SOLAR WIND INTEGRATED SYSTEM ON OFFSHORE WITH LOW FREQUENCY POWER TRANSMISSION

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Abstract— Now a days renewable energy is widely used such as wind energy and solar energy, due to their extreme abundance. So they should be properly interfaced with the power grid with suitable devices. In this project a system of offshore wind with low-frequency ac (LFAC) transmission system which increases the power capacity and transmission distance is proposed along with a photovoltaic integration on the offshore itself results more stability in the power system. A cycloconverter is designed for the low frequency transmission and also to interface with the main power grid. The wind power plant collection system is dc based, and connects to the LFAC transmission line with a 12-pulse thyristor converter. Simulation results are observed to analysis the output voltages and currents of the two renewable sources and to illustrate the performance of the system.

Index Terms—Renewable sources, wind offshore, photovoltaic cell (PV cell),Power transmission, cycloconverter, thyristor converters, under-water power cables, low frequency ac (LFAC).

I. INTRODUCTION

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enewable energy systems can provide clean, reliable, secure and competitive energy products and services to help meet the rapidly increasing global energy demand. In a Carbon constrained world of the future, renewable energy sources with zero net greenhouse gas emissions will have an increasingly important role to play. Being widely distributed, renewable energy sources have the potential to provide electric power, heating, cooling and vehicle transport fuels for the millions of people currently with limited or no access to them. Progress towards including the full externality costs relating to the use of fossil fuels in comparative economic analyses of energy supply systems, together with the rate at which the costs of renewable energy technologies can be reduced as a result of mass production of energy conversion devices and greater project experience, will determine how significant the contribution of renewable energy to the global energy supply mix will become over time.

Wind offshore is a good suitable source with low frequency transmission by implementing a the system with suitable controllers like cycloconverter and thyristor based inverters [1]. Solar energy is the most abundant energy which can be used to generate electrical energy using solar panel [2]. Wind power offshore plants become the significant systems of the future electric generation. Offshore location is considered mainly because of their strong flow of wind on offshores [5], [6]. The integration of offshore wind power plants with the main power grid is a subject of ongoing research [5]. HVAC transmission is advantageous because the designing of protection systems and to change voltage levels using transformers are easy. However, the high capacitance of submarine ac power cables leads to considerable charging current, which, in turn, reduces the active power transmission capacity and limits the transmission distance. HVAC is adopted for relatively short (up to 50–75 km) underwater transmission distances [7]. HVDC is applied for distances greater than 100 km for offshore wind power transmission. A universal bridge is added parallel along with the filter on both side i.e. on sending end and receiving end which reduced the harmonics in the transmission line. Here connected bridge acts as a voltage source as we know that voltage source acts as active filter by reducing harmonics. The main advantage of HVDC technology is that it imposes essentially no limit on transmission distance due to the absence of reactive current in the transmission line [8]. Capacitor banks, ac filters, and static synchronous compensators are required to reduce low order harmonics [6]. On the other hand, VSC-HVDC systems are able to independently regulate active and reactive power exchanged with the onshore grid and the offshore ac collection grid. Photovoltaic system is one of the most able technologies because of its distinctive advantages like long life, low maintenance, and environmental friendly and reliable nature. Photovoltaic (PV) generation has increased by 20% to 25% over the past two decades. The demand for PV systems is growing worldwide. Research activities are being conducted in this direction for improvement of cell efficiency, cost and reliability for better utilization. Besides HVAC and HVDC, high-voltage low-frequency ac (LFAC) transmission has been recently proposed [9]–[10]. Cycloconverter is used to maintain the low frequency that lowers the grid frequency to a smaller value, typically to one-third its value. LFAC technology
increases the power capacity and transmission distance for a given submarine cable compared to 50-Hz or 60-Hz HVAC which leads to substantial cost savings due to the reduction in cabling requirements like ac breakers for protection purpose. In this project, a novel LFAC transmission topology is analyzed in which energy from wind is transmitted through low frequency cables and is interconnected to the grid using cycloconverter and also a PV(photo voltaic ) system is integrated to the grid to stabilize the output power and also to eliminate the fluctuation with low harmonics.

