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Modification of the Conventional Power Flow Analysis for the Deployment of an HVDC Grid System in the Indian Subcontinent

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***Abstract*—**The Indian subcontinent is facing a massive challenge with regards to the energy security in member countries, i.e. providing a reliable source of electricity to facilitate development across various sectors of the economy and thereby achieve the developmental targets it has set for itself. A highly precarious situation exists in the subcontinent which is observed in the series of system failures which most of the times leads to system collapses-blackouts. To mitigate the issues related with energy security as well as keep in check the increasing supply demand gap, a possible solution that stands in front of the subcontinent is the deployment of an interconnected electricity 'Supergrid' designed to carry huge quanta of power across the sub continent as well as provide the infra structure for RES integration. This paper assesses the need and conditions for a Supergrid deployment and consequently proposes a meshed topology based on VSC HVDC converters for the Supergrid modeling.

***Keywords*—**Super grid, Wind and Solar Energy, HVDC, Electricity management, Load Flow Analysis.

I. Introduction

CLIMATE change activism as well as a limited access of primary conventional fuels is setting the platform for a subtle shift to a CO_2 neutral, multi layered energy system. In this transformation renewable energies will play a leading role followed by the formation of energy corridors for transport of the clean energy. A great potential of renewable energy has been estimated in the Indian subcontinent. Large amounts of wind and solar energy have been estimated in some parts of the subcontinent while as others have a high potential for biomass and hydro. Procurement and hence introduction of such a vast potential involves the deployment of a superimposed network level that spans across international boundaries into various countries of the Indian subcontinent. Such an integration of the huge quantum of energy into a grid that transcends borders is one of the biggest challenges of this century. Moreover what sets this challenge apart involves bringing the measures of technical quality and power supply reliability as well as the maintenance of stability in the same

A huge energy potential has been estimated in areas not in immediate proximity to future production or load centers and hence need high voltage corridors to connect them to the already existing power focal points. Transport of electrical energy will require the unbundling of electricity generation and distribution based on the politically motivated general factors related to electricity deregulation. The established power corridors can provide a reliable supply based on the transference of controlled conventional power over large distances in times of high demand and consequent low supply from local focal points which are actually the local energy centers. Advances in the technical, political and regulatory underpinnings involving power intensive energy transport is necessary to see a large interconnected South Asian energy market endowed with large amounts of variable as well as conventional electricity providing reliable, sustainable and a superior quality of electricity across the Indian subcontinent. Hence on a local scale large structural modifications have to be carried out for the imminent changes.

Transmission and thus making available this huge quantum of power at the nodes requires the development of high voltage energy corridors that have the capability to transfer such massive energy in a reliable and most efficient way. These energy corridors will consist of an interconnected network of extra high voltage transmission lines. Economics of grid deployment in addition to efficient transmission have to be taken into account while designing and deploying these corridors. Moreover social protocol in addition to technical orientation has to be respected for specifying the technology used [1]-[3].

Consequently the application of a super grid in the Indian Subcontinent which is actually a high voltage energy transmission system mainly working on the high voltage DC transmission will provide the required platform to connect the five countries to a sustainable and a massive energy resource as well as providing an energy market for the free trade of electricity in the international market. Electricity has to be deregulated and treated as a commodity that is supplied without qualitative differentiation across a market. Global trading of electricity provides the consumers the opportunity to be exposed to a very good quality of electricity and hence introduce competition in the local market thus leading to regulations in the price of electricity. The super grid can also lead to an interconnection of national energy markets and hence completely transforming the way electricity is produced, transmitted and consumed in the subcontinent.

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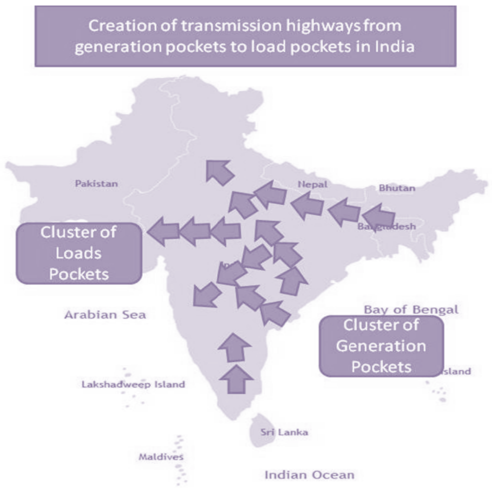

Fig. 1 Creation of transmission highways from generation pockets to load pockets in India

