Vol. 06, No. 2 (2024) 711-722, doi: 10.24874/PES06.02.028

Proceedings on Engineering Sciences

www.pesjournal.net

OPTIMIZED WIND ENERGY SYSTEM INTEGRATION WITH VSC HVDC FOR POWER TRANSMISSION

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Received 23.05.2023.
Received in revised form 04.09.2023.
Accepted 15.10.2023.
UDC – 502.174.3

Keywords:

VSC HVDC, Power Losses, Wind Energy, Optimization

A B S T R A C T

Increased demand in renewable power move towards the balancing conventional dependent energy source lead the increase in technical development in reliable power generation. This model contains the wind speed variation, capacity, uncertainty, and production are considered in system evaluations to bring the wind power to more sustainable energy. More reliable VSC HVDC technology in power transmissions for longer distances is preferred to transmit the renewable generated energy to remote end areas. Authors introduced particle swarm optimization method into the wind integrated HVDC System. The system is developed in MATLAB/Simulink to evaluate the wind power generation performance and Transmission performance. The simulation results are correlated and validated with the existing VSC HVDC link parameters. The supremacy in wind energy with particle swarm optimization performance is validated and more viable to integrate wind energy system with VSC HVDC system to transmit the reliable power to remote areas.

1. INTRODUCTION

Growth in economy with increased electricity demand in India (Panos et al., 2015, Sen et al., 2023). encourages the expansion in the renewable power generation (Li et al., 2008), which reduces the negative effects on environment caused by burning fossil fuels and large-scale greenhouse gases (GHGs). Renewable energy is suitable and adoptable in place of coal (Liu & Chen, 2015, Guan et al., 2016, Yujun, 2017). Renewable power impact on Indian energy market is discussed by Chattopadhyay. Drastic climate change concerns increase in the expansion of photovoltaic and wind power extraction in Industrial developing countries (Sato et al., 2017, Vournas et al., 2004). India must achieve the energy targets, it has seen a significant increase in wind power production to 41.6666 GW of wind power installed around the country as of 30 September 2022, it became fourth largest in world, It has been found a drastic decline in the cost of wind power in India. A levelized tariff of 2.77 (3.5) US cents per kWh was introduced in March 2021, but it was rose to 3.57 US cents in July 2021. To minimize risk to contractors in developing wind plants, a tariff-based wind auction guidelines are introduced by central government in December, 2017.

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Through the National Institute of Wind Energy (NIWE), the government of India has set up more than 800 stations, which monitors the wind energy production at 50m, 80m, 100m, and 120m above ground level. The wind capacity installation for every financial year is shown in Figure 1. A thorough study is to be done to assess HVDC operation and the power level of wind, which can be transmitted to the isolated island (Rosyadi et al., 2015 Thadkapally, Karunakar et al., 2014). Authors contribution evaluates the amount of maximum wind power generated by wind farms and power transmission through VSC HVDC, an algorithm is proposed that incorporates wind energy characteristics and HVDC systems. The criteria used to estimate the maximum wind power generation to transmit with reliability and stability in power system. In addition, the type of interconnection influenced penetration rate. Wind power penetration can be assessed in real time using the proposed method in power system operations and planning. T&D loss need to be considered in reliability of the transmission system for long transmission lines (Karunakar et al., 2022; Jahan et al., 2017; Tada et al., 2017). For long transmission, losses will increase with inclusion of more transmission parallel paths. It needs to be considered to get the lower losses by reducing the number of parallel paths in a link. Increase transmission power capacity and decrease in parallel transmission paths in case of HVAC system can be achieved by high voltage DC transmission system for longer distances.

One of the main reasons behind develop the HVDC in India is to make one Grid one Nation policy. Already many HVDC stations established in India to make power accessible to each corner of the country. Back-to-Back HVDC stations and Power import/Export HVDC Stations are commissioned in India. Two HVDC technologies are available on the market. First is the HVDC based on line switching (LCC) which uses a thyristor. The second is the HVDC-based voltage converters (VSC) with a bipolar transistor (IGBT) insulation gate. Due to the advantage of fail-storm blocking power, poor CA device activity and constant maintenance of DC voltage in changeable current directions, VSC dependent HVDC takes more care of. Two separate back-to-back configurations would make the multi-terminal network more desirable as it needs fewer terminals and supports a failing power flow in the DC line. The HVDC PLUS technology features the approach of a Modular Multilevel Converter (MMC) was discussed. The basic concept of MMC is to build up a converter from six so-called Converter. The MMC model having promising advantages such as excellent output performance, better modularity, easy scalability, low voltage, and high current rating for the power switches, which has gained considerable attention and development. For ac grid requirement, in case of line or cable fault the fast couple to avoid blockage of the system and availability of power transmission. This makes it hard for any dynamic disturbance to go through the dc link to the other end.

