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On Integration of Wind Power into Existing Grids via Modular Multilevel Converter based HVDC Systems

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Abstract- Due to the advent of advanced solid-state power devices and converters, it is now promising to transmit huge quantities of renewable energies to the main electrical grids. One of the major renewable energy resources is the wind power plant, which has the benefits of very low generation cost, simple infrastructure, lesser operating staff, lesser erection times, and negligible environmental pollution. Various far located power stations including offshore and mainland wind power plants, as well as big industrial loads can be joined together with the existing AC grids by implementing multi-terminal HVDC transmission systems. This recently established strong feature of HVDC systems is making them more feasible for future grids. The current source converter (CSC) is a mature technology used in HVDC systems, worldwide. Rigorous research is being carried out on the voltage source converters (VSCs), especially on Modular Multilevel Converters (MMCs) based HVDC systems that are distinguished by their benefits of lower harmonics, lower maintenance, almost absence of bulky DC link capacitors and AC filters, black start capability, smooth control of powers, and integration of renewable power using DC cables with the existing AC grids. In this paper, technical features associated with wind power plants and the interconnection of such plants via MMC-HVDC systems to the present AC grids are discussed in detail. Mathematical modeling and performance analysis of advanced MMC technology is carried out by performing simulations in Matlab/Simulink®. The deduced technical outcomes remarkably show the effectiveness of this converter in the near future grids.

Keywords Wind turbine generator (WTG), High voltage direct current (HVDC) converters, Multi-terminal direct current (MTDC) systems, Modular multi-level converter (MMC), Fundamental cell (FC).

1. Introduction

Electrical energy can be considered as a worldwide power source performing tasks as a servant of the people. It can be generated easily from various energy resources as well as can be reconverted back into various useful forms of energy. These energy resources can be classified into two categories i.e., conventional resources (like thermal, nuclear, and hydroelectric, etc.), and non-conventional resources (like wind, solar, fuel cells, geothermal, tidal, and biomass, etc.). The electrical energy generated from the wind resource offers an interesting supplement to gas, oil, and coal-fired power stations that involve a lot of fuel cost and environmental pollution [1].

In recent years, electricity generation from wind is greatly increased due to improvements in the design of associated generators and power electronic converters. The world electricity generation's share related to wind energy has reached about 600 GW till 2018 in which 50 GW has been installed in 2018. This energy contributes a share of 6% of the world's total electricity demand. China and the USA have the world's biggest wind power sectors [2].

A wind turbine captures the wind energy by moving the rotor of the mechanically coupled generator. Various types of electrical generators can be used when harvesting energy from wind. The output of the generator may be of AC/DC nature with varying parameters. Power electronic converters, connected electrically to the output of the generator can change the variable parameters into the desired parameters. DC cables can be successfully used to interconnect a large number of mainland and off-shore wind turbine generators (WTGs). The integration of wind power into existing AC grids can be achieved by using power electronic-based high voltage direct current (HVDC) systems [1]–[3]. HVDC systems have certain advantages over high voltage alternating current (HVAC) systems like the absence of reactive power flow problem, limitation in short circuit currents, asynchronous connections, lesser number of conductors, easy right of ways (R.O.W), and provision of use of long length underground/submarine cables [4], [15]. HVDC systems have two main converter topologies i.e. the line commutated converters (LCCs) and the voltage source converters (VSCs). Although LCC is a proven sophisticated technology, continuous developing efforts mark VSCs' features more dominant, thus making it a viable alternative to LCC based HVDC systems. Provision of multi-terminal direct current (MTDC) connections are possible along with black start capability when using VSC based HVDC systems [4], [5], [14], [19]. Modular multilevel converters (MMCs) are an advanced type of VSC technology, having further competitive features such as scalability to higher voltage levels, and ease of maintenance due to modularity [6]–[9], [18]. The appealing features of MMCs like the ability of filter-less and transformer-less operations, strong redundancy strategies and fault ride-through capability, high reliability, low total harmonic distortion (THD) thus good quality output waveforms have made this converter topology as one of the most favorable configurations in medium and high voltage industrial applications [20]–[22]. Therefore, analyzing various aspects of MMC operation such as modeling, switching, modulation, quality of output waveforms, and efficiency appears to be significant. Modeling, modulation, and control for MMCs having 8 levels, 16 levels, and 22 levels, respectively are done along with Fast Fourier Transform (FFT) based THD analysis, and critical outcomes are drawn in favor of MMC technology.

This paper is structured as follows: Section 2 provides a general view of the wind attributes along with the impacts. Associated generators' schemes are listed in Section 3 whereas, associated HVDC converters are discussed in Section 4. HVDC transmission types and DC cables are studied in Section 5. Section 6 describes the types of wind farms and their integration into the main grids, whereas Section 7 depicts some main features of MTDC systems. The description and analysis of MMCs are given in Section 8. This includes mathematical modeling represented in Section 8.1, whereas the detailed switching mechanism and switching states are given in Section 8.2. Time-domain simulations of the MMC model are carried out in MATLAB/Simulink® environment and the results are discussed in Section 8.3. Furthermore, a technical outcome-based comparison is done in this section to deduce the prominent advantages of the MMC. Lastly, the overall conclusions are emphasized in Section 9.

