The Use of Half-Wavelength Transmission Line to Integrate Large-Scale Wind Power Plant

A. F. N. C. Moro, M. C. Tavares, F. B. Costa

***Abstract*—Wind power generation is a renewable source that has grown in terms of energy generation contribution to electrical power systems in the last few years. In this sense, there is a huge interest in the integration of this kind of source in the electrical network. Once large wind power potential in general is located far way from the load centers, it is important to consider bulk power transmission corridors over long distances. In this work, the wind power integration through the half-wavelength transmission line is evaluated. Electromagnetic transient study is implemented to analyze the characteristics of this system. The results prove the robustness of the half-wavelength transmission alternative.**

***Keywords*—Electromagnetic transient, Half-wavelength transmission line, Wind power plant integration.**

I. Introduction

The world is facing challenges related to global warming and, in this sense, there is a concern about greenhouse gases emission. The energy sector is the source of three-quarters of emissions and this fact boosted the consensus on reaching net zero by 2050 [1]. To accomplish this goal, investments have been addressed in renewable sources of energy, such as wind and photovoltaic power. According to [2], the forecast for global renewable energy capacity expansion is to grow 2400 GW by 2022-2027. Among renewable sources, wind power has increased in contribution to the energy generation scenario. For global wind power capacity, it is expected over 570 GW by 2022-2027. Only in the United States, the wind power capacity increased by 6.4 GW in 2023, bringing the cumulative total to almost 150.5 GW, which represents the second-largest wind power producer in the world [3]. In China, the installed capacity is of 444 GW [4]. Therefore, it is necessary to develop rigorous studies considering large wind power plant integration.

Although the increase of renewable energy sources penetration brings many benefits, there are important aspects that need careful analysis, such as the impact on power system transient stability, small-signal stability, frequency stability, power quality [5], [6], and protection system [7]. The response of the electrical power system with high penetration of generation sources interfaced by converters is very different from those based on synchronous machine generation [8], [9]. In this sense, electromagnetic transient studies are important to analyze the influence of wind power plants on the electrical power system behavior [8].

Wind resources frequently are available far from major load centers. For example, in Brazil, significant wind potential lies in the Northeast region, approximately 2700 km away from large load center located at the South/Southeast. Similarly, in China major wind resources are located approximately 2100 km from main load region, near Shanghai. This geographical distribution underscores the necessity for long-distance power transmission. High Voltage Direct Current (HVDC) transmission lines are widely employed for this purpose, leveraging their well-established technology. The break-even-distance for HVDC technology for onshore transmission is approximately 800 km [10]. For offshore transmission, the break-even distance is approximately 130 km, primarily due to AC transmission losses [11].

Line-Commutated Converter (LCC) HVDC transmission lines are usually applied for long-distance power transmission of wind power generation in remote areas. Nevertheless, when some large HVDC systems attend the same electrical region, the multi-infeed phenomenon may arise, causing simultaneous (or subsequent) commutation failures after an AC-side fault event. In the specific case of wind power plant, commutation failures can affect wind farms causing transient voltage disturbance and critical overvoltages [12]. Besides that, HVDC converters consume an amount of reactive power of approximately half of the transmitted active power, requiring large capacitor banks [13]. Furthermore, the cost of the power electronic terminals is still a drawback when HVDC system substation is compared to HVAC ones [10]. In this sense, the half-wavelength transmission lines can be an alternative resource to mitigate these problems.

The half-wavelength transmission line is an AC link without intermediate substations that has a length of half the wavelength, meaning 2500 km for 60 Hz system and 3000 km for 50 Hz system. Due to the negligible Ferranti effect, no shunt compensation is required in order to remove the terminals' voltage gain [14]. This line has different characteristics when compared to conventional AC long lines, with voltage and current profile along the line that change with the loading level and the power factor [15]. Therefore, the half-wavelength line must be operated as an AC link, in a similar condition to most HVDC transmission lines: a point-to-point transmission in which only active power must be transmitted between the sending and receiving terminals.

At present, there are few works that explore the feasibility of the half-wavelength transmission line to integrate wind

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power plants. In [16], the authors analyzed the integration system to evaluate the characteristics of the system that can cause a resonance. However, the work did not account for the impact of wind power plant start-up or wind speed variation. Similarly, [17] and [18], focused on evaluating the line parameters and the design of a tuned half-wavelength line, respectively. Conversely, this work introduces the integration of a large-scale wind power plant to the electric power system through a half-wavelength transmission line. This is a competitive alternative to HVDC transmission lines that might be considered, mainly because this technology is not a power electronic-based technology, which brings more simplicity and economical advantages. In order to validate the proposed alternative, electromagnetic transient studies were implemented in PSCAD/EMTDC, using high-fidelity models of both the electrical power system and the wind power plant.