The required dc voltage level can be built by using high-power dc–dc converters [11], [12] and/or by the series connection of wind turbines [13]–[14]. For example, multi-MW permanent-magnet synchronous generators with fully rated power converters (Type-4 turbines) are commonly used in offshore wind plants. By eliminating grid-side inverters, a medium-voltage dc collection system can be formed by interconnecting the rectified output of the generators [15]. The main reason for using a dc collection system with LFAC transmission is that the wind turbines would not need to be redesigned to output low-frequency ac power, which would lead to larger, heavier, and costlier magnetic components such as step-up transformers and generators. At the sending end of the proposed LFAC system on offshore side, a dc/ac 12-pulse thyristor-based inverter is used to generate low-frequency (20- or 16 2/3-Hz) ac power, as shown in Fig. 1. At the onshore substation that is at receiving end side, a thyristor-based cycloconverter is used as an interface between the low-frequency side and the 60- or 50-Hz onshore power grid. Thyristor-based converters can transmit more power with increased reliability and lower cost compared to VSC-HVDC systems. However, large filters are necessary at both ends to suppress low-order harmonics. Similarly output power from PV system is also integrated here only.

II. DESIGN OF RENEWABLE ENERGY SOURCES

A. Wind turbine

Wind turbine with Doubly fed induction generators are used here. An induction generator with power supply on the rotor is a main part of the DFIG wind turbine. Wind turbine is connected to the DFIG using gear box and the output from the DFIG is connected to be coupling three phase transformer as shown in figure 1. Finally a bridge circuit is used to converter this ac power to dc power.

B. Solar panel

Solar cells naturally exhibit a nonlinear I-V and P-V characteristics which vary with the solar irradiation and cell temperature. The typical I-V and P-V characteristics of solar cell are shown in figure 1.

![Characteristics of solar cell](image)

The fundamental parameters related to solar cell are short circuit current (Isc), open circuit voltage (Voc), maximum power point (MPP), efficiency of solar cell and fill factor. Solar panels on the offshore are connected parallel to wind energy dc collection cables.

III. PROPOSED TOPOLOGY AND CONTROL

The proposed wind and solar integrated system with LFAC transmission system is shown in figure 3, the active power(p) transmitting over the transmission lines, which should be cables for connecting offshore e wind farms ,which can be expressed by

\[ P = \frac{V_s V_r}{X_L} \]  \hspace{1cm} (1)

Where Vs and are Vr sending end voltage and receiving end voltages, respectively. XL is the line reactance. \( \delta \) is the transmitting angle. Eq. (1) is valid when the cable is short that neglects the effect of the line angle, increasing transmitting power is either by increasing the voltage level or lowering the impedance of the cable. Furthermore, with the fixed sending end voltages, the only way to improve the transmission capability by reducing the impedance of the cable. The reactance is proportional to power frequency f

\[ X = 2\pi f L \]  \hspace{1cm} (2)

Here L is the total induction over the line decreasing the electricity power can proportionally increase the transmission capability. The LFAC system uses low-frequency to reduce the reactance of the transmission system thus, its transmission capacity can be increased several fold. For instance, when frequency is 50/3 Hz, the theoretically transmission capability can be raised three times. The LFAC system can also improve the voltage stability given the same amount of reactive power transmission as given in eq. (3).
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\text{Change in voltage } V = QX/V^2 \times 100 \quad (3)

the nominal voltage, \( Q \) is the reactive power flow of the cable. Because the impedance is reduced in the LFAC system due to the power lower grid frequency, the voltage drop over the cable is proportionally reduced accordingly.

\begin{align*}
V_{\text{dc}} = \text{cosine wave crossing method} \\
\alpha_s = \text{sending end inverter firing angle}
\end{align*}

\begin{align*}
V_p &= \text{peak value of the cosine wave} \\
V^* &= \text{reference voltage} \\
\alpha_s &= \text{sending end inverter firing angle}
\end{align*}

12-pulse inverter at the sending end can synchronize with the 20-Hz voltage, and starts the transmission of power.