2. Wind Attributes

The wind possesses energy due to its velocity and mass. A cubic meter of air having a speed of 10 meters per second, has kinetic energy equal to about 60 Joules. If this moving air is blocked by a wind turbine, the wind will deliver some of its kinetic energy to that wind turbine, which will further drive an electric generator to produce electricity. The approximate formula showing wind inherent power (P) in watts is:

$$P = 0.5\rho A v^3 \tag{1}$$

where 'ρ' is the density of air in kg/m^3, 'A' is the moving area of wind turbine's rotor in m^2, and 'v' is the wind velocity in m/s. This approximate formula assumes a complete standstill in wind speed (v). In practical only 30% to 40% of this power can be extracted from the moving wind. For power generation from wind, the useful wind speed ranges between 5m/s to 15m/s. There are several attributes of wind to be focused on when harnessing power from the wind. These are listed in Table 1 [1].

3. Associated Generators' Schemes

The most common design of a wind turbine is 'three blades, horizontal axis' having a maximum rating up to 5 MW. For commercial applications, the wind turbines are connected to make a wind farm. There may be five different generating schemes that can be used to generate electricity from wind. These are based on [1], [10]–[13]:

- A DC generator connected to DC batteries and feeding DC loads/inverter-based AC loads.
- An induction generator (squirrel cage type) connected to the grid and moving at a constant speed. Gearbox, reactive power generating capacitors and transformer are also used.
- An induction generator (squirrel cage type) connected to the grid and moving at a constant speed. Gearbox, variable frequency converters (at generator's stator side), and transformer are also included.
- A doubly-fed induction generator (wound rotor type) moving at variable (sub-synchronous/super-synchronous) speed. Gearbox, variable frequency converters (at the generator's rotor side), and transformer are also used in this scheme.
- A permanent magnet AC generator connected to the grid and moving at variable speed. Variable frequency converters (at the generator's stator side) and transformer are also included in the design.

Table 1. The wind attributes and impacts

S. No.	Wind Attributes	Impacts
1	Wind energy demands no fuel and is pollution-free.	Not any problem with fuel purchasing and transportation is faced. The waste disposal problem is also absent.
2	The power generated by a wind turbine can be supplied into a power grid or stored in DC batteries.	The fulfillment of synchronization conditions, and the requirement of the step-up transformer/DC batteries with appropriate circuitry are necessary.
3	The speed of the wind can vary within +-25% in an interval of a few minutes.	The output of a connected generator should be precisely controlled by using power electronic converters.
4	The direction of the wind may be changed.	An adjustable revolving wind turbine with a yaw motor should be used.
5	The data regarding wind's speed, direction, and duration should be collected before the erection of the wind turbines.	Measurement and data logging instruments are required at the site.
6	Whenever the wind power crosses the generator capacity, it must be taken to a boundary limit.	Power converters with appropriate circuitry should be used.
7	When high-speed storms and hurricanes pass through a wind turbine, the turbine blades must be brought into a complete halt to prevent it from mechanical damage.	A braking mechanism or alternate should be involved.
8	High rising wind turbines may face lightning strikes.	Arrestors should be installed for protection.

Figure 1 depicts a typical WTG connected to the AC grid through power electronic converters and grid-tie transformer.

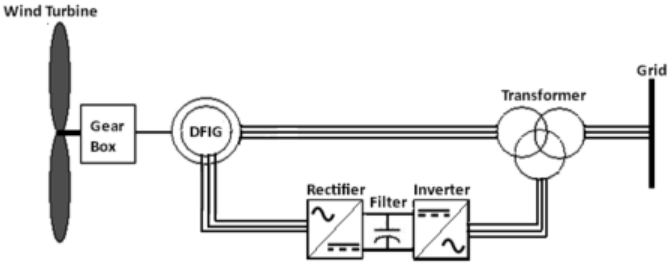


Fig. 1. Interconnection of WTG with AC grid.

4. Types of HVDC Converters

Power electronic converters, connected in between wind farms and grid are classified as [5], [16], [17]:

a) Line Commutated Converters (LCCs) or Current Source Converters (CSCs),

b) Self Commutated Converters (SCCs) or Voltage Source Converters (VSCs).

The above converters are used to obtain a constant voltage and frequency from variable input parameters. Also, they generate a sinusoidal waveform having the least harmonics, so that grid connection codes should be fulfilled. CSC HVDC systems are a mature and sophisticated technology using thyristors as switching devices. CSCs and VSCs HVDC transmission systems have their characteristics and limitations while using in the formation of the MTDC grid. CSC HVDC transmission systems are on a point-to-point basis, whereas VSC HVDC systems can be based on a multi-terminal structure.

In recent years, VSCs have achieved a bigger edge over CSCs because of their prominent advantages like black start capability, independent control of active and reactive powers, reduced size of DC-link capacitors, good quality of output waveform, a lesser requirement of filters, multi-terminal connections, etc.