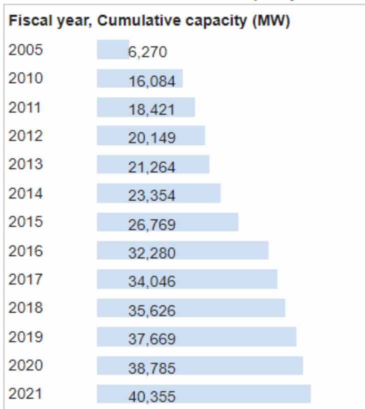

Figure 1. Wind energy installation in India for every financial year

This article is incorporating the optimization technique into HVDC link between the Pugalur station and Trichur station for study purpose. The simulation studies are analyzed by penetrating the wind energy at Pugalur AC grid. The simulation studies enumerate the necessity of VSC HVDC technology for transferring the renewable power to utility networks through an HVDC link for longer distances.

2. HVDC CONVERTER TRANSMISSION LINK TOPOLOGY)

Voltage source converter (VSCs) and Line-commutated converters (LCCs), both are prominent HVDC technologies. For VSC converter topology is not required much ac system strength for converter operation but in case of Classic HVDC a minimum ac system strength is required to operate the converters to deblock. Such advantages in HVDC light raises the superiority in direct current conversion technologies. The evolution in thyristor-based semiconductors made the DC conversion to a higher power level and more reliable in operating the system. The major advantages in voltage-sourced converter (VSC) topology makes the boost in renewable power advancement in grid integration point of view with lower ac grid strength, it become a most opt able solution than classis HVDC in power system. Still classis HVDC system is proving the superiority in longer transmission lengths and high-power transmission.

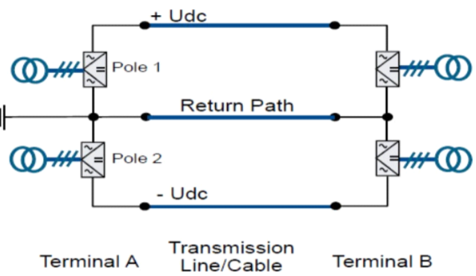

Figure 2. The Converter fed bipolar link

The bipolar configuration link needs further developments in transmission for higher power levels and higher voltage levels. The advancement in multi-link topology further enhances the grid stability, which connects two bipoles in parallel to reduce the converter power outage effect on the grid. The momentary transient power disturbance in one pole can be taken care by the other poles by allowing the shorter overload disturbances. The concept of dedicated metallic return concept is developed to avoid the power outages in case of one of the transmission line failures. The HVDC transmission system with underground cable not feasible as overhead transmission line due to the effect of higher charge capacitance generated by the cable. The proposed concept in cable transmission is cost effective. The further advancements required in current topology makes the transmission system more reliable and economical.

Several technology advancements in voltage source converters from two- and three-level topologies to modular multilevel converters (MMCs) was a major technical achievement in this technology. Modular multi-level converters mean connecting the multiple submodules in series to get a smoother AC waveform towards the grid side, which eliminates the harmonics generated by the converter, which is a most economical towards the reactor eliminating in converter DC side. Thus, DC filter and AC filter requirements can be eliminated comparing with the classic HVDC.

As shown in figure 2, a bipolar link with HVDC converter topology used, the metallic return as a return path for bulk power transmission system, to avoid the earth a as return path. The same topology can be implanted in voltage source conversion technology as a combination of two symmetrical monopole operation. In bipolar operation two poles are operated with positive and negative with neutral as a return path or grounded at converter station for reference to generate the voltage to the required high voltages. During converter operation, each pole converters are powered to same voltage level, to avoid the unbalanced current flow in return path, so the converter link I^2R losses can be reduced. The effective operation reduces the link losses.

In bipolar configurations, design includes the redundancy at least ensures the power level up to 50%. One converter outage does not affect the other converter operation or the DC link during the normal power flow case.

3. HVDC SYSTEM WITH WIND PENETRATION

The various applications demonstrate the superiority of HVDC in bulk power transmission over longer distances alternative: (1) Asynchronous grid integration. (2) The longer distance over 600 kilometers economic power transmission. (3) The power transmission through cables under the sea and land in environmentally friendly zones. (4) Renewable power integration using voltage source converter technology. Superiority in the transmission advantages, the above advantages can be merged to get economical and reliable power transmission. The Figure 3 illustrates the wind plant integration with AC grid through the voltage source conversion technology. The VSC high voltage DC transmission light system features with series connected IGBT modules, the system design approaches a model called Modular Multilevel Converter (MMC) (Flourentzou et al., 2009). The MMC model consists of six arms, in which three are upper positive arms and three are lower negative arms defines the Converter station phase arms. Presence of IGBT devices, system can operate at higher frequencies.

The controllable power electronic devices and Voltage Source Converter technologies are rapidly improving its expansion in the field of HVDC transmission and FACTS systems. Latest, research on the Multilevel Converter technology and series connected sub-modules (SMs) technology, has overcome the limitations in HVDC transmission applicational topologies. In Multi Modular Converter topology and sub module topology (SM) are the commercially accessible topologies, which are mainly the half bridge (HB) and full bridges (FB) types. It makes the system requirements in semiconductor losses, converter structural costs and fault ride through capabilities.