The main contributions of this research are significant, as there are few studies focused on evaluating the impact of half-wavelength line energization in the context of wind power as a source. Additionally, this work will analyze the impact of wind speed variation and the occurrence of critical faults. The analysis will assess the half-wavelength line connected to both strong and weak systems. By nature, a half-wavelength line is considered a weak system since the short-circuit ratio (SCR) is lower, and changes in the equivalent system parameters have a limited impact on the SCR. However, this research will demonstrate that the system response differs when the equivalent system is modified. Moreover, the contributions of this work include the development of an alternative method for integrating wind power plants into electrical power systems and demonstrating the feasibility of half-wavelength transmission lines as a wind power plant corridor.

II. Half-Wavelength Transmission Line Main Characteristics

The steady-state condition for a balanced three-phase system can be represented using two-port network theory. The voltage and current (positive sequence) is calculated by:

$$\begin{bmatrix}\hat{V}_L\\ \hat{I}_L\end{bmatrix} = \begin{bmatrix}\cosh(\bar{\gamma}\cdot l) & -\bar{Z}_C\sinh(\bar{\gamma}\cdot l)\\ -\frac{\sinh(\bar{\gamma}\cdot l)}{\bar{Z}_C} & cosh(\bar{\gamma}\cdot l)\end{bmatrix}\cdot\begin{bmatrix}\hat{V}_R\\ \hat{I}_R\end{bmatrix} \quad (1)$$

where l is the distance from the local end, γ is the positive-sequence propagation constant, $\bar{Z}_C$ is the positive-sequence characteristic impedance, the subscript term L means variable of the local end and the subscript term R means variable of the remote end.

Considering the receiving end is open, $\hat{I}_R = 0$ and $\hat{V}_R \neq 0$, for the half-wavelength line with length $= \lambda/2$, the relation between $\hat{V}_R$ and $\hat{V}_S$ is given by:

$$|\frac{\hat{V}_R}{\hat{V}_L}| \approx 1 \quad (2)$$

From (2), there is a voltage unity gain for the half-wavelength line. Even for lines with losses, the gain remains very close to the unity, which means that there is no significant Ferranti effect [14]. Therefore, no shunt compensation is required at line terminals.

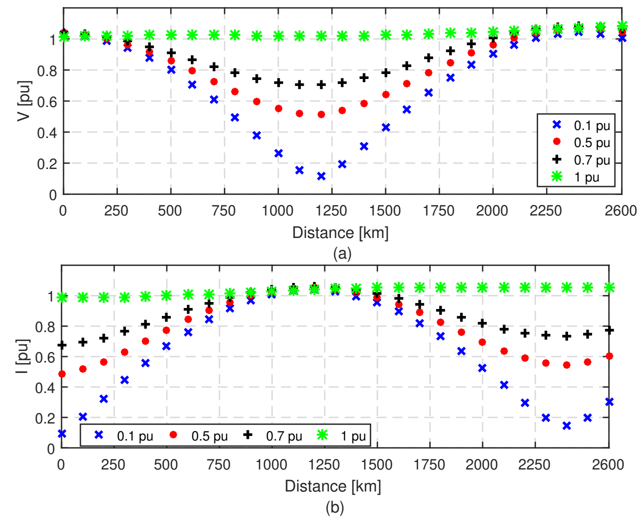

Fig. 1. Voltage (a) and current (b) profile of a half-wavelength transmission line for f = 60 Hz.

Fig. 1 introduces the voltage and the current profile of a 2600 km-long half-wavelength line with different loading levels (0.1, 0.5, 0.7 and 1 pu) considering a unitary power factor for a 60 Hz system. In the central region, the voltage is proportional to the loading level. For instance, if the half-wavelength line is loaded with 0.5 pu, its voltage in the central region will be close to 0.5 pu. In Fig. 1 (a), where the 0 km corresponds to the remote terminal, this relation is properly shown. On the other hand, if the line is loaded with very low power, the current in the central region is almost a nominal current, as shown in Fig. 1 (b), while voltage reaches very low values. This voltage characteristic at the terminals is attractive for integrating intermittent sources, such as wind power, because there is no need for reactive compensation to keep the voltage at adequate range.

The half-wavelength line must be operated as an AC link, in a similar condition to HVDC: a point-to-point transmission where only active power must be transmitted between the terminals. The maximum active power is shown in Fig. 1, and it is not appropriate to transfer reactive power through the very long AC link. Therefore, the optimal point to operate the half-wavelength line is close to its SIL (surge impedance loading), limited to 120% of the line capacity due to the voltage response at the middle of the HWL line, and its power factor is close to 1.