Control of bidirectional apparent power flow is possible in VSC HVDC systems, while active (P) and reactive (Q) powers can be expressed by Eq. (2) and Eq. (3), respectively.

$$P = V_c I_c \cos(ø) = (V_c V_g \sin(\delta)) / X \tag{2}$$

$$Q = V_c I_c \sin(ø) = (V_c (V_g \sin(\delta) - V_c)) / X \tag{3}$$

where V_c = converter voltage,

V_g = voltage of AC grid,

I_c = converter current,

ø = phase displacement between V_c and I_c,

δ = phase displacement between V_c and V_g, and

X = series reactance of conductor connecting HVDC converter with AC grid.

5. DC Cables

CSC HVDC and VSC HVDC can be set up using either aerial transmission lines or by undersurface/submarine DC cables. For the aerial conductors, the related transmission distance can be unlimited but lightning strokes will produce DC faults.

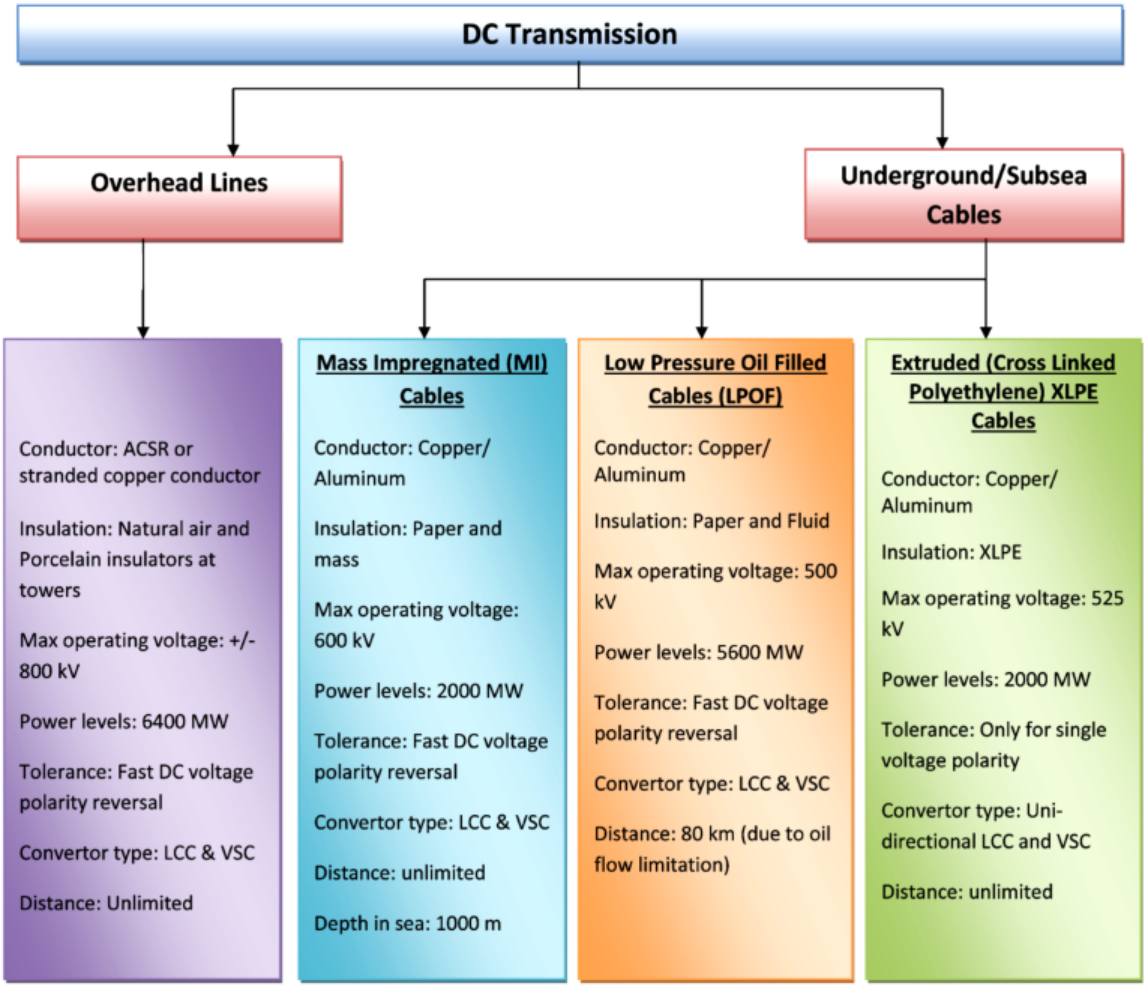


Fig. 2. Classification of HVDC transmission medium.

On the other hand, DC cables have the same advantage of unlimited transmission distance and also less vulnerable to lightning strikes. Generally, three types of cables can be used in HVDC systems [15]:

- Extruded cross-linked polyethylene (XLPE) cables
- Low-pressure oil-filled (LPOF) cables
- Mass impregnated (MI) cables

The detailed classification of HVDC transmission mediums is given in Fig. 2.

The mentioned cables can be employed for both undersurface and submarine applications as well as for both AC and DC transmissions. The difference between the underground and subsea cables is based upon [16]:

a) The material type of conductor, i.e., aluminum is used for underground cables and copper for subsea cables due to the high mechanical strength of copper.
b) The armoring layer, i.e., strength is provided by steel armor in the subsea cable so that it can withstand the longitudinal mechanical tightness during placing and operation phases.