The control structure for the sending end inverter is shown in Fig. 2. The controller regulates the dc bus voltage \( V_{\text{dc}} \) by adjusting the voltage \( V \) at the inverter terminals. The cosine wave crossing method is applied to determine the firing angle. Firing pulses are generated by the crossing points of both wanted and threshold voltages of reference voltages. This method demonstrates superior properties, such as minimum total harmonic distortion of output voltages, and simplicity of implementation. The firing angle for the 12 pulse inverter is given by

\begin{align*}
\alpha_s &= \arccos \left( \frac{V^*}{V_p} \right) \quad (1)
\end{align*}

Where \( V_p \) is the peak value of the cosine wave, \( V^* \) is the reference voltage and \( \alpha_s \) is sending end inverter firing angle. Note that \( V<0 \) and \( 90<\alpha<180 \) (using common notation), since the converter is in the inverter mode of operation. \( V \) And \( V_S \) (line-to-neutral, rms) are related by

\begin{align*}
V &= \frac{6\sqrt{3}V_S}{\pi\eta_S} \cos \left( \alpha_s \right) \cdot \quad (2)
\end{align*}

A phase-locked loop (PLL) provides the angular position of the ac-side voltage, which is necessary for generating the firing pulses of the thyristors. It also outputs the rms value of the fundamental component of the voltage, which is used in the firing-angle calculation.
IV. CONTROLLERS

A. Controller for Cycloconverter

The structure of the cycloconverter controller at the receiving end is illustrated in Fig. 4. The control objective is to provide a constant 20-Hz voltage of a given rms value \( V_{cyc}^* \) (line-to-neutral). The fundamental component of the cycloconverter voltage is obtained with the signal conditioning logic depicted in Fig. 5.

The basic control principle of the three-phase, six-pulse cycloconverter is to continuously modulate the firing angles of the individual converters (positive and negative converters), according to its control algorithms. Here, the cosine wave-crossing method with the circulating current free mode or blocking mode of operation is selected for its switching sequences, since the proposed control algorithm has demonstrated the following properties. The partial circulating current mode can prevent discontinuous operations during bank-exchange operations from the positive to negative bank, or conversely, with minimal circulating loss. Distortion of output-currents can be eliminated in this mode. Firing pulses are generated by the crossing points of both wanted and threshold voltages of reference voltages. Cosine wave crossing method is used to reduce the total harmonic distortion (THD) of output-voltages.

The firing angles of the phase-a positive and negative converters are \( \alpha_{AP} \) and \( \alpha_{AN} \) respectively. For the positive converter, the average voltage at the 20-Hz terminals is given by

\[
V_{AP} = \frac{3\sqrt{6}}{\pi n_R} V_G \cos(\alpha_{AP})
\]

Where \( V_G \) is the rms value of the line-to-neutral voltage at the grid side, and \( n_R \) is the turns ratio of the transformers. The condition

\[
\alpha_{AP} + \alpha_{AN} = \pi
\]

Ensures the average voltages with the same polarity are generated from the positive and negative converter at the 20-Hz terminals. The firing pulses \( S_{AP} \) and \( S_{AN} \) are not simultaneously applied to the “Bank Selector” block of Fig. 5, which operates based on the filtered current. Note (for later use) that the maximum line-to-neutral rms value of the 20-Hz cycloconverter voltage is both converters, in order to obtain a non circulating current mode of operation. This functionality is embedded in

\[
V_{cyc}^{max} = \frac{3\sqrt{3}}{\pi n_R} V_G
\]

Voltage ratio is

\[
' = \frac{V_{cyc}}{V_{cyc}^{max}}
\]

In practice, the theoretical maximum value \( r=1 \) cannot be achieved, due to the leakage inductance of the transformers, which was ignored in the analysis.
B. Main components

The main power components are selected based on a steady-state analysis of the LFAC transmission system shown in Fig. 1, under the following assumptions:

- Only fundamental components of voltages and currents are considered. The receiving end is modeled as a 20-Hz voltage source of nominal magnitude.
- The power losses of the reactor, thyristors, filters, and transformers are ignored.
- The resistances and leakage inductances of transformers are neglected.
- The ac filters are represented by an equivalent capacitance corresponding to the fundamental frequency.
- The design is based on rated operating conditions (i.e., maximum power output).