III. Test System

The test system is composed of a wind power plant and a half-wavelength transmission line based on [19], [20], and the system details are shown in Fig. 2. Fig. 3 presents the details of the wind turbine electromechanical system and control. The Point of Common Coupling (PCC) is at the local terminal of the line. The transmission line has a natural power of 4800 MVA and the power frequency is 60 Hz. For the wind power plant, the simulated cases consider the wind speed, the loading level variations and the response of the system for faults. The results of these simulations provide

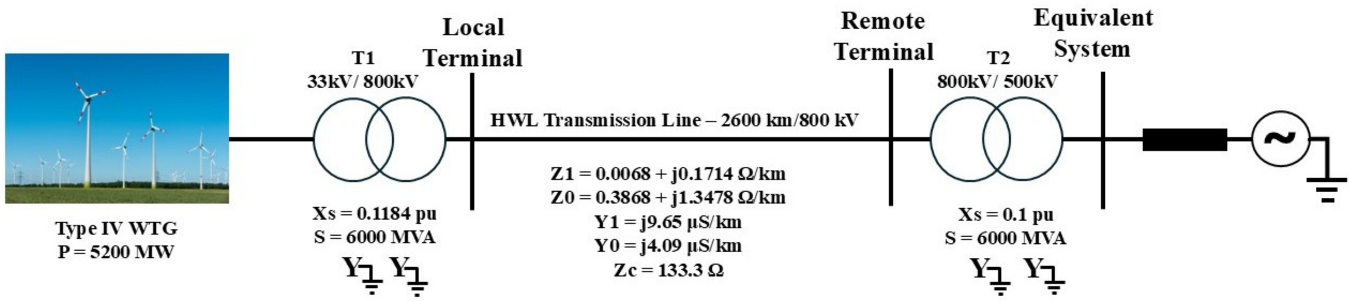

Fig. 2. AC Test system.

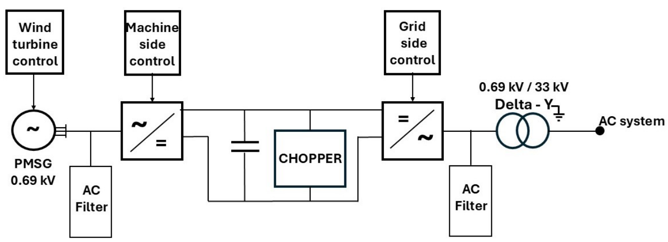

Fig. 3. Wind power plant electromechanical system.

TABLE I
MAIN VALUES OF THE WIND POWER PLANT.

Variable	Value
Unitary Nominal Active Power (WTG)	2 MW
Number of WTG	2600
Terminal WTG Voltage	0.69 kV
Nominal Wind Speed	10 m/s

information about the control influences the line voltage and current and how the reactive power must be controlled to attend to half-wavelength line characteristics.

A. Wind Power Plant

The wind power plant is composed of a type IV wind turbine generator, a full-converter system, which consists of a permanent magnet generator (PMSG) [21]. The mechanical power extracted by the wind turbines are modeled by considering the wind and pitch controller. The mechanical power is calculated as follows:

$$P = \frac{\rho}{2} \times A_r \times V_w^3 \times C_p(\Lambda, \theta) \tag{3}$$

where P is the mechanical power (W), ρ is the air density in $\frac{kg}{m^3}$, A_r is area swept by the blades in m^2, V_w is the wind speed in $\frac{m}{s}$, Λ is a constant that represents the tip speed ratio, θ is the pitch angle, and C_p is the power coefficient, which is function of Λ and θ. Therefore, the calculated power serves as a reference for the converter controllers.

The converter is a back-to-back type and consists of: a grid-side converter and a controller; a machine-side converter and a controler; a DC-link chopper; low-pass filters; and a scalling component to represent an aggregated wind farm. The low-pass filter is applied on AC sides to reduce the impact of the harmonics on the grid. The Chopper is used to avoid overvoltages at the capacitor in the DC-link during fault conditions. Both converters operate as voltage-source converters. The model is fully detailed in [22] and some variables are shown in Table I. The transmitted power is 8.3% greater than the line SIL.