6. Types of Wind Farms

Two types of wind farms can be integrated with existing grids i.e. [15]–[19],

1. Mainland wind farms and their large-scale integration with grids,
2. Offshore wind farms and their large-scale integration with grids.

These types are discussed in detail in the following sections:

6.1. Mainland Wind Farms and their large-scale integration with grids

Fig. 3 depicts a typical single line diagram of a mainland wind power plant consisting of 33 individual WTGs each of 1.5 MW capacity. 0.69 kV from each WTG is stepped up to 22 kV with the help of a generator side transformer, which is then combined at point-of-common-coupling (PCC) by using XLPE underground cables. Generator side transformers are selected based on the minimum power factor of the WTG.

To ensure a high-power factor, 8 capacitor banks of combined capacity 20 MVAR (8 x 2.5MVAR) have also been installed. 22 kV voltage is stepped up again to 132 kV by using two 50 MVA power transformers connected to the national AC grid. Power transformers are selected with a 100% redundancy approach i.e.; each unit will not handle more than 50% of its full load capacity.

Unlike conventional power plants where generators and turbines are not noticeable due to the indoor type, wind turbines have a highly visual presentation. Turbines are selected based on the economic factors, wind potential at the site, and the ability to go under a maintenance routine. Moreover, comprehensive protection arrangements have also been installed to prevent the turbine and related equipment from any damage.

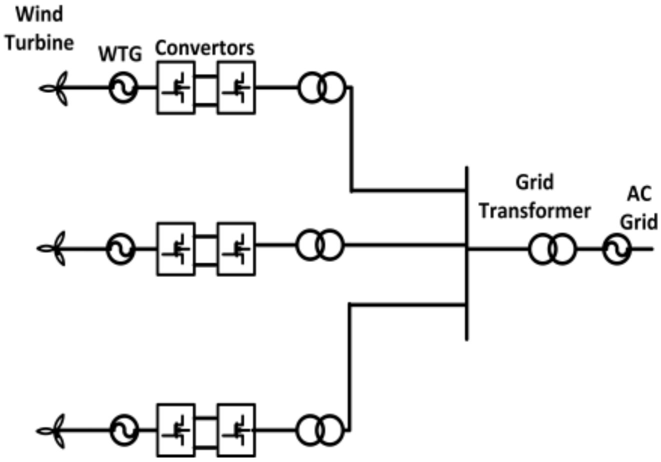


Fig. 3. Schematic of integration of mainland WTGs with AC grid.

6.2. Offshore Wind Farms and their large-scale integration with grids

The offshore wind turbine generators (WTGs) can be interconnected with the mainland AC grids either via individual radial AC or DC links. Another option for the radial approach is the concept of making offshore clusters. Several offshore wind power plants will jointly make an offshore cluster from which generated electricity can be transmitted to the onshore grid via a single large offshore HVDC hub plant farm. The advantage is distributing the development costs of the transmission infrastructure among several developers. Another advantage is the lesser environmental effects as only one transmission link will connect many wind farms to the mainland grid (see Fig. 4).

The interconnection of offshore wind turbine generators with the mainland AC grids can be done by two configurations [15]–[19]:

a) AC submarine cable joining WTG's transformers with the onshore AC transformer.

b) HVDC submarine cables joining offshore HVDC converter with the onshore HVDC converter.

The first configuration is feasible for an undersea distance of 70 km beyond which a generation of reactive power of cable is an enormous amount while for larger distances the second configuration is recommended. The common output voltage from WTG's transformers is in the range of 30 to 33 kV although the obtainability of WTGs rated at 66 kV is underway. This increased voltage decreases the conductor losses and permits extra WTGs to be linked with a sole offshore connection. This also allows the spreading of the collector grid over a large length without intolerable voltage profiles. Thus, resulting in lesser AC collector platforms and reduction in principal investments.

Hence, we can summarize that following physical entities should be present while integrating numerous offshore WTGs with the onshore AC grid i.e.,

