Efficient Utilization of Offshore Wind Energy Generation and Transmission during Normal Speed and Wind Gust through Pitch Control and HVDC Lines

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Abstract:

The range of offshore wind speed variation is higher than onshore with high frequent of wind gusts. This paper propose an efficient utilization system for offshore wind energy generation and transmission to the power grid. Pitch controlled wind turbines are modelled and pitch controller is developed to track the available wind power and to keep the generated power at its maximum even during wind gust incidence. Secondly, for transmission of the generated wind power to the grid, voltage-source converter (VSC) stations with High voltage direct current (HVDC) technology is used to minimize the transmission losses. The results shows that the proposed pitch controller is stable and capable to capture the maximum wind power. Also the proposed scheme ((VSC-HVDC-VSC) succeeds to export the active power generated in offshore wind farm to the grid using four quadrants PWM-VSC converter by controlling the DC voltage.

Keywords: Wind energy, offshore wind farms, Pitch control, HVDC transmission, VSC

1.   Introduction:

Currently most of the onshore wind farms nearly connected with the public grid substations through AC cable. In future, the offshore wind energy conversion will be increased as the offshore wind speed is generally higher than onshore speed and the available sites for feasible onshore wind farms will be decreased [1]. On the other side, the offshore wind speed has a wide range of variation and air over water can be gusty. Consequently, the off shore wind farms have to be designed to track the maximum power under normal speed and wind gust. The generated power from offshore wind farm is generally transported over long distances by submarine cables to the onshore public grid. The alternating current (AC) submarine cables suffer generally from high capacitive currents and consequently high conductor as well as dielectric losses. In addition, the intermittent nature of wind speed and then the corresponding power generated would result in a relatively low capacity factor of the transmission. Therefore, HVDC transmissions are more feasible than the traditional HVAC for offshore wind energy transmission with minimal losses [2, 3].

Efficient HVDC transmission requires two converter stations voltage source converters (VSC). Thereby, the active power exchange can be controlled by adjusting the phase angle of the VSC voltage, where reactive power control by adjusting the magnitude of VSC voltage independent of the HVDC power transmission [4]. Recently, the wind turbine speed is controlled such that it should the maximum amount of power from the wind farm. This requires establishing of grid codes for power control, power quality, system stability, emergency tripping and fault ride-through capability (LVRT). To achieve these codes, the wind turbine assumed to employ pitch angle controller to adjust electrical power produced by the generator according to the available wind power. The pitch control used to optimize the power production under high, medium, low wind as well as emergency conditions. Also during the wind gust, the mechanical power can be reduced by pitching turbine blades when the shaft speed increases above its limit [5-6]. The main objectives of this paper are maximum utilization of wind energy during normal speed and wind gust conditions using pitch controller and also efficient

transmission using HVDC technology for transmitting the generated power from offshore wind farm to the public grid. This target is achieved in two stages, first stage is to design a pitch angle controller to track the MPP of the off shore wind turbines for different wind speeds; while in the second stage the generated power is transmitted with minimum losses by HVDC lines.

2.   Studied power system

The single-line diagram of the studied power system is displayed in Fig. (1). It consists of offshore wind farm containing fixed-speed induction-generator wind turbines with pitch control. The wind farm is modeled as an aggregated system. A submarine cable of length 150 km connected the offshore wind farm with the onshore system. For the VSC-HVDC converters, PWM modulation is implemented with a switching frequency of 2 kHz and a 7000 μF capacitor used in the DC link. The used AC harmonic filter eliminates or reduces the high order harmonic generated in the converters. The studied wind farm represents a part of an existing system in Suez Gulf area, Egypt with typical manufacturer turbines technical data with the electrical parameters of the associated feeders. It consists of three subsystems with medium voltage 22 kV feeders and each subsystem contains sixteen 660 kW wind turbines low voltage network (690V).The wind turbines are located in four rows and the wind speed for each row is recorded. The turbines are equipped with pitch controller and has a step up transformer with 800 KVA capacity and voltage ratio of 690V/22kV. The average wind speed in the site is 10 m/sec measured at 40 m above ground level.

