An Overlay of MTDC Grid to Relief Congestion of Power System

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***Abstract*—Large amounts of wind power integration are expected to take place in the Indian grid in the next decade. This is likely to create several challenges from the point of view of power evacuation and power routing in the existing system. This may also require significant infrastructural construction to meet the increasing power flow demand. In this paper, the existing 765 and 400 kV networks are investigated for large scale wind power injection with penetration exceeding 5200 MW. It is identified that this will lead to significant congestion on the existing system. An HVDC overlay solution with an identification of the buses is proposed. It is shown that the solution will result in no congestion on existing network and may bring in additional benefits from the point of view of stability and additional operational flexibility.**

***Index Terms*—Wind integration, power congestion, MTDC system.**

I. INTRODUCTION

The advantages of the large power system are well known but it increases the risk of grid failure. The continuous increase of load demand and advancement on power electronics devices is increasing the integration of renewable energy into AC grid [1]. The increase in renewable energy penetration is mandated by a policy decision of the government of India. The inclusion of renewable energy sources may lead to reduce damping and increases the likelihood of blackout [2].

The renewable energy sources typically located in a remote location and require sufficient means to evacuate power. The renewable energy sources in India, especially wind energy, are located in the western and southern parts [3]. These locations are either remote or away from the load centres. In addition, 175 GW of renewable energy sources is mandated to be added to the grid by 2022 [4]. Table I shows the state-wise installed capacity of wind energy in India. The southern state of Tamilnadu and the western states of Maharashtra Gujarat and Rajasthan have the largest wind energy installation in the country [3]. In addition, the growth of installed wind energy capacity in India has been steadily increasing with the capacity being about to 32 GW at end of 2016 [4]. This may require long transmission lines thus making high voltage direct current (HVDC) transmission as feasible option [5]. Usually, line commutated converter (LCC) based point to point HVDC systems are employed. Which is feasible but these systems have large reactive power requirement and may have difficulties in operating with a weak grid. Besides the power flow reversal is a complicated affair since it involves voltage polarity reversal.

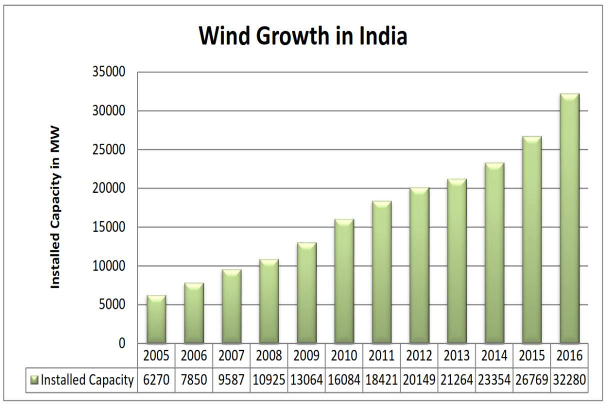

Fig. 1: Growth in wind energy in India

TABLE I: State-wise Installed Capacity

SI.	States	Wind Installed (MW)
1	Andhra Pradesh	1393.5
2	Gujarat	4030.65
3	Karnataka	2878.3
4	Kerala	43.4
5	Madhya Pradesh	2171.9
6	Maharastra	4670.65
7	Rajasthan	3994.9
8	Tamil Nadu	7652.15
9	Telangana	77.5

The increased power production by renewable sources may also cause problems for routing power flow and may lead to congestion in the existing AC network [6]. There could also be challenges regarding voltage profile increased the losses and concern regarding system stability due to increase in power production [7]. Apart from this the recent advancements in power electronics, the high voltage DC grid appear to be feasible. This grid based on voltage sources converter offer several benefits compared to conventional LCC base system. The voltage source converter (VSC) system facilitated easy power reversal along with decoupled real and reactive power and enhanced performance with the weak grid. They also have a black start capacity [8]. These features make the VSC based grid an attractive option for grid integration of renewable energy sources.