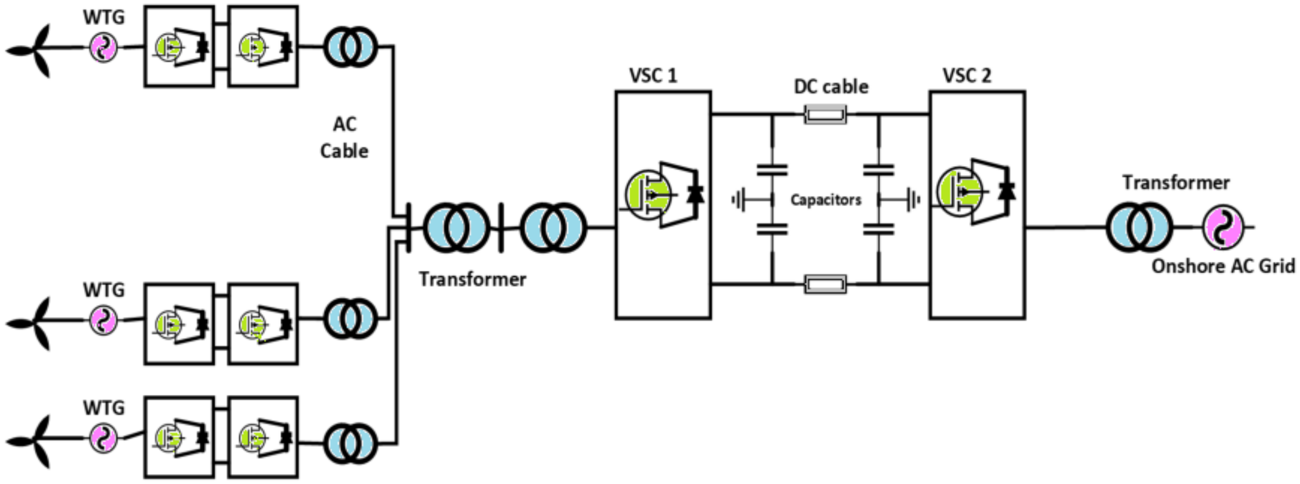


Fig. 4. Schematic of integration of offshore WTGs with AC grid via HVDC systems.

- WTGs
- Offshore AC substation housing transformers, circuit breakers, bus bars.
- Offshore AC export cables connecting offshore wind farm substation with the offshore HVDC converter transformer.
- HVDC converter transformer and HVDC converter located offshore.
- Offshore HVDC cables connecting offshore converter with an onshore converter.
- Onshore HVDC converter and AC grid transformer.

The offshore HVDC converter is generally startup by the onshore HVDC converter; responsible to deliver the requisite ancillary power for WTGs. We may use auxiliary diesel engine generators in the offshore AC substation to energize the WTGs. These generators may acquire reactive power compensation equipment as XLPE AC cables of 33 kV may produce 100-150 kvar/km while cables rated at 132 kV produce about 1000 kvar/km.

7. MTDC Systems

About a decade ago, HVDC systems have the limitations of the only point-to-point power transfer, although its counterpart HVAC has the features of both point-to-point power transfer and multi-terminal power transfer. Several generating sources and industrial loads can be connected to HVAC systems which gives greater acceptability to these systems. By the advent of modern VSC HVDC systems, multi-terminal power transfer capability is now also possible as shown in Fig. 5.

An MTDC system can have more than two converter stations. An existing two-terminal system can be simply converted into an MTDC system by introducing a new HVDC terminal's tapping along with the HVDC link [14], [19].

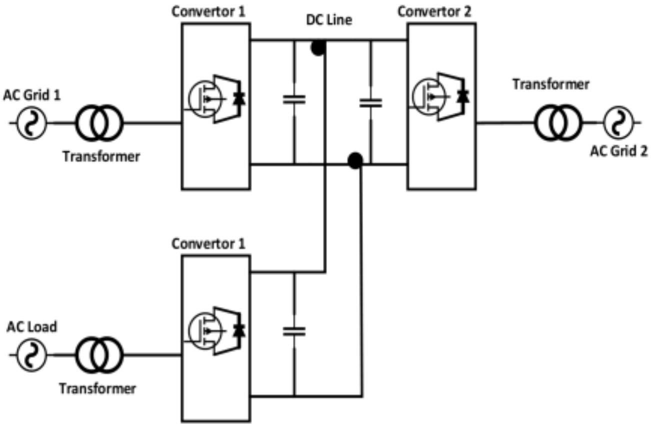


Fig. 5. Schematic of a simple MTDC system.

Mainland and offshore wind farms can be linked to the existing AC grids by employing these MTDC systems. This creates the HVDC structures further feasible for implementation in upcoming grids [15].

8. Modular Multilevel Converters (MMCs)

2-level or 3-level VSC converters using pulse width modulation (PWM) techniques are usually used, but MMCs are also now considered as a better alternative (see Fig. 6).

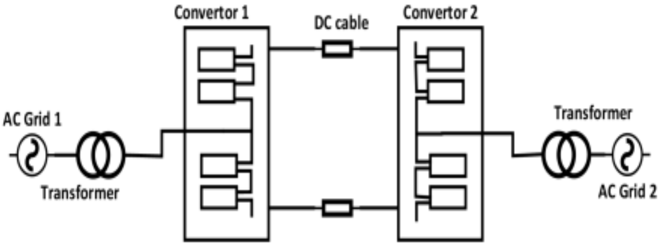


Fig. 6. Schematic of a modular multilevel converter based HVDC system.

The MMC VSC HVDC is a better choice for making DC grids because of its better fault bearing capability and lesser switching losses. Also, the requirement of transformers and huge AC side filters is greatly abridged. MMC based HVDC systems have also good features of the better-quality output waveform, modularity, and hence more reliability [23]–[25].

8.1. Mathematical modelling of MMC

Fig. 7 depicts the internal structure of one fundamental cell (FC) of an MMC, whereas Fig. 8 presents one-phase of the symmetric modular multilevel converter.

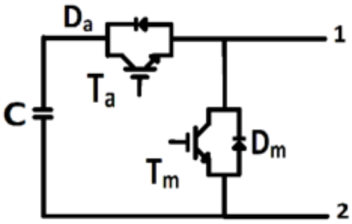


Fig. 7. Structure of a single FC.