At the steady state, the average value of the dc Idc current is equal to \( I_w \), so the power delivered from the wind turbines is

\[
P_w = V_{dc} I_w
\]  

(9)

For the 12-pulse converter, the rms value of the current at the transmission side is

\[
I = \frac{2\sqrt{6}}{\pi M} I_w
\]

Hence, eq. (9) can be written as

\[
I = \frac{2\sqrt{6}}{\pi M} P_w
\]

with

\[
M = \frac{2\sqrt{6}}{\pi M V_{dc}}
\]

(10) system is shown in Fig.6. The equivalent capacitance of the sending end ac filters at the fundamental frequency is \( C_{eq} \). The transmission line is modeled by \( \pi \) equivalent (positive-sequence) circuit using lumped parameters.

The well-known hyperbolic trigonometric expressions for \( Z' \) and \( Y' \) are used. Given a power rating of a wind power plant \( P_{prated} \), the maximum reactive power that is absorbed by the 12-pulse inverter can be estimated according to eq. (14),

\[
V_S = V_S - 0 \quad \text{and denote the phasor of the line to neutral voltage and line current, respectively. Since } -1 \text{ lags by } \alpha \text{, it follows that } \]

\[
I = I - 180 - \alpha_S
\]

The active power delivered by the 12-pulse inverter is given by

\[
P_S = P_w = 3V_S I \cos(\alpha_S - 180^\circ) = -3V_S I \cos(\alpha_S) > 0
\]

(13)

Substitution of eq. (11) into eq. (13) yields

\[
\cos(\alpha_S) = -\frac{1}{3MV_S^2}
\]

(14)

and

\[
\sin(\alpha_S) = \sqrt{1 - \frac{1}{9M^2V_S^2}}
\]

(15)

The reactive power generated from the 12-pulse inverter

\[
Q_S = 3V_S I \sin(\alpha_S - 180^\circ) = -3V_S I \sin(\alpha_S)
\]

(16)

From (13)–(16), it follows that

\[
Q_S = P_S \tan(\alpha_S) = -P_S \sqrt{9M^2V_S^2 - 1}
\]

(17)

The negative sign in (16) and (17) indicates that the 12-pulse inverter always absorbs reactive power. Eq. (17) shows that can be expressed as a function \( Q_S = f(P_S, V_S) \). Based on the aforementioned analysis, the steady-state single-phase equivalent circuit of the LFAC transmission system is shown in Fig. 7.
The well-known hyperbolic trigonometric expressions for \( Z' \) and \( Y' \) are used. Given a power rating of a wind power plant \( P_{\text{rated}} \), the maximum reactive power that is absorbed by the 12-pulse inverter can be estimated according to eq. (14), which yields

\[
Q_{\text{rated}} = P_{\text{rated}} \sqrt{3} M^2 V_0^2 - 1
\]

(18)

Where \( V_0 \) is the nominal transmission voltage level (line-to-line rms). Here, it is assumed that the sending-end ac filters supply the rated reactive power to the inverter. Therefore

\[
C_q = \frac{Q_{\text{rated}}}{\omega_c V_0^2}
\]

(19)

Where \( \omega_c = 2\pi f \text{ rad/s} \). In addition, the apparent power rating of the transformer at the sending end should satisfy

\[
S_{tS} > \sqrt{P_{\text{rated}} + Q_{\text{rated}}^2} = \sqrt{3} P_{\text{rated}} MV_0
\]

(20)

At the 60-Hz grid side, the reactive power capacity of the ac filters and the apparent power rating of the transformers depend on the cycloconverter’s voltage ratio \( r \), which is a design parameter, and the 20-Hz side power factor, which can be estimated as follows. For a given transmission cable, the voltage ratings (nominal and maximum voltage), the current rating, and the distributed cable parameters (resistance, inductance, and capacitance per unit length) are known. Here, it is assumed that a power cable is chosen to handle the cable’s voltage and current ratings. (The relationship between active power through the cable and maximum transmission distance, given a certain cable.)