An HVDC grid may provide a solution to effectively utilizes large amounts of renewable energy by relieving congestion. It also provides a possibility to leverage the temporal shift in peaks of the power demand between eastern and western part of the country. The excess power from southern and western grid could also be rapidly transferred to utilizes the tariff differences. Thus reducing the cost of power [4].

The paper proposes an overlay of the MTDC/HVDC grid system on the existing high voltage network in India to relieve transmission line congestion and increase the penetration level of the renewable energy sources in the grid. To this effect, the paper assumes an increase in power generation at certain buses and identifies congestion on power lines along with the associated high voltage buses using power flow techniques. The increase in penetration level indicated that more lines get congested as amount of power injected is increased. In a subsequent step, the congestion is relieved by the inclusion of VSC-based five terminal HVDC grid. The location of five terminals are identified based on the congestion observed and the HVDC terminal power ratings are chosen to be greater than the amount of power injected.

II. PROBLEM DEFINITION

With reference to system of Fig. 2 the paper aims to identifies the congested AC transmission lines when new renewable energy sources are added to the region 5. It also identifies the buses at which VSC based HVDC terminals are to be added to relieve the aforementioned congestion. The adopted process assumes gradual increase in renewable energy penetration and step-by-step addition of VSC terminal and HVDC line to the system. The study is restricted to the five regions indicated in the Fig. 2 and thus congestion relieving outside the region indicated is not considered.

III. SYSTEM DESCRIPTION

A sub-part of the Indian high voltage grid is considered for investigation in this paper. Fig. 2 shows a partial view of the grid under consideration. Fig. 2 shows only certain lines whereas other lines though present in the database have not been shown. The modeled system is obtained from an utility. The buses and the lines have been renamed to retain anonymity of the study. The system is divided in to five regions that are connected with high voltage lines. The 765 kV and 400 kV voltage levels shown in the figure. The existing network is constructed with on HVAC transmission lines. These lines are likely to get overloaded when large power is injected in the system. The investigation of the system assumes large amount of power generation is added to Region 5. With such large power addition the power flow in the system are altered drastically.

IV. TEST CASES

For investigation, eight test cases are defined. The details of the test cases are given in Table II. The base case assumes the system as is without any additional power being injected. The base case is executed to determine if there are any inherent congestion in the network. The test cases starting from Case 2 to Case 4 progressively add wind power in Region 5 of the system. This progressive addition of new generation leads to increased green energy penetration in the system. The peak value of renewable energy penetration is assumed to be 5200 MW. The test cases from Case 5 to Case 8 progressively add the VSC-based HVDC lines to the system. The power flow investigations for the system are conducted in PSS/E. The wind generator is modeled as equivalent source and VSC terminals are modeled as an equivalent converter system.

TABLE II: Test cases

Test cases	Description
1	Without wind integration
2	1500 MW wind integration
3	3000 MW wind integration
4	5200 MW wind integration
5	One HVDC line and two converter station
6	One HVDC line and one converter station
7	Two HVDC line and one converter station
8	Two HVDC line and one converter station