Every FC has two switches each consisting of 'T_a' (called auxiliary switch), 'T_m' (called the main switch), and one DC capacitor. When the switch T_m is ON and T_a is OFF, the output between FC terminals 1 and 2 would be zero. When the switch T_a is ON and T_m is OFF, the output would be V_c. Each leg of the converter consists of dual arms comprising 'm' number serial wise fundamental cells. Every FC has an identical value of DC capacitor. The two arms of one phase leg are connected via upper arm inductor L_{Au} and lower arm inductor L_{Al}, while the grid is connected in between the two arm inductors. The grid has inductance L_{Ag}, and resistance R_{Ag}.

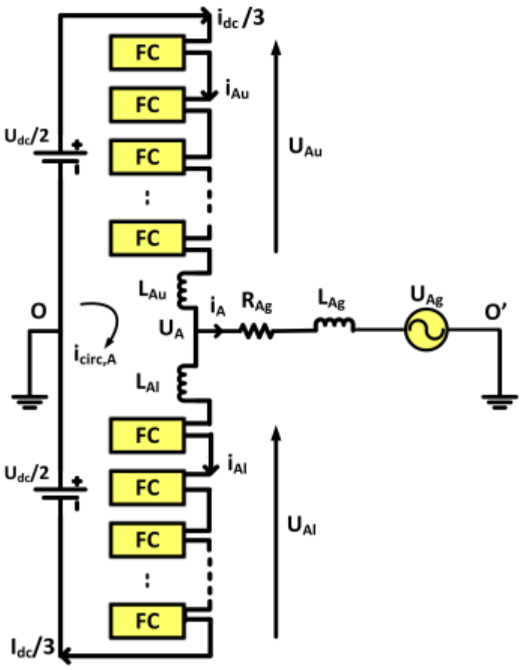


Fig. 8. Schematic of one phase of an MMC.

Depending on the switching states, the fundamental cell capacitors can be introduced or bypassed in the leg. The summation of all series-connected capacitors in the upper arm results in the output waveform of the higher arm (U_{Au}), while the summation of all series-connected capacitors in the lower arm results in the output waveform of the lower arm (U_{Al}), respectively. The difference of these arm voltages would be the synthesized output voltage (U_A) of the MMC. Mathematically, these can be represented by:

$$V_{FC} = S_i\, V_c \tag{4}$$

where, S_i, the ith switch can be 0 or 1 (ON or OFF).

$$V_c = U_{dc}/n \tag{5}$$

$$U_A = -\, U_{Au} + U_{dc}/2 = U_{Al} - U_{dc}/2 \tag{6}$$

Upper arm current of phase A,

$$i_{Au} = i_A/2 + i_{dc}/3 + i_{circ,\,A} \tag{7}$$

Lower arm current of phase A,

$$i_{Al} = -\, i_A/2 + i_{dc}/3 + i_{circ,\,A} \tag{8}$$

Circulating current of phase A,

$$i_{circ,\,A} = (\, i_{Au} + i_{Al}\,)/2 - i_{dc}/3 \tag{9}$$

8.2. Output Waveforms and the Switching States

Fig. 9 shows an output voltage waveform of an MMC having nine levels. More the levels are included by inserting series connected FCs, better is the quality of the voltage and current waveforms.

Table 2. depicts the related FC switching states. Note that a ‘0’ represents an “OFF” state, whereas a ‘1’ represents an “ON” state of respected switch.

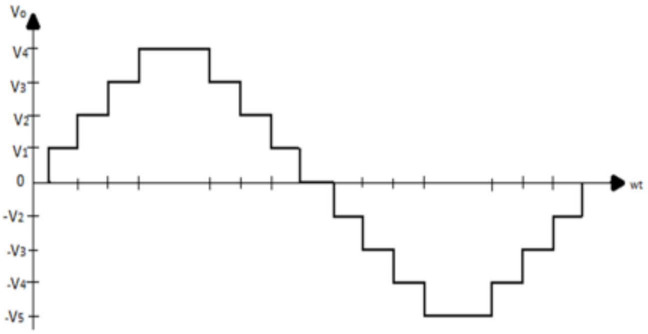


Fig. 9. Output voltage waveform.

Table 2. FC switching states.

T_a state	T_m state	Status of FC capacitor	FC terminal voltage
1	0	Charging	$+V_c$
0	1	By pass	0
1	0	Discharging	$-V_c$
0	1	By pass	0
1	1	Short circuit	-
0	0	Open circuit	-

8.3. Performance Analysis

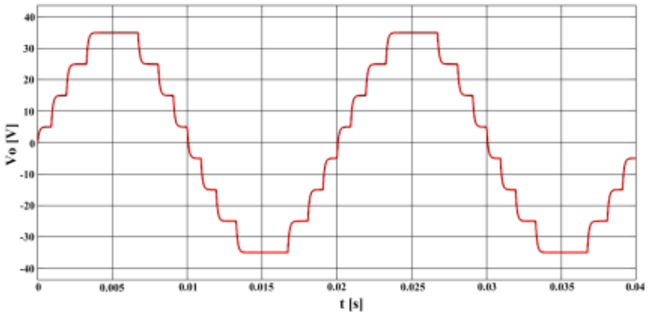
For analyzing the performance of an MMC, MATLAB/Simulink® models of MMC were made. The simulations were done for three different configurations having levels of 8, 16, and 22, respectively. The output voltage and current waveforms were examined and effects on respective THDs/quality of waveforms were analyzed. The output voltage levels were obtained by implementing parameters of Table 3.