The submodule in converter model can be full bridge or half bridge depends on the system requirements. Half bridge type sub-module consists of two IGBT's are connected together with a capacitor to charge or discharge through a transmission link to get power transmission between the stations. Full bridge type sub module consists of four number of IGBT's connected together to form a full bridge, which is connected to a capacitor to charge or discharge the capacitor through the transmission link to transmit the power between the stations. Multi modular converter topology works with the submodule switching. The IGBT's are controlled by the converter controller to switch for the capacitor into the circuit to get the required voltage level.

There are three main sub-module structures.

- Half-Bridge: A capacitor and two IGBTs structural composition.
- Full-Bridge: A capacitor and four IGBTs structural composition.
- Hybrid-Bridge: it is a Half-Bridge and Full-Bridge structural composition.

All the Sub modules connected back-to-back with limiting reactors in series. The function mainly to limit the short-circuit currents in case of fault in valves and also to control the balancing phase currents to minimum values between the phases.

Table 1. Half -Bridge Sub-Module operation.

Status	IGBT 1	IGBT 2	Variable cases
Block State	0	0	if $i_{pharm} > 0$: $Vsm_n=Vc_n$ if $i_{pharm} < 0$: $Vsm_n=0$; Vc_n = Float
On State	0	1	$Vsm_n=Vc_n$: $i_{pharm} = i_{Cn}$:
Off State	1	0	$Vsm_n=0$: $i_{Cn}=0$

In VSC HVDC and FACTS systems, multi modular converters (MMCs), contains many no. of SMs (Gu et al., 2017). Therefore, controlling the system and each submodule is very difficult, so required proper controls and protection systems modelling for such converters. Table 1. summarizes the submodule operation states and parameters of the half-bridge. Half-bridge circuit consists of 3 operating modes: Block state, ON state and OFF state. In case of faults in the system, the submodule goes to block state to limit the fault severity, which is later turned it to OFF state.

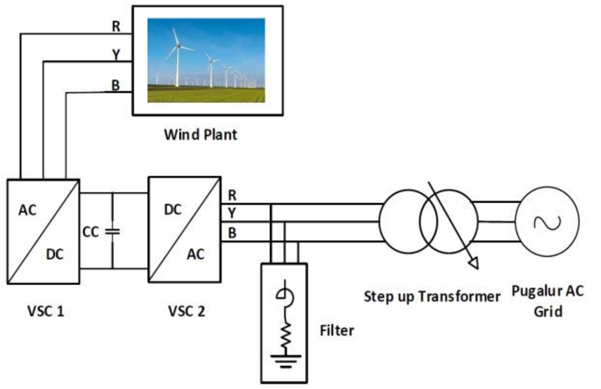

Figure 3. Wind Energy penetration illustration into grid system

Different wind control technologies are discussed in (Yoshida et al., 2015), and it has been established with different technologies have different voltage and current rating depending on their power rating. High voltage DC transmission with wind plant using various optimization methods can be optimal in power transmission in economical point of view (Gu et al., 2017).

Table 2. HVDC Parameters.

S.	Parameter	Ratings/Topology
1	Rated Power Flow	1000 MW
2	MMC Levels	331
3	Sub-module	Half bridge
4	Rated Pole Voltage [U_{dc}] (Positive to Negative)	640 KV
5	Pugalur AC Grid	50 Hz, 400 kV, 36.4 GVA, X/R =10
6	Thrissur AC Grid	50 Hz, 400 kV, 36.4 GVA, X/R =10
7	Converter Transformer	400/380 kV, 367 MVA,
8	Leakage Impedance	17.5%
9	Neutral Grounding Reactor	Lg = 6 kH, Rg = 2.5 kΩ,
MMC Sub-module Parameters		
10	Nominal Switching Frequency	100 Hz
11	Capacitor	8.5 ±2% mF
12	Peak Turn-off Current	3300 A
13	DC Reactor per arm	90 mH
Power Transmission Parameters		
14	Conductor size	2500 mm2
15	Conductor	Copper
16	Insulation	XLPE insulation
17	OHL length	143 km
18	Cable Length	32 km
19	OHL DC Resistance	23.27 mΩ/km
20	Cable DC Resistance	9.2 mΩ/km

The Pugalur is naturally high windy area, can extract high wind energy by installing the wind plants. Hence, the recent study proves the superiority in wind power integration with Pugalur AC grid using particle swarm optimization in power generation optimization. This article mainly focuses the voltage source conversion technology on wind power optimized using PSO algorithm integrated with AC grid of Pugalur (High wind zone) connected to AC grid of Thichur (Remote islanded area) via voltage source converter HVDC link. The existing converter link between the Pugalur and trichur2, the main circuit parameters are shown in Table 2.