A. Wind Turbine Modeling:
Fixed-speed turbines using self-excited squirrel cage induction generators (SEIG) have low-cost, robust, reliable operation and are simple to maintain [7]. A large number of fixed-speed wind turbines were installed over the past two decade. In future, more fixed speed turbines continue to be installed in parallel with variable speed turbines. Thus in this study Fixed-speed turbines with (SEIG) is used. The available wind power Pw in blades swept area, A, is given by:

$$P_w = \frac{1}{2}\rho A V_w^3 \qquad (1)$$

Where, ρ is the density of air and V_w is the wind velocity m/s. It should be noted that the turbine can capture only a fraction of this wind power, which can be expressed as Pm, given by

$$P_m = \frac{1}{2}\rho A V_w^3 \text{Cp}(\lambda, \beta) = P_w \text{Cp}(\lambda, \beta) \qquad (2)$$

Where, Cp is the power coefficient, which represents the fraction of the wind power captured by the turbine. The maximum theoretical power extracted by an ideal wind turbine under ideal conditions is limited to 59.26% of the power available in the wind [7]. This limit is known as the Betz limit. The power coefficient $C_p(\lambda, \beta)$ of equation (2) is expressed as a function of tip speed ratio λ and pitch angle β. Any change in the rotor speed and/or wind speed results in a change in tip speed ratio change leading to new operating point on the power curves for various speeds and pitch angles [8, 9]. For rated wind speed, the generating power equals the nominal power of the turbine. If the wind speed continues to increase the output power will be theoretically increased, which can damage the turbine. By turbine over-speed protection, the turbine will shut down if the speed exceeds its maximum permissible value.
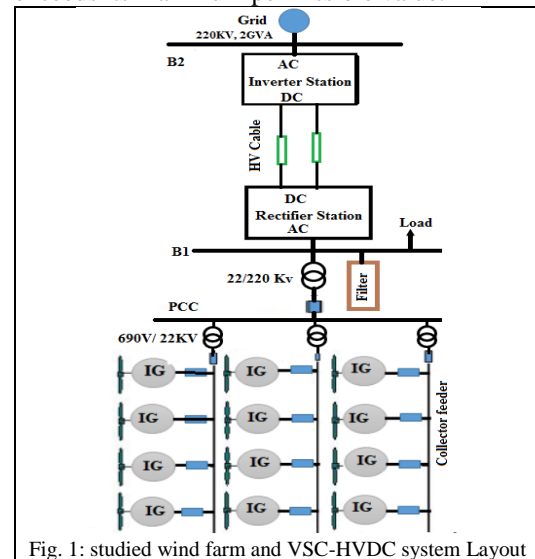

Fig. 1: studied wind farm and VSC-HVDC system Layout

B. Modeling of HVDC Transmission System:
In this study, two converter stations separated by two HVDC cables. Theoretically, the ground current is zero in this configuration since normally both poles operate with equal current. The main advantage of this configuration is reliable operation as one of the conductors can continue to transmit the wind power in case the other one is in its outage state. Thus, the two poles may be used independently, if both neutral points of converter stations are grounded.
One of the VSC-stations works as rectifier, while the other works as an inverter. Two-level VSC defined as the three phase, two level, six-pulse bridge, is the simplest configuration suitable for HVDC transmission. Such a converter consists of six valves with anti-parallel diodes and is capable of generating two voltage levels -0.5 VDC and

+0.5 VDC. A transformer is used to interconnect the VSC with the AC network of the wind farm. The transformer impedance has a value of R and L. The main circuit of a three-phase AC-DC voltage source converter is shown in Fig. (2). If a balanced three-phase, system with neutral connection is assumed and neglecting the resistance r of the switches, the voltage source converter can be modeled by using equations:

$$C\frac{dv_{dc}}{dt} = \sum_{k=1}^{3} i_k D_k - i_{dc} \qquad (3)$$

$$L\frac{di_k}{dt} + Ri_k = e_k - v_{dc}(D_k - \frac{1}{3}\sum_{n=1}^{3} D_k) \qquad (4)$$