Table 3. Simulation parameters.

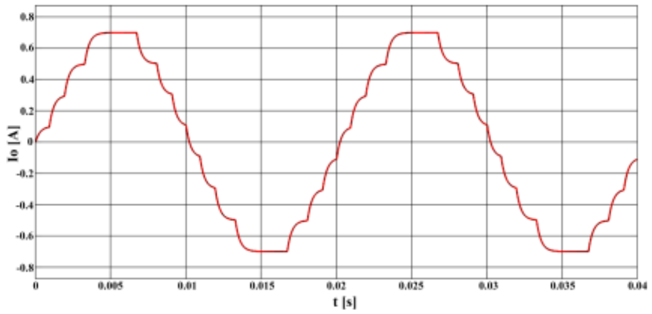
Parameters	Values
Number of FCs/arm	7, 15, 21
Number of FCs/phase	14, 30, 42
FC capacitor voltage	10 V
FC capacitor	10 uF
Modulation	NLC
Output frequency	50 Hz
Arm inductor	1 mH
Load inductor	10 mH
Load resistor	1 ohm

Here modulation technique of step waveform i.e., nearest level control (NLC) was used. Remember that for ‘m’ number series-connected FCs in upper, and ‘m’ number series-connected FCs in lower arms, i.e., for ‘2m’ FCs; the number of output waveform has ‘m+1’ levels without interleaving.

Related waveforms are shown in Fig. 10.



(a)



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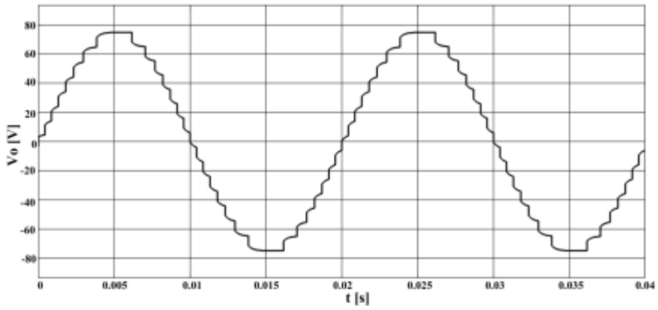

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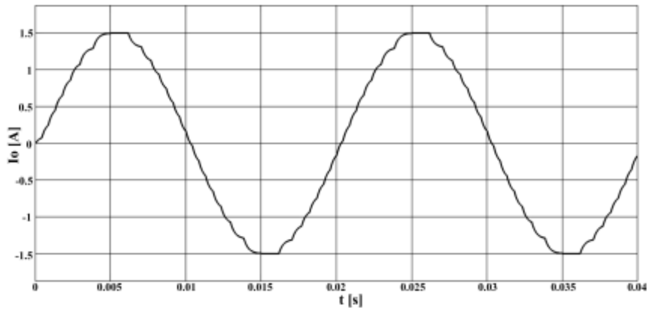
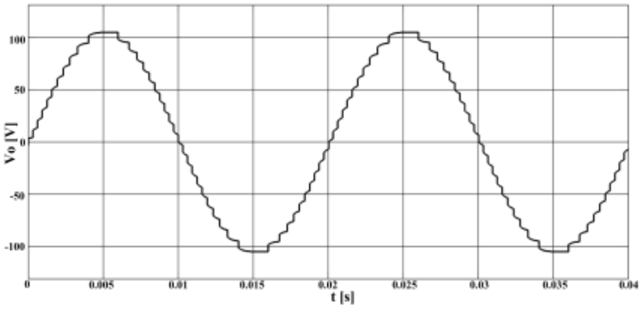
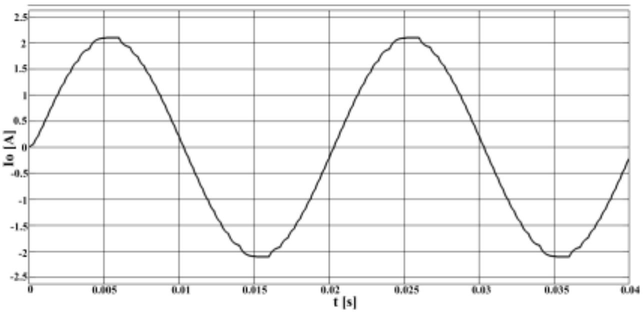


(d)



(e)



