in the $R_v$ case to achieve a similar transient current peak (0.5 pu) and settling time ($5T = PIT$) as the PIR case, as shown in Fig. 10a.

Transients in WPP active and reactive power output, and in RMS AC voltage at the WPP and PCC-2 terminals are shown in Fig. 10b for both cases. It is clear that $R_v$ effectively limits the inrush transient peak by decreasing the voltage in a smooth manner like in the case of a physical soft-starter. Moreover, there are no second transient power peaks in the $R_v$ case as opposed to when the PIR is bypassed at 1.6 s.

In case of PIR the main voltage drop occurs between the WPP and PCC-2 terminals (i.e. across the PIR), which is reflected by the relatively small variation in the WPP terminal voltage in Fig. 10b. In contrast for $R_v$ the main voltage drop can be said to occur (virtually) through $R_v$ i.e. inside the GFM WPP acting as a voltage sources (as shown in Fig. 9), which is reflected by the significant drop in the the WPP terminal voltage in Figs. 10b (RMS) and 10c (3-phase instantaneous). This can be corroborated by calculating the (virtual) voltage drop across $R_v$ and removing it from the WPP terminal voltage response ($V_{\text{WPP}} + I_{\text{WPP}}R_v$) as shown in Fig. 10c.

It can be inferred from Fig. 10c that although $R_v$ is able to limit the transient inrush current peak similar to a PIR (Fig. 10a), it does so at the expense of the WPP terminal voltage, which can drop significantly — to levels that can be as low as those characteristic of faults. Fault clearing during energization is dependent on under-voltage trip relays due to the low short circuit levels and thus, the application of the $R_v$ method to the energization of HV transformers may require different protection settings. As the bottom plot in Fig. 10c moreover suggests, some of the protection changes could rely instead on a virtual voltage calculated using the given $R_v$ and local voltage and current measurements. Additionally, different $R_v$ initial values and time constants can be used for different resulting voltage dips and transient current/power peaks as shown in Fig. 11. Likewise, other time characteristics/functions (i.e. different from that of Eq. 2) may also be used for $R_v$.

V. CONCLUSION

In this paper virtual resistance has been implemented in the wind turbine converter control during energization of its transformer. This helps avoid using a pre-insertion resistor during sequential hard-switching and without any loss of fault selectivity as in the soft-start case. However, the brunt of the transient is borne by the wind turbine DC link and thus, rotor-side control is essential for governing the dynamics. Simulation results show that the inrush transients during open
circuit energization of transformer can be reduced similar to using a pre-insertion resistor. Moreover, the sensitivity analysis gives insight into how the virtual resistance value impacts the transients in current/power output and DC/AC voltage of the wind turbine. Additionally, the study on the energization of downstream transformers in a string by a grid forming wind turbine demonstrates that virtual resistance can reduce transient current peak for both best and worst case residual flux. However, it is important to note that worst case residual flux leads to significant sympathetic interaction lasting for a sustained period of time, with virtual resistance effective only in reducing the peak amplitude. Finally at the wind power plant level, the virtual resistance method can also be used to minimize the inrush transient during the large offshore transformer energization. However, protection settings need to be changed to avoid under-voltage trips due to the voltage dip.

ACKNOWLEDGMENT

The authors gratefully acknowledge Asger B. Abrahmsen for discussions leading up to this work.

REFERENCES


This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2022.3159620, IEEE Transactions on Sustainable Energy


APPENDIX A

![Fig. 12: Inrush current characteristic of 8 MVA WTTr during open circuit energization by an ideal 0.69 kV voltage source.](image)

TABLE I: Main circuit parameters of the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT Rating</td>
<td>8 MW</td>
</tr>
<tr>
<td>WTTr</td>
<td>0.69/66 kV, X = 0.1 pu</td>
</tr>
<tr>
<td>WT GSC Filter</td>
<td>( L_f = 10% ), ( C_{f} = 5% )</td>
</tr>
<tr>
<td>WT GSC Switching frequency</td>
<td>2 kHz</td>
</tr>
<tr>
<td>WT DC link</td>
<td>1.45 kV, ( C_{DC} = 30000 \mu F )</td>
</tr>
</tbody>
</table>

TABLE II: Tuned controller values in pu.

<table>
<thead>
<tr>
<th>Scope</th>
<th>Control</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSC</td>
<td>Real power control</td>
<td>PI</td>
<td>0.012, 0.21</td>
</tr>
<tr>
<td></td>
<td>Reactive power control</td>
<td>PI</td>
<td>0.012, 0.21</td>
</tr>
<tr>
<td>RSC</td>
<td>DC voltage control</td>
<td>PI</td>
<td>0.09, 0.92</td>
</tr>
<tr>
<td></td>
<td>Absolute limit</td>
<td>Min, Max.</td>
<td>±1.1</td>
</tr>
<tr>
<td></td>
<td>Power ramp-rate limit</td>
<td>Up, Down</td>
<td>±0.1 s(^{-1})</td>
</tr>
</tbody>
</table>

Oscar Saborio-Romano (S’12) received the BSc (Hons) degree in Electrical Engineering from the University of Costa Rica in 2013. In 2015, he received the MSc degrees in Electrical Engineering and Wind Energy from Delft University of Technology and the Norwegian University of Science and Technology, respectively. He joined the Department of Wind Energy at the Technical University of Denmark, where he completed his PhD degree in 2019 focusing on the integration of wind power plants connected to HVdc via diode rectifiers, and offshore wind, HVdc transmission, power electronics converter control, system ancillary services, and electro-magnetic transient studies.

Jayachandra N. Sakamuri received the MTech degree in Electrical Engineering from the Indian Institute of Technology (Kanpur) in 2009, after spending a year as an exchange student at the Technical University of Berlin in 2008. He obtained his PhD degree in 2017 from the Department of Wind Energy at the Technical University of Denmark, where his work focused on coordinated control of wind farms in offshore HVdc grids. Before the PhD he worked for Grid System R&D, ABB on HVdc System Design for three years and also at Crompton Greaves Ltd. on HV switchgear design. Currently, he works at Vattenfall Windkraft A/S (Kolding, Denmark) as Lead Grid Study Engineer. His research interests include HVdc, offshore wind farm integration and control, and HV switchgear design.

Nicolaos A. Cutululis (SM’18) received the MSc and PhD degrees, both in Automatic Control, in 1998 and 2005, respectively. Currently, he is a professor at the Department of Wind Energy, Technical University of Denmark. His main research interests are grid integration of wind power, with a special focus on offshore wind power, HVdc transmission, control and ancillary services, and electrical infrastructure design and optimization.