The control strategy is a grid-following inverter-based which is mature and its anti-disturbance capability is strong [23]. For this reason, the grid voltage is used as a reference. Therefore, the output is generated based on the system conditions and the control scheme, and dynamic behavior must be considered. The grid-side controller and the machine-side controller have the same interface and the main differences are the values of some parameters and the purpose. The grid-side controller is used to regulate the DC and AC voltage, while the machine-side controller regulates the active power and the AC voltage at the PMSG terminal.

The current and voltage are per-unitized and transformed to dq-axis for a decoupled control. The control of current production by the grid-side converter allows for adjusting the power flow between the generating unit and the electrical grid. To control the converter's output current, it is necessary to act on the three-phase voltage generated at the converter's output by adjusting its amplitude and angle. The grid-side controller is able to inject reactive power during faults to guarantee voltage stability.

The machine-side controller remained with the same parameters as the model. The reactive power parameter in the grid-side converter was adapted to keep reactive power transferred through the half-wavelength line in very low level.

B. Equivalent System

The equivalent system was designed to have different short-circuit levels at the 500 kV system, representing the strength of the system. Table II presents the calculated values considered, namely for a strong and a weak equivalent system. As the half-wavelength transmission line is very long, there is a minor difference in the SCR for both equivalent system scenarios, as shown in Table III. These values characterize the half-wavelength line system as a weak grid [24].

It is a challenge to synchronize the wind power plant phase locked-loop (PLL) with a weak grid in case of nearby faults [25]. However, the half-wavelength transmission line operates as a short line, in the third quadrant of the $P-\delta$

TABLE II
VALUES OF THE EQUIVALENT IMPEDANCE SYSTEM.

	S_{sc} (MVA)	X_{1th} (Ω)	R_{1th} (Ω)
I_{sc} = 40 kA	34,611	7.125	1.186
I_{sc} = 20 kA	17,078	14.44	2.410

TABLE III
VALUES OF THE EQUIVALENT SYSTEM CONNECTED AT THE PCC.

	S_{sc} (MVA)	SCR
I_{sc} = 40 kA	9025	1.74
I_{sc} = 20 kA	8689	1.67

curve [26], eliminating this condition. Therefore, an important contribution of this paper is to show the good performance of the wind power plant into the electric power system through a half-wavelength line corridor.

IV. Performance Assessment

To validate and characterize the wind power plant integration, the challenging simulation scenarios were selected: Wind power plant start-up, transient faults and wind speed variation. The reactive power used in the control strategy was limited from -0.05 pu to 0.05 pu, where the pu base is calculated by considering the reactive power at the turbine output and the nominal power of the wind power plant.

This section explores the worst-case scenarios to analyze system response and feasibility. In this context, two critical cases are addressed: a three-phase fault with low fault resistance and a 50% variation in wind speed (both an increase and a decrease). All these challenging scenarios will consider both strong and weak equivalent systems.

A. Scenario 1: Start-up of the Wind Power Plant Case

The first analyzed scenario is the start-up case. This simulation is important mainly to evaluate the overvoltages that can occur due the power plant integration. The result can indicate the need for overvoltage mitigation method or control adjustments. In this case, the entire amount of power is connected at the same time to test the robustness of the system and whether the line will not be subjected to very large overvoltages. The grid side converter and the wind turbines are deblocked in 0.1 s and 0.2 s, respectively, after the simulation begins. Then, after 0.5 s the machine side converter is deblocked, totaling 0.6 s to start the connection procedure. The simulation considered the nominal wind speed and both equivalent systems presented in Table II.

Fig. 4 presents voltage and current behavior at the PCC for both equivalent systems. Fig. 4(a) and (b) are the instantaneous voltage for 40 kA and 20 kA equivalent system, respectively. The transient overvoltages are rather small, below 1.5 pu, and promptly the 2600 km long AC line is under steady-state.

Regarding the local terminal current, in Fig. 4 (c) and (d), the values remained close to 1 pu as well. Fig. 4 (e) and (f) present the maximum voltage along the line during the connection procedure. The values do not surpass 1.6 pu and the result is approximately equal to the obtained results for the energization of half-wavelength line connected to conventional synchronous generator systems [27]. This behavior is explained by the significant attenuation of the traveling waves due to the length of the half-wavelength line [28].

Fig. 5 presents the RMS voltage and current at the remote terminal, the power factor at the PCC and the source frequency. At the steady state condition, considering the system under nominal speed condition, the RMS voltage and current are close to 1 pu for the both equivalent system condition. The power factor is close to 0.98, which is an appropriate condition to operate the half-wavelength transmission line.

B. Scenario 2: Fault at the Secondary of Transformer T2

The second simulation scenario considered a three-phase fault at the secondary of the transformer T2 with a fault resistance of 0.01 Ω. The fault begins at 2 s and its duration is 100 ms.