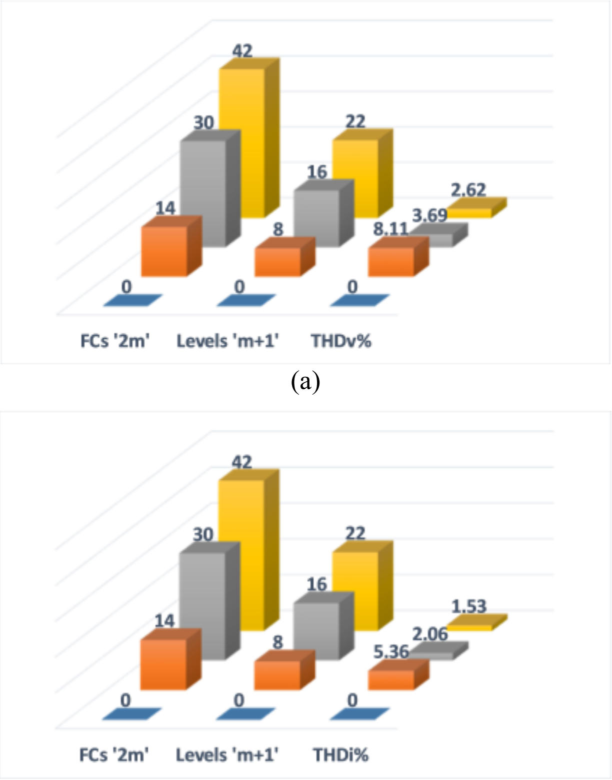
(f)

Fig. 10. MMC output waveforms (a) 8-levels of voltage (b) 8-levels of current (c) 16-levels of voltage (d) 16-levels of current (e) 22-levels of voltage (f) 22-levels of current.

Table 4. Analyses of the output waveforms.

No. of FCs (2m)	**No. of output levels (m+1)**	**THDv%**	**THDi%**
0	0	0	0
14	8	8.11	5.36
30	16	3.69	2.06
42	22	2.62	1.53

The corresponding voltage and current waveforms for a various number of output waveform levels, show voltage ‘v’ and current ‘i’ THDs as mentioned in Table 4. The graphical analyses are shown in Fig. 11.



(a)

(b)

Fig. 11. MMC output waveforms analyses (a) Effect of no. of FCs and Levels on THD of voltage wave (b) Effect of no. of FCs and Levels on THD of current wave

8.4. Technical Outcomes

The above analyses noticeably indicate that increasing the number of MMC' FCs, and levels, positively increase the voltage levels, decrease the respective THDs, and improves the quality of the output waveforms. Improved quality of the output waveforms results in higher efficiency, lesser energy unit cost, lower production of electromagnetic interference (EMI), lesser damage to the equipment insulations, lesser decrease in equipment kVA ratings, and improved total power factor. On the other hand, NLC modulation significantly reduces the switching losses and increases efficiency as compared to high-frequency PWM switching involved in 2-level VSC converters. Technically, by enlarging the number of levels, the required DC link current is imposed on several branches. Therefore, the constant voltage sources, as well as the fundamental cells (FCs), are required to generate small current. As a result, each branch only produces small conduction loss and the total conduction losses of the system will be reduced as well.The MMC scalability feature can increase voltage levels from medium to high voltage range, thus making more power transfer capability at higher voltages with lesser line losses. Also, the FCs modularity and redundancy features can give greater ease in maintenance and fault-tolerant operation. These outcomes are summarized in Table 5 below.

Hence, we can say that renewable energies in general, and wind energy in especially; can be integrated into the existing AC grids using MMC based HVDC systems in a more viable manner.

Table 5. Comparison w.r.t. outcome parameters.

Outcome Parameters	**LCC**	**VSC**	**MMC**
Black start capability	Not practicable	Practicable	Practicable
Interconnection with weak AC networks	Very difficult	Possible	Possible
Multi-terminal connections	Very difficult	Possible	Possible
Commutation failures	Large	Less	Less
Independent control of P and Q powers	Difficult especially when distance increases	Possible	Possible
Scalability	Possible with difficulty	Possible with difficulty	Easily possible
Modularity	Less	Less	More
THD	High	Moderate	Low
Switching losses	Moderate	High	Low
Need of Transformer	High	Low	Low or nil
Need of DC/AC filters	High	Low	Low or nil
Maintenance and fault-tolerant operation	Difficult	Difficult	Easy

9. Conclusions

Hence, it is well said that wind power has a worldwide promising place in the future of electricity generation. It can be truly considered as one of the most inexpensive energy resources for harvesting electricity due to the absence of fuel cost. On the other hand, HVDC systems have obtained significant acceptance in recent times because of their specific advantages over conventional HVAC transmission systems. The viability of huge power transmission over larger spans is much cost-effective by utilizing these HVDC systems. HVDC systems have two main converter topologies i.e. CSC and VSC whereas, CSC is proven for its mature technology, high efficiency, and fault ride-through capability. Continuous developing efforts are also going on VSC especially the MMC based HVDC systems that have the benefits of low THD, low losses, less space requirement due to the reduction of bulky DC link capacitors and AC side filters, flexible control of apparent powers, and interconnection of wind energy through DC cables with existing grids by using multi-terminal configurations. Technical aspects presented in this paper, noticeably identified the significance of wind energy as a prominent renewable resource for electricity generation, as well as MMC based HVDC systems as a good choice to integrate this resource with the existing grids due to their auspicious features. Simulations were done in Matlab/Simulink® regarding the performance of MMCs, clearly demonstrate good quality of output waveforms without the need for high-frequency switching, thus reducing switching losses up to a great extent. Other encouraging outcomes drawn from these simulations, also show the supremacy of MMC technology over conventional converters' technologies. Hence, Researchers and technologists should focus on the associated enhancement and training of the personnel so that these promising technologies can be further explored in their real colors.

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