Where; k , represents the index for the three-phase; D_k represents the duty cycle; e_k represents the phase voltage; i_k represents the phase current; v_{dc} represents the DC-link voltage; i_{dc} represents the DC current; L represents the inductance of the phase reactor; R represents the phase resistance [6]. Expressing the balanced 3-phase system in d-q reference and neglecting the switching losses the input active and reactive power input to the SVC are given by:

$$P_{in} = \frac{3}{2}(V_d I_d + V_q I_q) = V_{dc} I_{dc} \qquad (5)$$
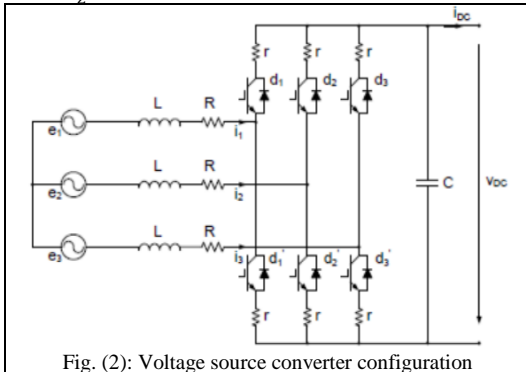
$$Q_{in} = \frac{3}{2}(V_q I_d - V_d I_q) \qquad (6)$$

Fig. (2): Voltage source converter configuration

3. Proposed control scheme:

The proposed scheme target is to capture MPP from the offshore turbines and efficiently transmitting this power to the grid.

A. Proposed Pitch Control for maximum utilization of offshore wind Power Generation

The wind turbines usually employ pitch control to rotate the blades on a longitudinal axis to turn out/into the available wind. In addition, pitch control is a very important to avoid damage to the wind turbine at very high wind speeds. In low to medium wind speeds, the pitch angle is controlled to adjust the wind turbine power to its maximum value according to the available wind power as expressed in eqn. (2). While, in high wind speed region, the pitch angle is changed to shed the

excess aerodynamic power [10, 11]. The proposed model of pitch control is shown in Fig. (3), where the reference power and actual power are compared and the error drives the PID controller. PID controller outputs are summed and hard-limited to generate the pitch angle signal. The change of the pitch angle is limited by rate limiter as most pitch actuators cannot change the pitch angle more than a particular degrees /sec. The value used for the rate limiter in this paper is 5° / sec. The parameters of the PID controller is tuned using the Zeigler-Nicholas rules.
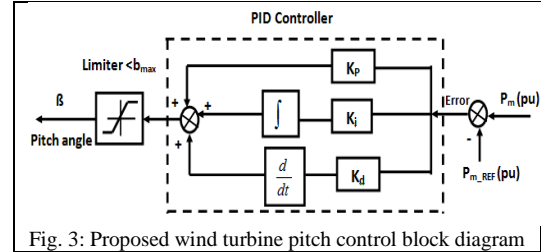

Fig. 3: Proposed wind turbine pitch control block diagram

B. Proposed Control of SVC Stations for efficient transmission of wind energy:

The proposed overall control structure for the VSC-based HVDC system is displayed in Figures (4.a and 4.b). The offshore VSC controller regulates the generated active power and maintain voltage magnitude (or reactive power), while the on-shore VSC controller regulates the DC voltage and maintain the AC voltage magnitude (or reactive power). This control scheme of the VSC allows the converter operation in the four quadrants. By this way, active and reactive power can be compensated under different operation conditions [12-14]. It should be noted that active power exported from the offshore wind farm should equal the active power supplied to the A.C. grid, otherwise the D.C. voltage in the HVDC system will rapidly change. Therefore, one of the converters must always control the D.C. voltage to achieve power balance. The other converter can set any active power value within the limits for the system.

The rectifier station illustrated in Fig. (4.a) consists of antialiasing filter with cut off frequency of 2000 Hz, discrete VSC controller in addition to PLL and Clark transformation devices. Generally, the rectifier station operation is based on power control mode. At this mode, the outer loop controls active power drawn from the wind farm and the reactive power is also compensated to regulate the ac grid voltage. The controller includes also the inner current control loop and DC voltage control. It should be noted that active power is controlled by d axis current, while

the reactive power is controlled by q axis current assuming that v_{dc} is a constant. In the implemented PWM, the Inverter modulation index (m) relates the A.C. voltage (V_{ac}) with the DC voltage of the (V_{dc}) as follows:

$$V_{Ac} = \frac{mV_{dc}}{\sqrt{2}} \qquad (7)$$

The inverter controller presented in Fig. (4.b) includes also two control loops. The outer control loop is dc-link voltage control, where this voltage is measured, compared with its reference value. The inverter station can also compensate reactive power to the grid. The inner control loops are the cross-decoupled d, q current control loops through decoupled dq control techniques.