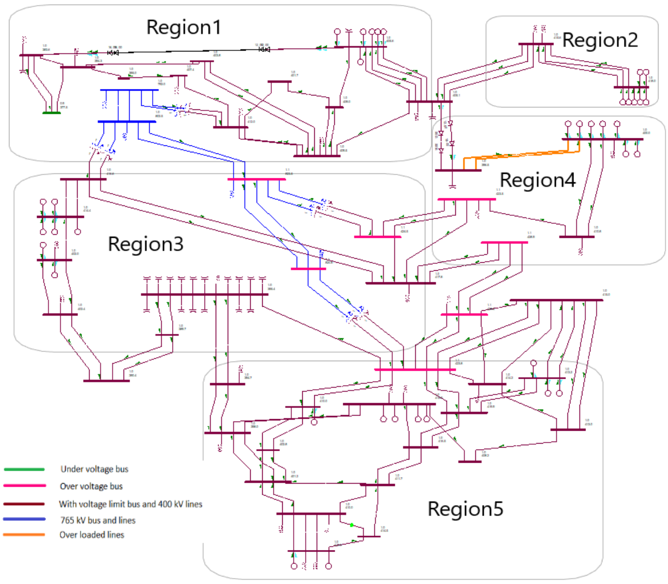

Fig. 2: Single line diagram without wind power injection

V. SIMULATION RESULT

A. Without wind integration

Fig. 2 and Table III show the results for the test cases 1 to 4 where the wind energy penetration is progressively increased from 0 to 5200 MW. In Fig. 2, the blue color indicates the 765 kV line and grey indicates 400 kV line. In order to differentiate the under and over voltage conditions three bus colors are used. In this classification, grey color is used for voltages which are within limits of $\pm 5\%$, pink color represents over voltage and green color is for under voltage situation. The results of base case without any addition wind energy indicate that 5 lines at 400 kV and zero lines at 765 kV are overloaded. The excess power flowing on these lines exceed their thermal capacity by maximum of 156 %. The excess power available in the region 2, 3 and 4 are being fed to the region 1 and 5. The direction of power flow are from region 2 to region 1 and region 3 to region 5. There are few lines which are overloaded. In the region 4 only a line connecting bus F202 to F214 is operating close to its thermal limit. The buses in the region 3, 4 and 5 are seen to have over voltages due to light loading condition. It can be easily projected that there would be several more power flow violation on the network as the wind power is added to region 5.

TABLE III: Transmission Line Loading for Different Wind Power Injection

Line Information					Without Injection		1500 MW Injection		3000 MW Injection		5200 MW Injection	
From bus	To bus	Lines	Region	Rated	Loading	% MW	Loading	% MW	Loading	% MW	Loading	% MW
T301	T313	6	Re1	515	556.2	108	538.2	104.5	523.5	101.6	504	97.9
T312	T313	7	Re1	515	666.7	129.5	608.7	118.2	561.1	108.9	495.8	96.3
T315	T348	8	Re1	777	1216	156.5	1095.8	141	993.3	127.8	845.7	108.8
T510	T511	9	Re1	777	768.5	98.9	755.9	97.3	744.5	95.8	726.1	93.5
F202	F214	10	Re4	517	506.3	97.9	506.3	97.9	506.3	97.9	506.3	97.9
F303	F310	11	Re3	692	-	-	-	-	656.6	94.9	745.2	107.7
F404	F405	12	Re5	517	-	-	-	-	615.5	119.1	533	103.1
F405	F410	13	Re5	517	-	-	-	-	667	129	746.5	144.4
F410	F429	14	Re5	517	-	-	-	-	630.8	122	687.2	132.9
F417	F429	15	Re5	681	-	-	-	-	631.5	92.7	687.2	100.9
T304	T340	16	Re1	515	-	-	-	-	-	-	533.6	103.6
T306	T341	17	Re1	515	-	-	-	-	-	-	581.1	112.8
T317	T340	18	Re1	515	-	-	-	-	-	-	541.3	105.1
T340	T304	19	Re1	1500	-	-	-	-	-	-	1621.4	108.1
T355	T309	20	Re1	1500	-	-	-	-	-	-	1619.4	108
T304	F301	21	Re1,3	2300	-	-	-	-	-	-	2448.3	106.4
F101	F301	22	Re3	2194	-	-	-	-	-	-	2723.3	124.1
F306	F309	23	Re3	681	-	-	-	-	-	-	848.1	124.5
F306	F311	24	Re3	517	-	-	-	-	-	-	517.4	100.1
F401	F418	25	Re5	517	-	-	-	-	-	-	575.9	111.4
F403	F404	26	Re5	517	-	-	-	-	-	-	636.5	123.1
F403	F404	27	Re5	517	-	-	-	-	-	-	691.6	133.8
F410	F415	28	Re5	517	-	-	-	-	-	-	512.8	99.2
F414	F601	29	Re5	517	-	-	-	-	-	-	546.4	105.7