4. CONVERTER LINK WITH HVDC NETWORK

As shown in Figure 4, two IGBT converter stations are connected with overhead DC line and DC cable, here DC cable and DC OH lines are connected by transition station. The HVDC link comprises the wind power transmission between the two AC grids, which are in southern part of India. Modular multilevel converters

(MMC) with IGBT switching technology proves a major advantage on power conversion from AC to DC. The MMC technology is developed using connecting the IGBT's in half bridge and full bridge called as sub modules, depends on the grid requirements. The greater number of sub modules per arm replicates the less harmonics in the energy conversion, which gives the harmonic free AC and DC power conversion. The Figure 4. shows the Voltage Source Converter HVDC transmission, operating at +/- 320 KV at DC terminal, mainly consists of symmetrical monopole configuration. The VSC HVDC (HVDC Plus) system configuration concentrates current control system and module management system. The PK-2000, VSC HVDC Project interconnects two AC grids which are 400 KV AC stations. The two 400 KV AC substations at Pugalur (Tamilnadu) and Thrissur (Kerala) are interconnected by VSC HVDC link. The bi-directional power transmission capacity is 2000 MW referred to the DC terminal of the sending end. Two DC systems with a rated power of 1000 MW installed at both Pugalur and Thrissur stations, consisting of a voltage sourced converter (VSC) in each station.

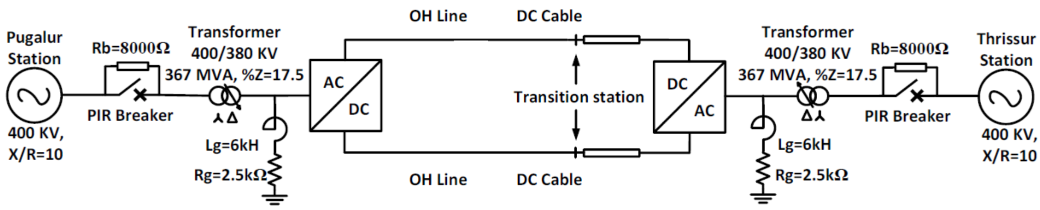

Figure 4. PK2000 VSC HVDC transmission line between Pugalur and Trichur

The converter link is a multi modular converter model and half-bridge model. The MMC consists of N Sub-modules per each phase arm which makes switching levels into (N+1) levels of line-to neutral voltage. Each Sub-module structure can be a half-bridge structure or full-bridge structure. Based on grid requirements, multi modular converter includes combination of both half and full-bridge sub modules in each phase arm. In PK2000 used half bridge topology for voltage source converter model.

The symmetrical monopoles are established with a hybrid transmission circuit consisting of approximately 143 km of DC overhead lines and 32 km of high voltage DC cables. Electrodes for ground return will not be provided. The DC cables will terminate directly in the North Trichur converter station. The other termination will be located in a remote transition.

5. PSO FOR MAXIMUM POWER AND TORQUE TRACKING

To track the maximum power and torque, an optimization method is preferred to get the better results. Authors are preferred PSO Algorithm to trach the power and torque of the wind system. PSO is a performance simulation of fish training or bird flocking. This algorithm uses real time data from the system for simulation to get optimized results from current engineering issues (Sato et al., 2017). Mainly particles will perform and generate the fitness function and the fitness values are to be optimized by their evaluations. So, that the particle movement and velocities are simulated through the particles (Franck, 2011).

The particle moment is tracked mathematically as below:

$$V_s(t+1) = wV_s(t) + c_1 r_1 (p_{best} - x_s(t)) + c_2 r_2 (G_{best} - x_s(t))$$
$$X_s(t+1) = X_s(t) + V_s(t+1) \qquad (1)$$

Where $V_s(t)$: change rate in displacement; $X_s(t)$: displacement; P_{best}: local optimum, G_{best}: global optimum; C_1 : Cognitive acceleration constants , C_2 : social acceleration constants are selected with expertise ($C_1+C_2 = 4$); w: inertia weight; and r_1 and r_2 are random values the chosen range is [0, 1] for optimization. The Algorithm is proposed for wind generation flow chart representation shown in Figure 5.

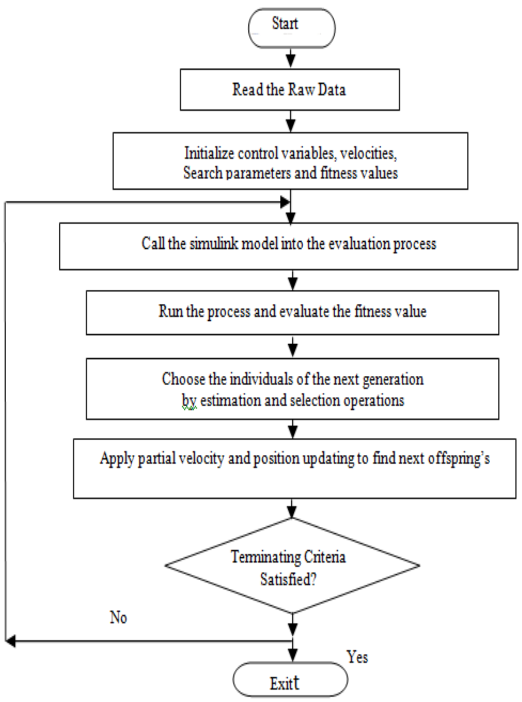

Figure 5. Flow chart of PSO Algorithm

The PSO derives the better Kp and K_I values to the system, as shown in Figure 6.

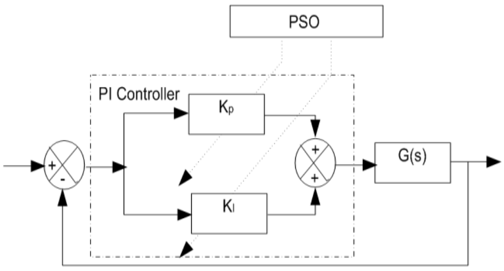

Figure 6. PI controller illustration.