Fault response in systems interfaced by inverters, such as wind power plants, differs from that of systems with synchronous generators [29], [30]. The fault response is determined by the applied control strategy. Whether the fault is symmetrical or unsymmetrical, the type IV wind turbine injects only symmetrical currents. However, this type of turbine can provide negative and zero-sequence currents if necessary. [31]. The type IV wind turbine can operate as a Static Synchronous Compensator (STATCOM), injecting or absorbing reactive power to or from the grid [31]. This capability is useful for providing voltage stability to grids connected to wind power plants. For instance, some European grid codes require reactive current contribution during under- or overvoltage conditions to ensure dynamic voltage stability [32].

The importance of the second scenario lies in evaluating the occurrence of overvoltages caused by a critical fault in the secondary of transformer T2. This location was chosen because it is the closest point of the 500 kV system to the half-wavelength line. Additionally, the objective is to analyze the system's robustness in maintaining stability and synchronization after fault clearance. Even though the half-wavelength transmission line should not transmit reactive power under normal operation, it must support this process to ensure voltage stability.

Fig. 6 presents the results for the instantaneous voltage and current measured at the PCC and the voltage measured along the line for both equivalent systems. Fig. 7 presents the RMS voltage and the RMS current measured at the remote terminal, the reactive power at the wind power plant output and the frequency of the system.

During the beginning of the fault, the voltage had low values, for both equivalent system cases. According to Fig. 7, there is a frequency disturbance, which causes an injection of reactive power. This injection provokes overvoltage at the PCC, not surpassing 1.2 pu in the interval between 2 s and 2.1 s. For current, the reactive power injection causes

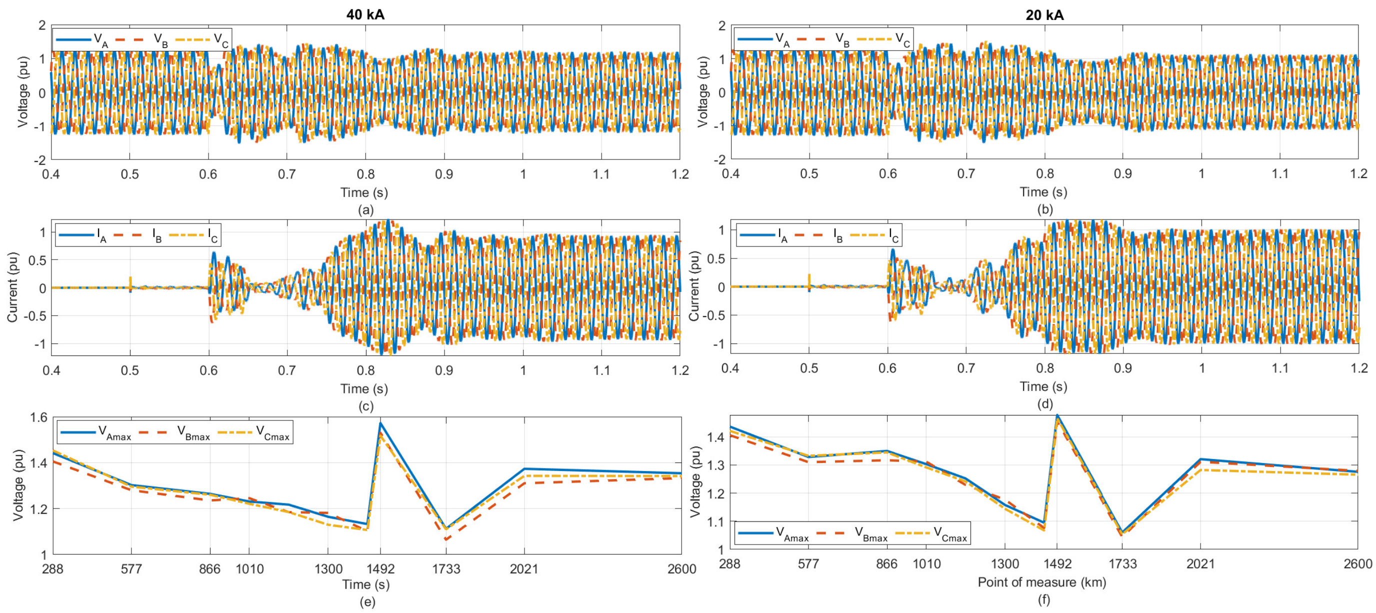

Fig. 4. Wind power plant start-up case at PCC: 40 kA - Instantaneous voltage (a), instantaneous current (c) and Maximum voltage along the line (e); 20 kA - Instantaneous voltage (b), instantaneous current (d) and maximum voltage along the line (f).

a reduction in the values for both systems. When the fault is cleared, initially, the voltage presented a peak of 1.8 pu and the current presented a peak of almost 1.3 pu, as seen in Fig 6 (a) and (c). The voltage and current values for the equivalent system with $I_{SC} = 40$ kA is quite near the steady state values, and the system returns to normal conditions in approximately 300 ms. The RMS voltage and RMS current values at the remote terminal, as indicated in Fig. 7(a) and (b) respectively, also reflect normal operating conditions, illustrating the control efficiency for the strong equivalent system.