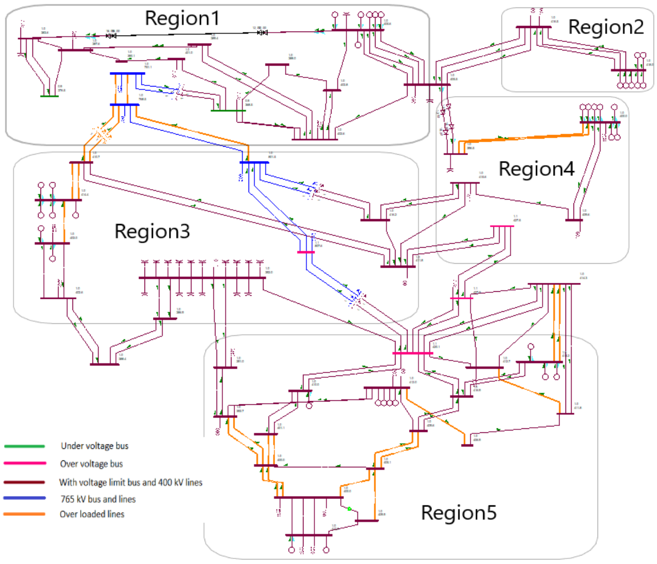

Fig. 3: Single line diagram with wind power injected

B. *With wind integration*

The test cases 2 to 4 represent a gradual increase in wind power penetration from modest value of 1.5 GW to 5.2 GW. This increase assumes that no infrastructural updates are made during this period. On the contrary as an outcome the required infrastructural upgrades can be identified. In our case study a maximum of 5200 MW wind power is injected into region 5. The location of wind injection bus is identified based on distance and voltage rating with assumption that wind farm is concentrated at particular location. The three buses T404, T405 and T417 are best location for wind injection based on information available. These buses are 400 kV bus and are located in the bottom of region 5. The injection of power is done in three stages: 1) 1500 MW injection in bus no F417 2) 1500 MW injection in bus no F405 and 3) 2200 MW injection in bus no F404.

As can be seen in the Table III with addition of 1.5 GW of wind power, the loading of certain lines reduces compare to the base case. The injection of 1.5 GW into bus no F417 has reduced the power coming from the region 3 and 4 into region 5. The power coming from region 1 to region 3 become almost zero and from region 1 to region 4 remain same due to power controlled HVDC line. There is no power congestion on any line except region 4, which is already congested line before wind injection. These is attributed to the locally met demand by addition of wind power in region 5.

For case 3, it is seen that with the injection of 3 GW of power some new lines start operating close to their thermal limits. The lines in region 2 see reduction in loading compare to case 1 and case 2. The injection of 1.5 GW into bus no F417 and 1.5 GW into bus no F405 has revised the direction of power flow from region 1 to region 3 and also from region 3 and 4 to region 5. Now the region 5 start to feed power to region 1. The power coming from region 2 to region 1 also reduced due to excess power coming from other regions. This wind injection has increased the power congestion on the lines in the region 5. As shown in Fig. 3 five lines out of eight overloaded lines are overloaded due to 3 GW power injection in region 5. The overloaded lines are shown in orange color. In a Table III, 9th and 10th columns show the actual loading and percentage loading with respect to their maximum limits.

The injection of 1.5 GW into bus no F417, 1.5 GW into bus no F405 and 2.2 GW into bus no F404 starts to over load the line connecting the region 1 and region 3 as well as lines in region 5. The lines overloaded in all regions are given in the 11th and 12th column of Table III. It is also depicted in the Fig. 3 using orange color line. In Table III, the loading of few lines are start to decrease and other lines start to increase because of direction of power flow. The case 4 results the addition 5.2 GW of power show that a large no of lines been overloaded thus represents heavy congestion and also indicates significant difficulties in evacuating power to