In Figure 6, PI controller the K_P and K_I gains are selected optimal values for the objective function. The output response with K_P and K_I gains, mentioned below:

$$G_c(s) = k_p + \frac{k_i}{s} \tag{2}$$

The controller output u(t) is given by,

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt \tag{3}$$

The wind plant requires to track and generate maximum power align with HVDC station requirements. Thus, this power tracking is taken care by the PSO algorithm, which discussed above. PSO is one of the best methods to get optimized results for the power tracking in wind energy system.

The proposed maximum power and torque tracked for a series of winds using PSO algorithm is expressed in the below equations:

$$P_{m-opt} = \frac{1}{2}\rho\pi R^5 \frac{C_{Pmax}}{\lambda_{opt}^3} w_m^3 = k_{p-opt} w_m^3 \tag{4}$$

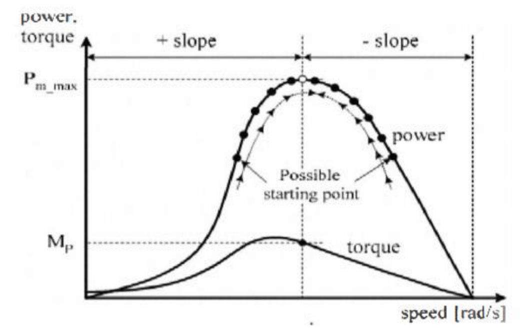

Figure 7. Maximum power and torque tracking process of wind speed with PSO.

Considering that $P_m = w_m T_m$, the T_m can be rearranged as follows:

$$T_{m-opt} = \frac{1}{2}\rho\pi R^5 \frac{C_{Pmax}}{\lambda_{opt}^3} w_m^2 = k_{p-opt} w_m^2 \tag{5}$$

The 2D optimization problem is used to get the acceleration coefficients for PSO algorithm.

6. SIMULATION RESULTS

As shown in Figure 8, The HVDC power link is implemented in MATLAB/Simulink by considering the RT (real-time) parameters and power flow requirements.

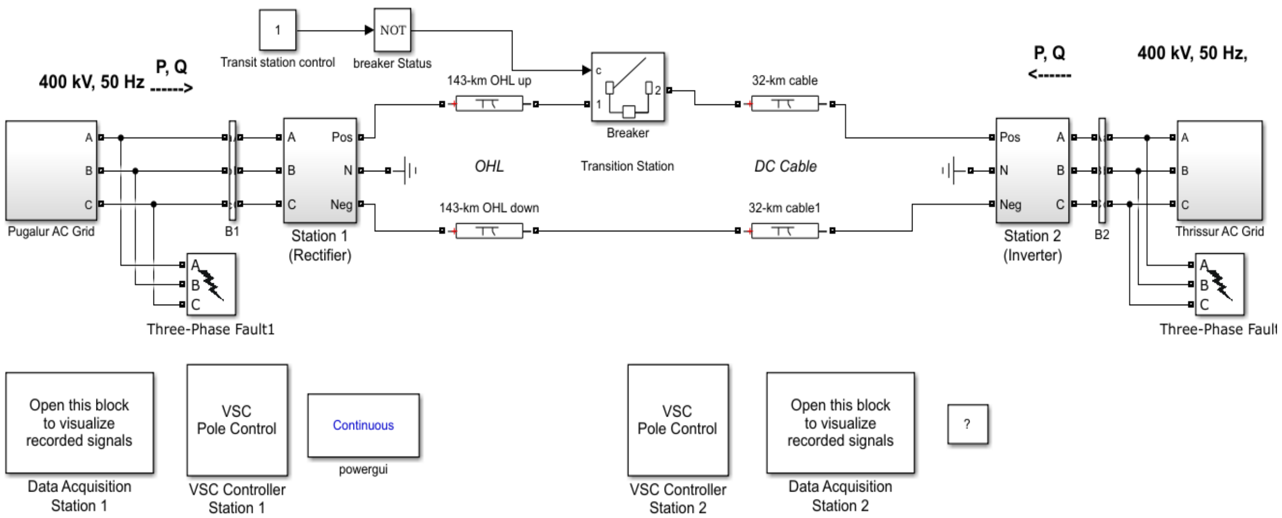

Figure 8. Dynamic simulation model of HVDC System

The present work focuses on real time data modelling of the wind energy source injecting into the Pugalur AC grid and there by transmitting the power to Thrissur AC grid. Figure 9 illustrates the modelling of Pugalur and Thrissur AC grid. Figure 10. illustrate wind energy subsystem model, which id fed into the Pugalur AC grid with control scheme. An optimal solution in renewable power generation will make the system to be more reliable and dependent. Authors proposed an optimal solution in wind dependent generators makes the system more reliable towards the power generation. Most optimal energy source is required to fulfill the global carbon free power initiative. the performance evaluation is done by considering an existing VSC HVDC station parameters and integrating with optimal wind source.