Nonetheless, for the weak equivalent system scenario, there was a larger reactive power injection, which probably was

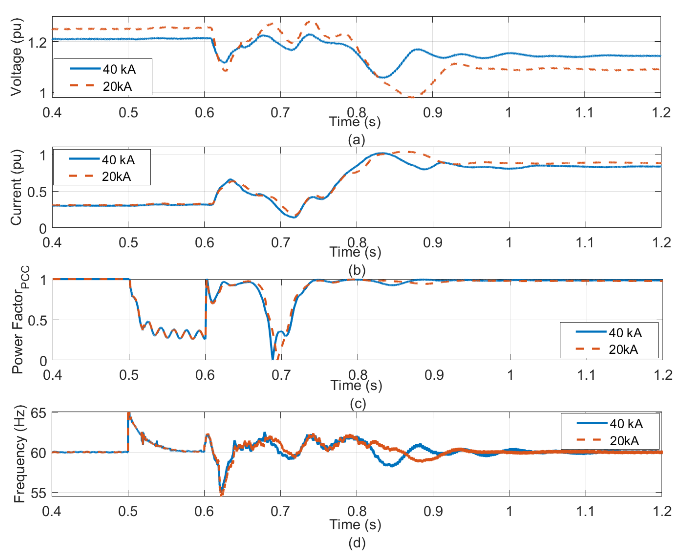

Fig. 5. Wind power plant start-up case: RMS Voltage (a) and RMS Current (b) at the remote terminal; the power factor (c) at the PCC, and the system frequency (d).

the reason why the frequency was not able to restore. In this case the system lost stability, preventing the use of the half-wavelength line as a wind power plant transmission corridor for a very low SCR system.

The present analysis highlights the importance of considering the half-wavelength lines for integrating wind power plant. The HVDC transmission lines are prone to commutation failures, which can be triggered by disturbances on the AC side of the HVDC system. Such failures could lead to interruptions in power transmission. In a multi-infeed scheme, a commutation failure can cause interactions between inverters, leading to failures in each bipole. In this sense, half-wavelength transmission line could contribute to reliability in systems with a large number of HVDC transmission lines converging in the same electrical region.

C. Scenario 3 - Wind Speed Variation

Since wind power is an intermittent source, the third scenario was simulated to evaluate the behavior of the half-wavelength line under wind speed variation. One of the main advantages of the half-wavelength line is its ability to maintain the terminal voltages close to 1 pu without compensation, even when the transmitted power is below 1 pu. Therefore, Fig. 8 presents the wind speed variation, the PLL frequency, the RMS voltage at the PCC and at the remote terminal, and active power at the PCC.

The nominal speed to generate the nominal power is 10 m/s. When the speed increases, there is no change in active or reactive power, and consequently the voltage keeps still. Reducing the wind speed causes a decrease in PLL frequency, followed by overvoltage at the PCC. When operating below nominal speed the voltage at the PCC goes above nominal value. Nevertheless, even with low levels of active power in the half-wavelength line, the voltage at remote terminal