TABLE IV: Transmission Line Loading for with and without MTDC lines

Line Information				5200 MW Injection		1^{st} HVDC line		2^{nd} HVDC line		3^{rd} & 4^{th} lines		5^{rd} & 6^{th} lines	
From bus	To bus	Lines	Rated	Loading	% MW	loading	% MW	loading	% MW	loading	% MW	loading	% MW
T301	T313	6	515	504	97.9	502.9	97.7	500	97.1	495.7	96.8	-	-
T312	T313	7	515	495.8	96.3	491.7	95.5	484.4	94.1	481.3	93.4	-	-
T315	T348	8	777	845.7	108.8	836.1	107.6	823.3	106	817.8	105.3	-	-
T510	T511	9	777	726.1	93.5	724.8	93.3	724	93.2	723.7	93.1	731.4	94.1
F202	F214	10	517	506.3	97.9	506.3	97.9	506.3	97.9	506.3	97.9	506.3	97.9
F303	F310	11	692	745.2	107.7	746.1	107.8	668.4	96.6	-	-	-	-
F404	F405	12	517	533	103.1	-	-	-	-	-	-	-	-
F405	F410	13	517	746.5	144.4	-	-	-	-	-	-	-	-
F410	F429	14	517	687.2	132.9	-	-	-	-	-	-	-	-
F417	F429	15	681	687.2	100.9	-	-	-	-	-	-	-	-
T304	F301	21	2300	2448.3	106.4	2545.4	110.7	-	-	-	-	-	-
F101	F301	22	2194	2723.3	124.1	2929.6	133.5	-	-	-	-	-	-
F306	F309	23	681	848.1	124.5	834.8	122.6	629.2	92.4	-	-	-	-
F306	F311	24	517	517.4	100.1	484.9	93.8	-	-	-	-	-	-
F401	F418	25	517	575.9	111.4	-	-	-	-	-	-	-	-
F403	F404	26	517	636.5	123.1	-	-	-	-	-	-	-	-
F403	F404	27	517	691.6	133.8	-	-	-	-	-	-	-	-
F410	F415	28	517	512.8	99.2	-	-	-	-	-	-	-	-
F414	F601	29	517	546.4	105.7	-	-	-	-	-	-	-	-

the other regions of the grid. This observation points toward significant infrastructure changes to overcome the challenges.

VI. IDENTIFICATION AND REQUIREMENT OF SOLUTION

Based on the results of test cases 1 to 4, it can be seen that changes are required to mitigate the issues of line congestion, voltage variation and control of power flow. Thus solution should have the capability of easily routing the real power and also facilitate easy manipulation of reactive power. It also expected that the performance of the propose solution should result in benefits for damping control and improve the dynamic performance of the grid during contingencies. The five regions of Fig. 2 a geographical separated by large distance which entails long high voltage transmission line. Thus requiring expensive right of ways and large compensating terminal equipment. These requirements are over and above the needed large power handling capacity. A VSC based HVDC system offer several benefits which are aligned with the above identified requirements.

A MTDC system consists more than two converter stations. A decouple inner current loop of each converter facilitates independent active-reactive power control. The power control loop can control the active power or DC voltage or frequency of the AC grid depending on the requirement. On the other hand the reactive power control loop fasilated automatic control of reactive power exchange between the converter and the AC grid as well as the control of AC side voltage. The tertiary level controller coordinate all converter, it may be locally control (droop control) or central control (master-slave control) [9]. The droop control eliminates the communication requirement because it generate reference signal at the converter station. The fast control action of VSC can be used to improve the damping performance with damping controller. The MTDC network does not allow to transfer the inter area oscillation which can remove the risk of cascading failure of grid. The controlled voltage and power can improve the load scheduling and help to avoid the congestion in power system. The report [10] on advance planning of transmission suggest that the new lines have to be installed in Indian grid to avoid the power congestion due to increasing generation and load demand. In report [6] on western wind integration and transmission plan suggest the high power transmission and HVDC lines are better option for grid expansion and wind integration. Thus HVDC grid may be a better suited solution for addressing the concerns of the grid operator and planning engineers.