Both station controllers are based on typical PI controllers and their proportional gain Kp and the integral gain Ki have to be determined by trial and error to obtain the best results. The inverter station consists also of AC bus filter, coupling transformers [15].

(a)

(b)

Figure (4): VSC-HVDC Control structure a) Rectification and b) Inverter

4. Simulation results:

To validate the proposed pitch control technique for tracking MPP and the VSC-based HVDC transmission with minimum losses, MATLAB/Simulink simulations are performed under normal wind speed and wind gust conditions. The behavior of the proposed pitch-control scheme under wind gust is shown in Figure (5). The maximum wind speed reaches a value of 18.5 m/s and minimum value of 9.6 m/s as shown in Fig. (5.a). For such case, the rotor wind speed is kept between the specified limits of 0.95 and 1.05 pu under different wind speeds using the proposed pitch control, Fig. (5.b). Moreover, Fig. (5c) displays the variation of the pitch angle during the simulation period. The pitch angle is changed between 0 and 43° to keep the generated power to its maximum level at the wind gust conditions. It can be noted that the wind farm is stable with the pitch control as shown Fig. (5.b and 5.c). Other sides, without pitch control the rotor speed exceeded 1.6 pu, which results in tripping of the farm by the installed over-speed protection devices as shown in Fig. (5c).

For the minimum losses transmission with constant dc voltage scheme results, the active and reactive powers generated by the wind farms are displayed in Figure (6). The reactive power at the wind farm side has initially, fast transients followed by damped oscillation with noticeable reduction at the instant of the maximum wind speed. The negative sign of the reactive power is coming from the fact that the induction generators of the wind farms require capacitive reactive power for excitation. The reactive power in both VSC-HVDC stations is controlled independently to adjust their voltage magnitudes. It should also be noted that the DC voltage in Fig. (7.a) is kept constant during the simulation. This is attributed to the efficient stations control scheme. In addition, the transmitted active power along the HVDC line is displayed in Fig. (7.b). The amount of the power produced by the wind farm is greater than the power received by the public grid due to the local loads in wind farm side. The grid side reactive power remains unchanged because there is no exchange of reactive power in HVDC transmission.