The system analysis represents the wind energy extraction and transmission to longer distances. The simulation results enumerate the actual power generation and transmission, which clarifies the possibility and incorporation of such technologies in existing HVDC systems. The results represent the actual performance of HVDC system, simulated by Matlab/Simulink.

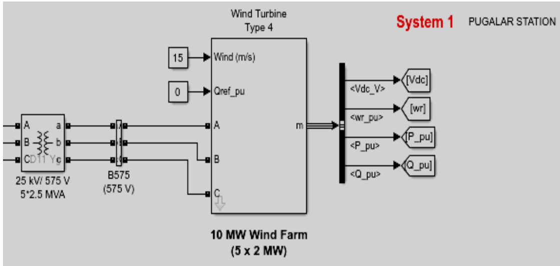

Figure 9. Wind Energy fed Pugalur AC grid.

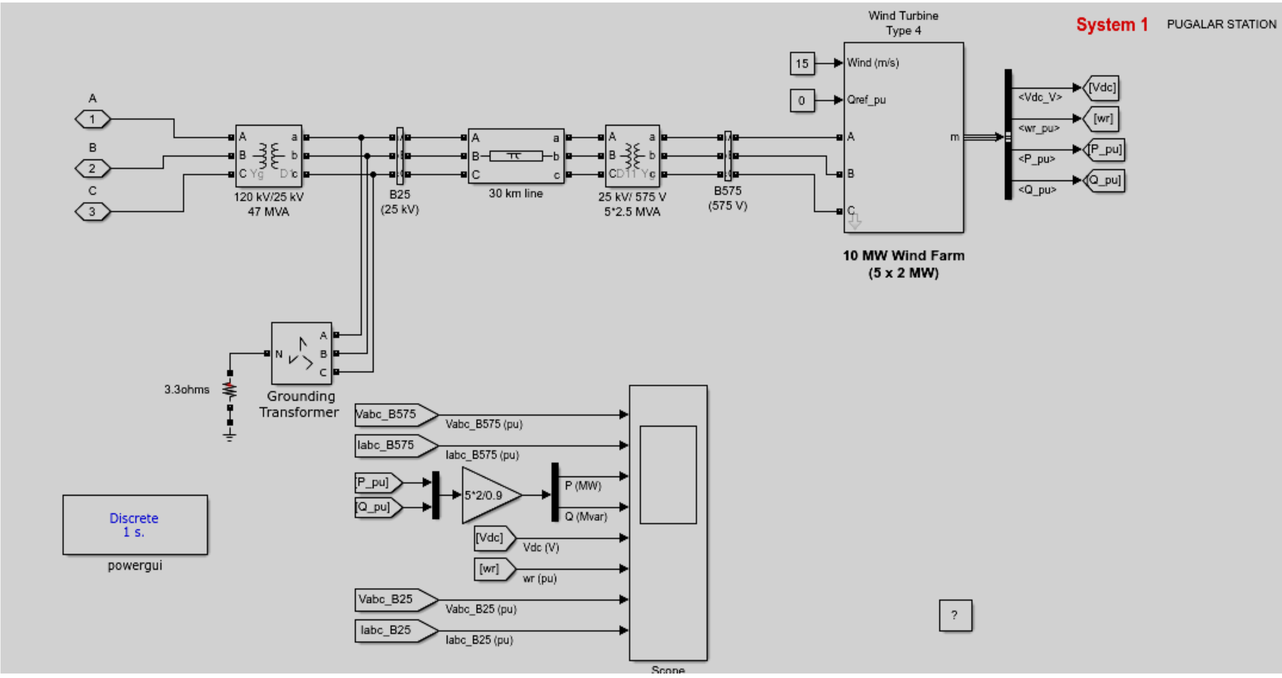

Figure 10. Wind energy fed grid Pugalur supply station illustration

System analysis represents the wind energy extraction and transmission to longer distances. The simulation results enumerate the actual power generation and transmission, which clarifies the possibility and incorporation of such technologies in existing HVDC systems. The results represent the actual performance of HVDC system, simulated by Matlab/Simulink.

The optimization technique used in voltage deviation and maximum torque tracking for various values of c1 and c2 as mentioned in equation 1. The number of iterations for different values of c1 and c2 are shown Figure 11. Various wind speeds versus maximum power generation, by tracking the peak values of generation represents the maximum power generation, which is illustrated in Figure 12. The optimum torque at various wind speed can be obtained the Figure 13, the maximum toque can be obtained by tracking the generated torque peak values.

The existing HVDC system parameters are considered for the simulation, later then converter to per unit values for better understanding. The system dynamic performance can be performed, further analysis can be performed by creating the parameter variations and system disturbances. The same parameters are considered in the existing MATLAB code/MATLAB Simulink. The simulation results are enumerating the system superiority in renewable integration with the HVDC system.