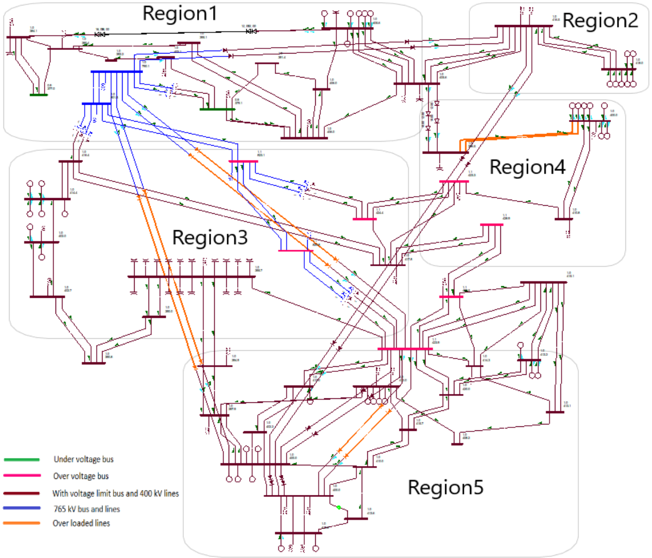

Fig. 4: Single line diagram with wind power injected and MTDC lines

A. Overlay of MTDC lines

An addition of wind power into AC grid reverses direction of power as well as it overloads the existing transmission lines. The extra power generated in the region 5 is feeding to the region 1 via region 3 which congests the lines of both the regions. In order to avoid the power congestion the capacity of existing lines has to be increase or new lines must be constructed. The geographical location of the buses and the AC lines increase the construction cost as well as power losses. With reference to the benefits of the MTDC system, discussed in section VI, an overlay is created. Initially, a point to point HVDC line of power rating of 1000 MW is added to the system between bus no F405 and F424. Fig 4 shows this as a color filled diode connected in the line. It can be seen from Table IV that this addition relieve power congestion on 9 lines of region 3 and 5.

In the next step a second HVDC line is added between buses F424 and T317, this addition also requires construction of a VSC HVDC converter station. Thus the overlay expand to being a three terminal system. This reduces the congestion on lines 21, 22 and 24 in regions 1 and 3. This is clearly depicted in the 7^{th} and 8^{th} column of Table IV where loading of the lines as reduce and certain lines have completely come out of congestion.

In the third step two HVDC lines are connected between buses 1) F404 to T317 and 2) F404 and F405 with an addition of VSC terminal at F404. All the HVDC converters and the transmission lines are rated for 1000 MW and voltage rating of 400 kV. The results of this test case shows that majority of congested line are eliminated and the overloading on other lines is significantly reduced. The lines which are still overloaded are connected between regions 1 and 2. This indicates the addition of converter terminals in region 1.

With the conclusion of test case 7, HVDC terminal was added to bus T516 in region 1. The terminal is rated 1000 MW and voltage level of 400 kV. A 5^{th} and 6^{th} HVDC lines are connected between 1) T516 to T317 and 2) T516 to F404 respectively. Thus the total no of lines in test case 8 is 2 with 1 VSC converter terminal. It can be clearly seen from the Table IV that the congestion is almost relieve for the system under consideration along with significant improvement in the voltage profile. An improvement in voltage profile indicates reduced power losses in the system. A fault on HVDC stations or DC line can result in large drop in wind power. This may not be acceptable and thus DC circuit breaker and DC fault blocking capacity may have to be incorporated in the overlaid MTDC system.

VII. CONCLUSION

The congestion in the power system due to an addition of wind farm into AC grid is discussed. The availability of wind power and scope of MTDC for India grid is addressed. Power injection buses are identified and direction of power flow with and without wind integration is observed. The wind power is added into three stages. The resulting effect of power congestion on AC line is simulated. The MTDC line is deployed to remove the power congestion on existing AC lines. The addition of MTDC line has removed the power congestion on a transmission line. The fast power controlling nature of VSC based MTDC system can improve the stability of power system. The MTDC system segments the areas which can eliminate the grid failure due to cascading failure of areas.

VIII. FUTURE WORK

The investigations need to be carried to determine losses, fault studies and quantification of benefits in terms of improvement of stability and dynamic performance of the grid.

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