The controller performance at the rectifier station is tested and the response of i_q and i_d current components are drawn in Fig. (8). From this figure, it can be noticed that both current signals are tracking their reference values. The current signals have initial transients and are settling fast to their final values. Similarly, the controller performance at the inverter station is displayed in
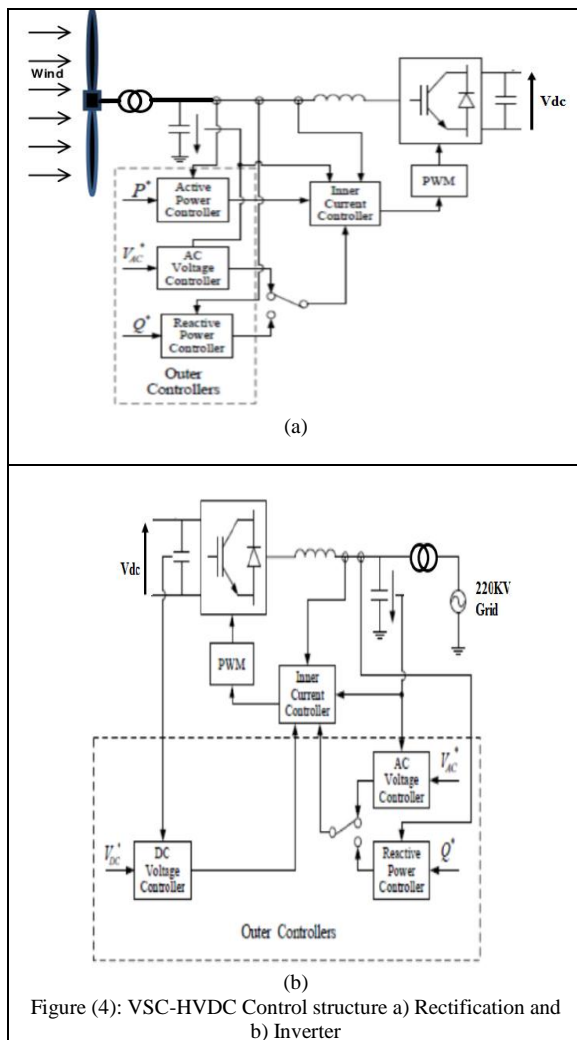
Fig. (9) and the corresponding current signals are also tracking their reference values. The signals are settled to their final values and have 60 Hz at PCC and B1, while at B2 they have 50 Hz frequency. Therefore, new synchronization with the grid cannot result in any difference in the power transfer from the 60 Hz offshore wind farm to the public grid.
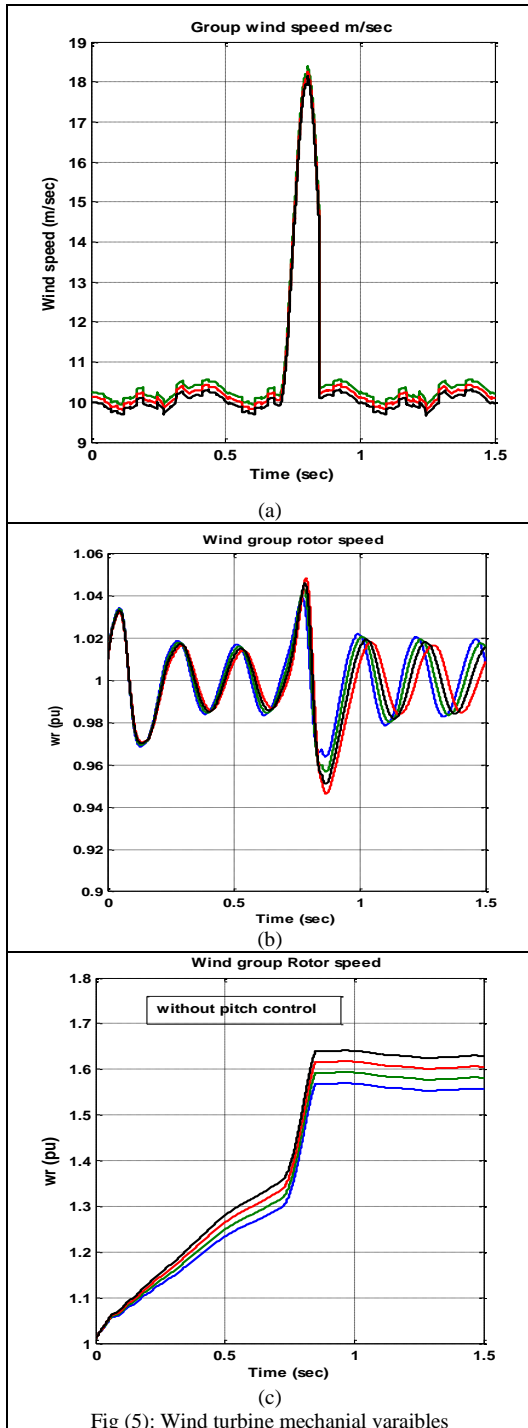

(a)

(b)

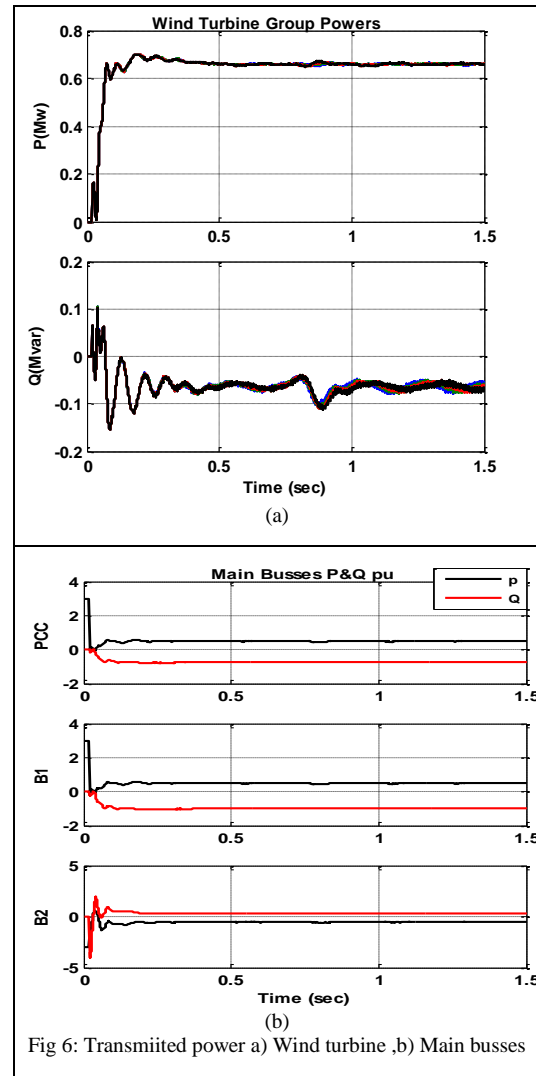Fig (5): Wind turbine mechanial varaibles