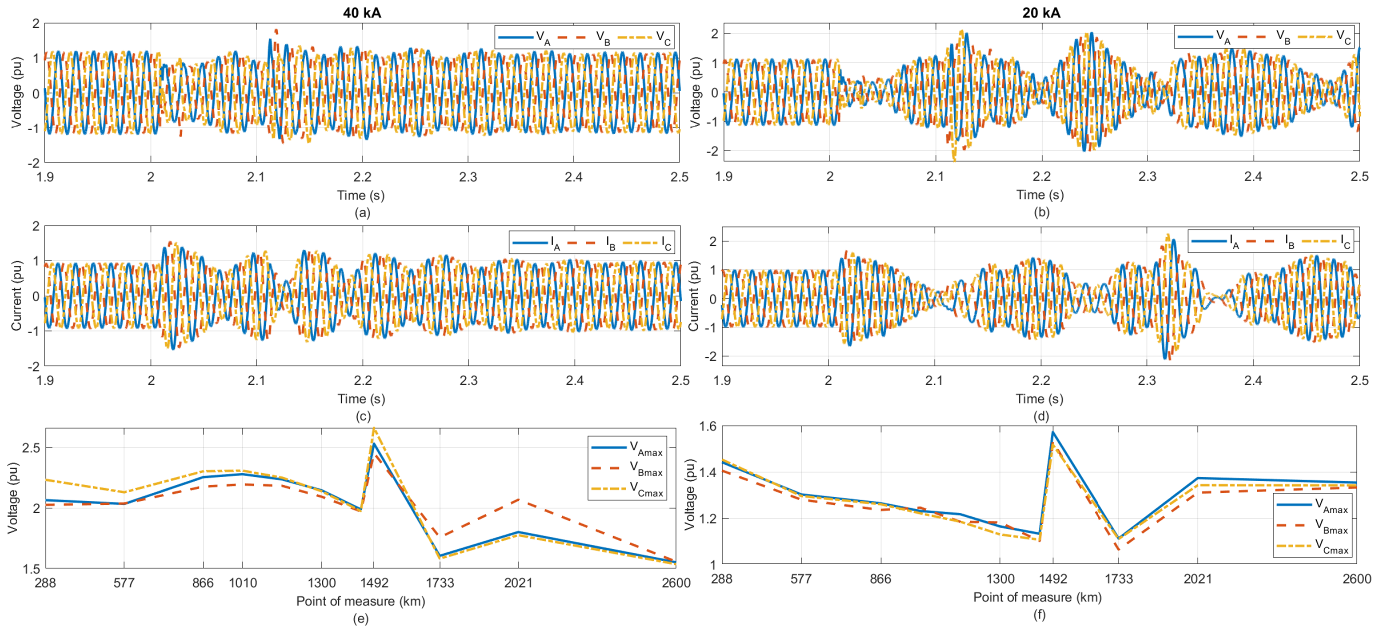

Fig. 6. Fault at the secondary of transformer T2 case - Measurement at PCC: 40 kA - Instantaneous voltage (a), instantaneous current (c) and Maximum voltage along the line (e); 20 kA - Instantaneous voltage (b), instantaneous current (d) and maximum voltage along the line (f).

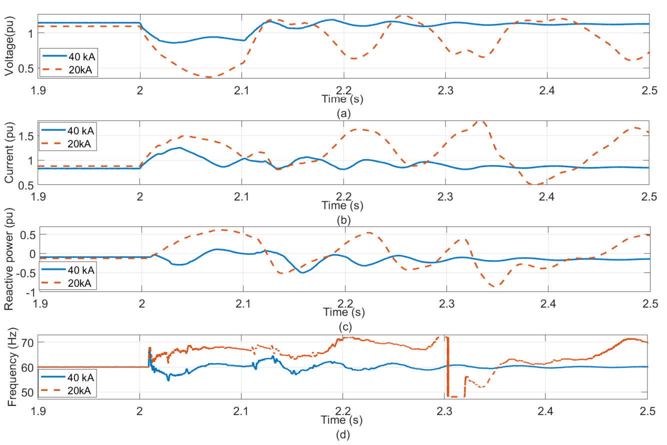

Fig. 7. Fault at the secondary of transformer T2 case: RMS Voltage (a) and RMS Current (b) at the remote terminal; Reactive power (c) at the output of the inverter, and the system frequency (d).

follows PCC voltage. Any further adjustment can be solved with control adjustment.

For all these wind variations, there were no severe overvoltages along the line. The performance was similar for both equivalent systems.

V. Conclusion

The half-wavelength line has specific characteristics that makes it an adequate alternative for bulk power transmission over long distances. Considering that the wind potential can be located far away from load centers, this study intends to prove that the half-wavelength transmission line can be a feasible alternative to inverter-based source transmission corridor.

The challenge of integrating wind power lies primarily in its intermittency and the distance between the power plant and the load center, which may require a long transmission system with a low short-circuit ratio (SCR) in some scenarios. This can result in voltage fluctuations and difficulties in system recovery after a fault event. Furthermore, another significant challenge, particularly when integration involves a High-Voltage Direct Current (HVDC) transmission line, is the risk of commutation failure due a fault, which could lead to the line corridor outage. For this reason, the simulated scenarios accounted for all these critical situations.

The assumption that an AC long line could not attend a wind power plant does not come true for the half-wavelength line, that has an extremely long length, but responds as a short line. Taking advantage of the half-wavelength line properties, the wind power plant could stand severe fault conditions at the AC side when connected to the strong equivalent system. For both strong and weak systems, the wind power plant had regular response during normal operation condition and also for different wind speed.