For simplicity, it is further assumed that the rms value of line-to-line voltage at both sending and receiving ends is \( V_0 \) and the current through \( Z' \) and \( L_d \) is approximately equal to the current rating of the cable. \( I_{\text{rated}} \). Since the ac filters are designed to supply all reactive power to the 12-pulse inverter at the sending end, the reactive power injected into the 20-Hz side of the cycloconverter can be estimated by using

\[
Q_{\text{cyc}}^{20} \approx \text{Im}\{V_0^*\} V_0^2 + \omega_c C_0 M^2 V_0^2 - 3 l_{\text{rated}} \text{Im}\{Z'\} - 3 f_{\text{rated}} L_f
\]

(21)

Where the first two terms represent the reactive power generated from the cable and the capacitor of the LC filter, and the last two terms represent the reactive power consumed by the cable and the LC filter’s inductor. The active power injected into the cycloconverter from the 20-Hz side can be estimated by using

\[
P_{\text{cyc}}^{20} = P_{\text{rated}} - \text{Re}\{Y'\} V_0^2 - 3 f_{\text{rated}}^2 \text{Re}\{Z'\}
\]

(22)

Where the first two terms represent the reactive power generated from the cable and the capacitor of the LC filter, and the last two terms represent the reactive power consumed by the cable and the LC filter’s inductor. The active power injected into the cycloconverter from the 20-Hz side can be estimated by usingWhere the last two terms represent the power loss of the cable. The 20-Hz side power factor can be estimated according to eq. (18) and eq. (19).

The 60-Hz side power factor at the transformers’ grid side terminals can be obtained using the 20-Hz power factor and the voltage ratio based on the analysis and calculations of (13, p. 358). Then, the apparent power rating of each of the three receiving-end transformers should satisfy

\[
S_{tR} > \frac{P_{\text{cyc}}^{20}}{3(\text{PF}^{60})}
\]

(23)

Also, it is assumed that the grid-side ac filters are designed to supply the rated amount of reactive power to the cycloconverter.

\textbf{C. Filter Design}

At the sending end, the 12-pulse inverter produces harmonics of order \( m=12k \pm 1, k =1, 2, ..., \) and can be represented as a source of harmonic currents. These current harmonics are filtered by two single-tuned filters for the 11th and 13th harmonic, and one damped filter for higher-order harmonics \( (\geq 23)^{rd} \). Generally, the filter design is dependent on the reactive power supplied at fundamental frequency (also known as the filter size) and the required quality factor (QF). The total reactive power requirement of these filters can be estimated based on eq. (18). Here, it is assumed that the total reactive power requirement is divided equally among the three filters.

A high quality factor (QF = 100) is used for the single-tuned filters, and a low quality factor (QF = 1) is used for the high-pass damped filter. Finally, with the capacitance and quality factor known, the inductance and resistance of each filter can be determined. With such filter design, the 12-pulse-related current harmonics originating at the sending end are essentially absent from the transmission line. At the receiving end, there are two groups of filters, namely, the ac filters at the 60-Hz side and the LC filter at the 20-Hz side. At the 60-Hz side, if the cycloconverter generates exactly one-third of the grid frequency, that the line current has only odd harmonic components (3rd, 5th, 7th, etc). Subharmonic and interharmonic components are not generated. Here, three single-tuned filters and one damped filter are used to prevent these harmonic currents from being injected into the 60-Hz power grid. These filters are designed with a procedure similar to that for the ac filters at the sending end.
At the 20-Hz side, the line-to-neutral voltage has harmonics of order 3, 5, 7, ..., without subharmonic and inter harmonic components. However, the harmonic components of order equal to integer multiples of three are absent in the line-to-line voltage. Therefore, as seen from the 20-Hz side, the cycloconverter acts as a source of harmonic voltages of order n=6k±1, k=1,2,..., . The design of the LC filter has two objectives 1) To decrease the amplitudes of the voltage harmonics generated by the cycloconverter 2) To increase the equivalent harmonic impedance magnitudes seen from the receiving end, indicated by $Z_R(\omega_0)$ in Fig. 7. The design procedure presented here takes into account the voltage harmonics of order 5, 7, 11, and 13. For cycloconverters, the amplitude of the voltage harmonics only depends on the voltage ratio r and the fundamental power factor at the 20-Hz side, under the assumption of sinusoidal output current, which is sufficient for design purposes. Generally, the voltage harmonics tend to become worse with decreasing r. Here, we set $r = 0.9$. Fig. 7 illustrates the relationship between the per-unit amplitudes of the voltage harmonics under consideration and the power factor angle $\Phi$. Apparently, for the 5th and 7th voltage harmonics, the amplitudes are symmetric with respect to $\Phi=0$, and positive (i.e., reactive power consumption by the cycloconverter) can result in reduced amplitudes of the 11th and 13th voltage harmonics. At $\Phi \approx 85^\circ$, minimum amplitudes are obtained. However, this value is unacceptably low, so $\Phi = 35^\circ$ is selected (for operation at rated power).