(a)

(b)

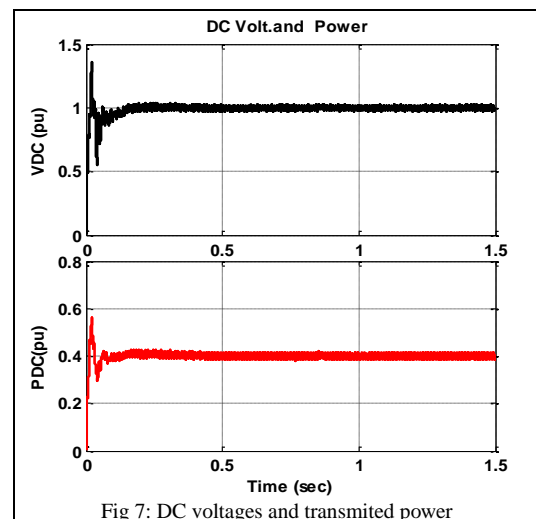Fig 6: Transmiited power a) Wind turbine ,b) Main busses

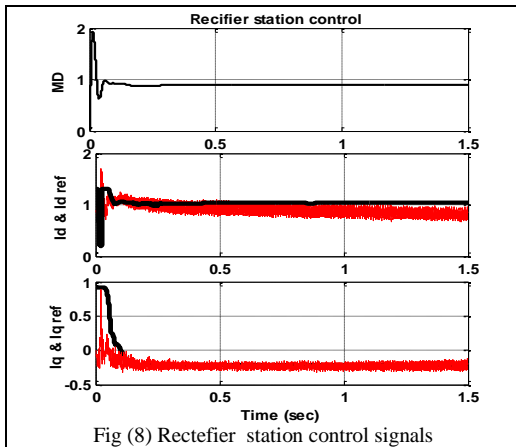Fig 7: DC voltages and transmited power
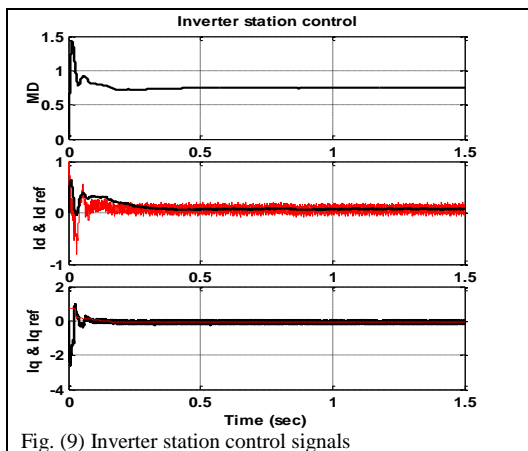
Fig (8) Rectefier station control signals

Fig. (9) Inverter station control signals

5. Conclusions

For utilizing the offshore wind energy, an efficient AC-DC-AC system was proposed. The mathematical model of the system, the optimal control algorithm of VSC-HVDC stations was formulated to regulate the DC link voltage to adjust the active and reactive power transfer into the AC side. PID controller to maintain DC voltage and the power transfer to the grid has been implemented by the inner and outer control loops of VSC-stations. This control strategy was developed in the d-q reference frame. The obtained results had validated the proposed system and the developed control strategies. The results show that, the system is stable and all signals has been fast settled to their final values. Moreover, the results indicated that the proposed pitch controller could keep the maximum turbine power even during the wind gust. Without the proposed pitch control, all wind turbines have been tripped out from the network if their rotor speed reached 1.6 pu. Moreover, the developed controller of the HVDC system has been validated and the DC voltage is kept constant and the transmission losses are minimum.

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