The results are validated with the real time running project, both station voltage and current profile matching with integration of wind energy in the One end of the source converter. The figure 12 depicts the maximum power through tracking the wind speed with particle swarm algorithm. The peak values of the power capability will be tracked by the graphical representation as shown in the figure 12. The figure 13 enumerate the generated speed with the torque. The optimum torque is observed by the peak torques. The station 1 output DC voltage is illustrated in the figure 14, which gives the per unit representation of the measured voltage, output voltage and the power. The gate pulse to the IGBT switching and the converter voltage controlled by modulation index at with which the pulse can be generated. The direct axis and quadrature axis voltage references are generated to the get the required converter voltage at the terminals od the converter by controlling the pulse width modulation.

The result analysis and waveform representation as given below,

1. The optimized voltage in power tracking through the number of iterations with modulating the c1 and c2 as shown in figure 11.
2. The Figure 12 & 13 illustrates the maximum power and torque tracked with optimized DC link voltage of HVDC and wind penetration system.
3. The results obtained for the station-1 and station-2 converter station outputs are shown in Figure 14 and Figure 15, the converter outputs DC voltage and Dc power are illustrated in per unit values.
4. The station-1 and station-2 converter control parameters to generate the switching pulses are shown in Figure 16 and Figure 17. The reference values for active power and reactive power are illustrated.
5. In Figure 18, illustrated the modulation index of the station-1 converter control and given converter voltage reference. In Figure 19, illustrated the station-2 converter station filter performance.

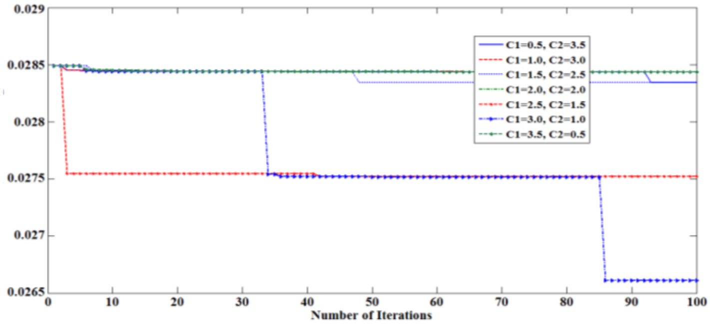

Figure 11. Voltage deviation optimization and power tracking using PSO Algorithm.

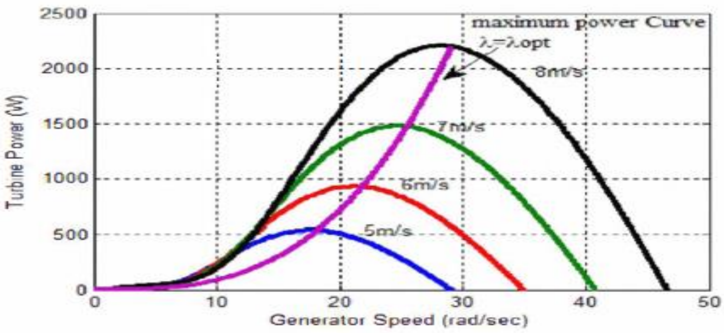

Figure 12. Maximum powers tracked for a series of wind speeds with PSO.

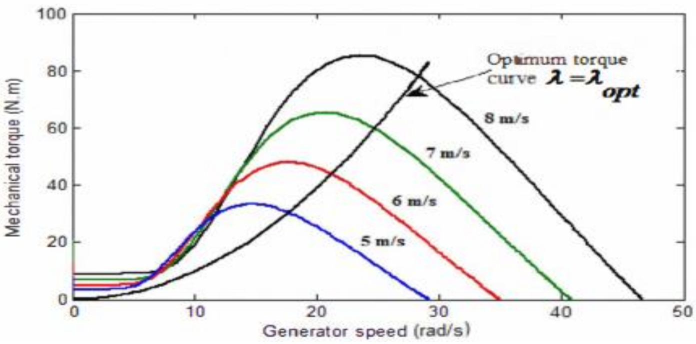

Figure 13. Maximum Torque tracked for a series of generated speeds with PSO.

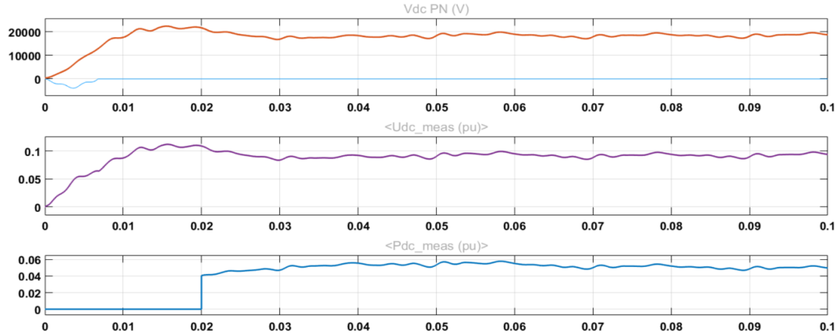

Figure 14. Station-1 output illustration.