The control implemented was the grid-following and, despite some oscillations, the half-wavelength line presented a stable operation. Furthermore, the start-up procedure, the fault at the secondary side of T2, or the wind speed variation did not cause severe overvoltages along the line.

Future works should analyze the application of tuned half-wavelength line, with lengths around 1500 km, to wind power plants. Comparison performance with HVDC was out-of-the scope of this paper, and a comprehensive comparison is proposed as future work. Another important analysis is the identification of scenarios that could potentially cause resonance. This phenomenon can lead to high overvoltages in the half-wavelength transmission line, compromising its integrity. Furthermore, SCR and reactive power provision limits for half-wavelength transmission lines integrating wind power plants need to be established to ensure

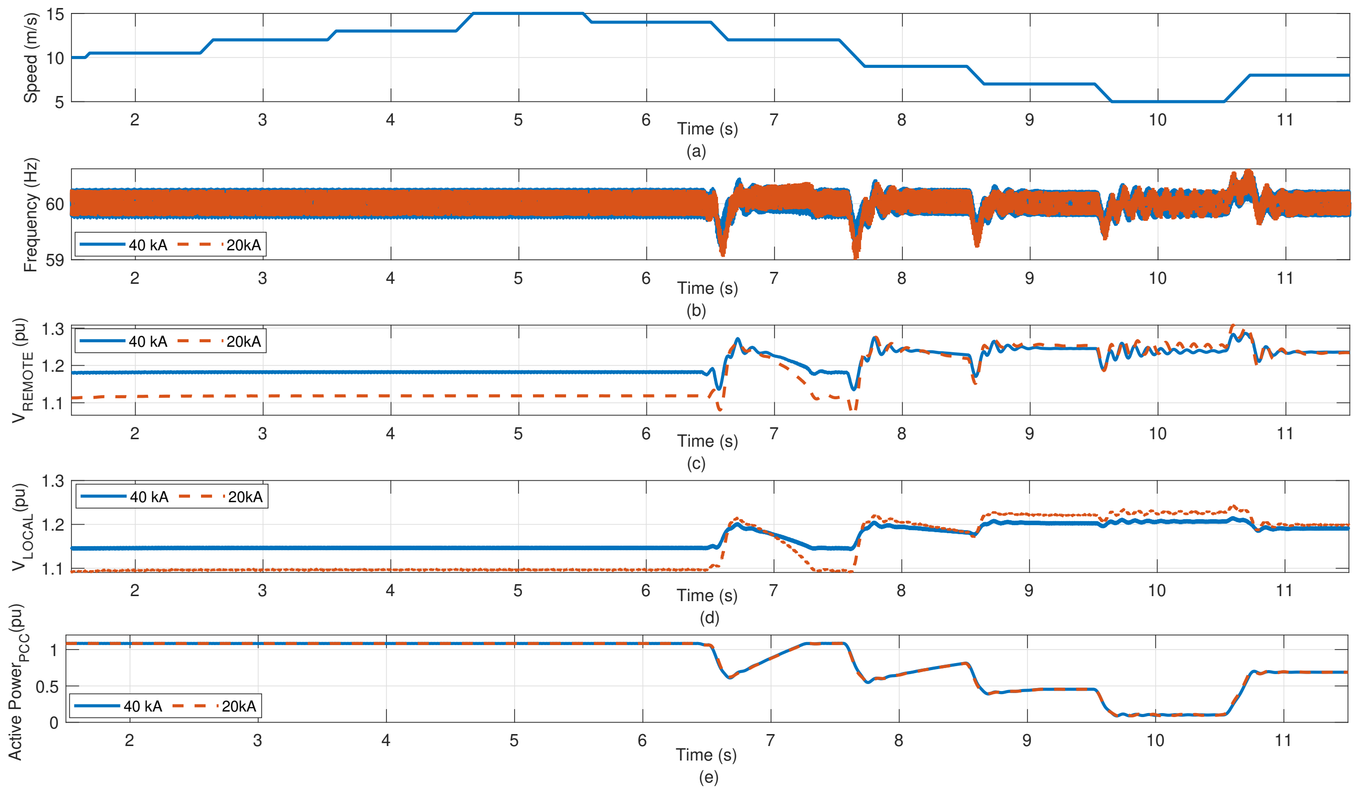

Fig. 8. Wind speed variation case: RMS voltage (a) and current (b) measured at the PCC, wind speed (c) and voltage along the half-wavelength line.

line stability and identify scenarios in which this system cannot operate.

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