After $\Phi$ has been determined, it follows from (21) and (22) that there is a linear relation between $L_f$ and $C_f$, as in

$$C_f = a L_f + b, \text{ since } tan(\Phi) = \frac{Q_{20}}{P_{20}}.$$  

However any $(L_f, C_f)$ pair determined based on this equation should only be used as an initial guess. These initial parameters might not yield the required power factor angle due to the simplifying assumptions made in the analysis. The proper LC filter parameters can be obtained by solving the circuit shown in Fig. 14. For example, given a value for $L_f$, the capacitance $C_f$ that leads to the right power factor angle can be found by searching around its initial guess value. Therefore, if varies within a certain range, a number of $(L_f, C_f)$ pairs can be obtained. Among these candidates, a selection is made such that the magnitudes for n= 5, 7, 11, 13 are deemed to be adequately large.

The 20-Hz LFAC system is designed to transmit 180 MW over 160 km. At the sending end, the dc bus voltage level is chosen as 30 kV and a 214-MVA, 132/13.2-kV, 20-Hz phase-shift transformer is used. Due to the lower frequency, this transformer would be larger compared to a 60-Hz transformer. This is a drawback of the proposed LFAC system. The total size of the ac filters at the sending end is 115 MVAr.

V. SIMULATION RESULTS

To demonstrate the validity of the proposed LFAC system, test system is modeled in MATLAB/ SIMULINK. Software. sending end inverter and receiving end cycloconverter. The rating of wind power plant is 180 MW, and the transmission line distance is 160 km.

The following graphs presents the simulation results of wind-farm with an LFAC-transmission system connected to a power grid, as shown in Fig. 9, 10, 11 and 12. The wind farm consists of a wind turbine system with DFIG and photovoltaic system commonly known as solar panel. The wind turbine systems are connected in series after the wind-generated power is rectified to DC, and the DC power is converted to AC power using 12 pulse inverter. A transformer rises the voltage to higher level and acts as an interface between 12 pulse inverter and low frequency transmission line system which transmits the power over a distance of 160-Km to the nearest power grid substation. At that point, a cycloconverter converts the LFAC power into 60-Hz AC power for the interconnection.

The fig. 9, 10, 11 and 12 are the simulated current and voltage waveforms at the sending end, receiving end, cycloconverter side and the 60HZ ac side respectively. Finally we observed a clear voltage and current waveforms with less harmonics in fig. 12. Transient waveforms during a wind power ramp event is shown in figure 13. From fig. 13, power from two renewable sources ramps from 0-180 MW and efficiency of the system is nearly 98%. Total harmonic distortion (THD) is observed as 4.57% in fig.14.
Simulated Voltage and Current waveform

Fig. 9. At sending end

Fig:10. At Receiving end
Fig. 11. At cycloconverter side

Fig. 12. At Ac 50HZ grid side
Fig. 13. Waveforms during power ramp event.

Fig. 14. Total harmonic distortion (THD) in output current.
VI. CONCLUSION

Offshore wind farm along with solar panel system and transmission of power through low frequency cables to the main power grid evaluated in this project. In this project, an LFAC system as a new and alternative solution to the conventional HVAC and HVDC systems which are so far deemed as the only solution for large solar and offshore wind farm connection. With the cycloconverter that converts the 50 Hz to the lower frequency, for instance 50/3 Hz, the transmission capability is greatly improved. Design process of the system components, filters with a bridge circuit which acts as a filter and control strategies have been discussed also with total harmonic distortion observation. The use of low frequency can improve the transmission capability of submarine power cables due to lower cable charging current. The LFAC system appears to be a feasible solution for the integration of renewable sources for medium distances.

REFERENCES