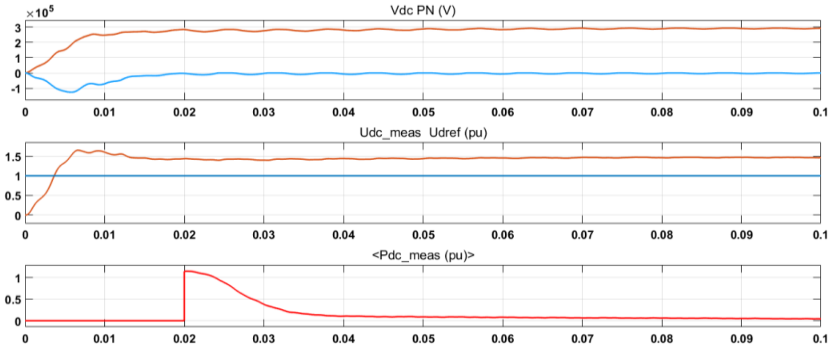

Figure 15. Station-2 output illustration.

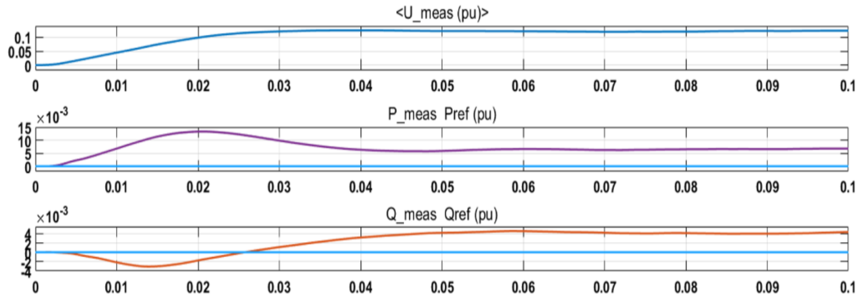

Figure 16. Station-1 VSC control station performance.

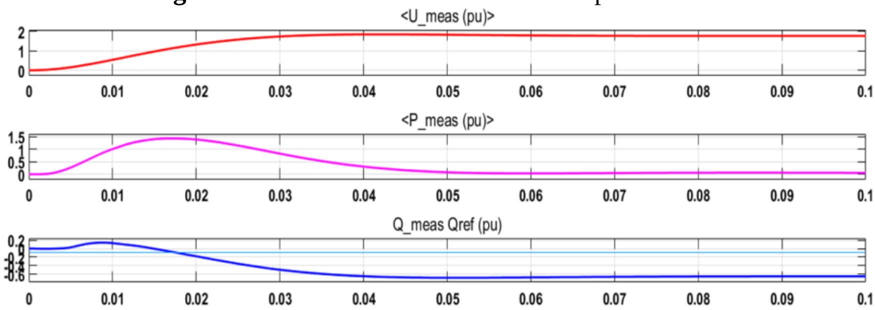

Figure 17. Station-2 VSC control station performance.

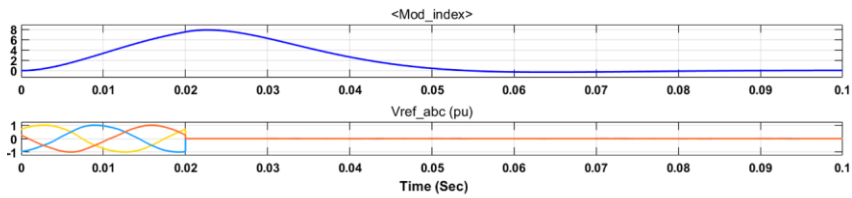

Figure 18. Station-1 modulation index and reference voltage.

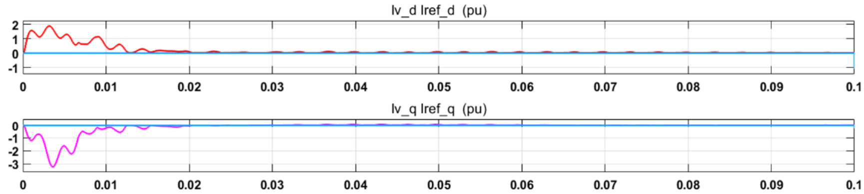

Figure 19. Station-2 filter performance.

6. CONCLUSION

The wide range of solution availability for the HVDC systems, the grid integration with renewable is having brighter scope with improved optimization methods. This article focused on performance analysis with particle swarm optimization logic incorporated in wind generation later then integrated with existing VSC HVDC link. This paper represents VSC HVDC integration with wind power and MATLAB simulation with power optimization are analyzed. The simulation results represent the maximum power tracking from wind energy, with improved AC grid parameters and DC grid parameters, which are validated with existing VSC HVDC link. The possible integration with renewable power in existing HVDC link is more adoptable. Renewable energy sources like Solar, Wind, Tidal, Hydro etc. can be integrate with existing grids. By combining HVDC with LCC & VSC technologies with renewable power generation can be fulfil future green energy initiative. To ensure sustainable and environmentally friendly power, HVDC technology is most adoptable. By Comparing both conventional and renewable power resources, the alternative power supply systems, further developments in technology are required. This simulation study concludes the existing grid integration can be possible with a high proportion of renewable energy sources will give effective results.

Acknowledgement: This paper gives the study and analysis of voltage conversion technology feasibility with renewable power integration with existing HVDC converter station. Then transmit the power over longer distances. This work was initially taken transmission link parameters form the existing HVDC converter station PK-2000 VSC HVDC Project (Power Grid Corporation of India Ltd).

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