II. Methodology of the Supergrid Deployment

In the search for the introduction of a stable and a reliable power infrastructure in the Indian subcontinent with the capability to bring energy and financial stability in the area, a super grid is by far the most viable solution that shows an average degree of feasibility in the subcontinent. By connecting supply chains to load centers using enhanced control, the super grid offers a comprehensive solution to the issue of energy instability. Moreover the geographical spread of such an infra-structure introduces a huge variety in the energy portfolio available and hence increasing the security of supply. Super grid deployment involves certain issues that pose a serious hurdle in its conceptualization. While as the technical portion can be figured out by utilizing the idea of a meshed smart grid system, the actual deployment in the subcontinent brings with it some other potential risks that need to be studied separately. Thus the deployment is crying out loud to address the technical and the regulatory issues separately. Modeling of the super grid has been done based on a comparative analysis in which the most feasible technology available has been shown to provide the links and nodes of the super grid. Moreover potential generation sites as well as potential load centers have been kept in mind while applying the concepts of power losses due to transmission and distribution. This analysis comes under the heading of “modeling of the super grid in the sub continent” and hence conceptualizes the transformation of connecting different nodes via high voltage energy links. The key risks before the deployment and consequent development of a super grid are non technical. An assessment, evaluation and ranking of the various non technical risks involved has to be done in highlighting the myriad of high risk items that are likely to impact the power sector throughout the development of the Supergrid [3]-[6].

III. Modeling of the Supergrid

The basic need for the introduction of the super grid is to provide an electricity highway for the flow of electric power between nations thus providing a capability to interconnect the asynchronous transmission systems of the subcontinent in order to efficiently control the exchange of seasonally varying production and storage capacities. The super grid thus consists of a planned approach towards grid modernization taking into account the interconnection between unsynchronized grids as well as being equipped to integrate and thereby distribute the huge renewable potential of the subcontinent. There are different considerations for the structure and type of technology for the energy corridors.

A. State of Technology

Due to some key advancements in the electricity transmission technology, certain key concepts have evolved for the construction of the overlay grids that can provide the energy transfer corridors:

1. Three- Phase AC technology 50 Hz (AC grids) with voltages >400 KV (750 KV,1000 KV)
2. Three- Phase AC technology with reduced frequency (AC grids16 2/3 HZ) with voltages > 400 KV
3. HVDC with network controlled converters (LCC-HVDC, HVDC classic)
4. HVDC with self commutated converters (VSC-HVDC)

Constant research into the development of three phase AC technology as a result of an increasing requirement on transmitted power and distance has lead to the introduction of increased voltage levels [7]. Overhead lines, Cables as well as Gas insulated lines (GIL) are now available as AC transport medium. Due to sophisticated technology as well as lower investment costs overhead lines provide a standard solution for high transmission voltages. Line conductor monitoring, high temperature conductors as well as considerable improvement of towers in respect with space and field strength distribution are some of the developments in overhead line technology. Reduced frequency three-phase systems as an alternative between AC and DC grids was introduced for discussions. A reduced frequency of 16 2/3 Hz was conceptualized which is also used in certain countries as traction power supply [8]. Larger distances can be bridged due to reduction in the line impedances. Additionally specific research needs to be done on such systems so as to introduce this technology with regards to high voltages. There is a strong criticism about these technologies as equipments like transformers for reduced frequency AC systems have larger dimensions. A considerable converter expense also needs to be planned which is larger than with DC grids.

The main aim of the introduction of HVDC systems technology was to provide a highly efficient and a flexible transmission system. With the increase in the number and power flow between energy corridors as well as an increasing need of the integration of renewable energy sources into the grid such as wind and solar energy the need for the presence of a transmission system that could provide the required flexibility was satisfied by the HVDC transmission system.

The HVDC system provides the platform to interconnect two AC power systems that are not synchronized as well as transfer of electric power between two distant nodal points through overhead transmission or submarine cables. HVDC systems are more cost effective than AC systems via overhead lines as the costs of transformer stations are not considerable. However the critical length is reached between 800 and 1200 kilometers. Even though up to this length the AC overhead lines are more economical today, HVDC has definite advantages with longer cable connections. For the Supergrid deployment the HVDC transmission system provides superior working conditions, a better power flow control and a definite platform for future additions on the supply side which can be from other conventional generation plants or renewable energy parks. The super grid would require a substantial control on the transferred power. The HVDC systems in parallel with the AC systems provide such a characteristic which can affect the controllability and flexibility of the bulk power system.

The converter stations from the backbone of the working of an efficient HVDC transmission system. Currently two kinds of converter technologies, consisting of the Line Commutated Current Source Converters (CSC's) and self commutated Voltage Source Converters (VSC's) are mostly used in the HVDC transmission systems.

HVDC systems based on the principle of conventional CSC's require a substantially large generation source with a very high level of short circuit ratio in order to operate satisfactorily. In other words there is a need for the transference of reactive power from the AC system at the point of contacts to the converter so accomplish the conversion process which amounts to nearly about 50 percent of the total active power through the converter. Moreover based on the CSC technology principle, power flow direction can be reversed only by reversing the Direct Current DC voltage polarity. This characteristic needs a highly complicated switching technique in case the CSC system is used for building an MTDC (Multi Terminal Direct Current System). On the contrary, VSCs utilizing the (IGBT) Insulated Gate bipolar transistor valves as well as pulse width modulation techniques can lead to the production of a near sinusoidal AC voltage which is fully controllable with respect to magnitude and phase of the AC wave. Unlike the CSC systems, VSCs have no reactive power demand and can as well exchange the reactive power with the AC grid.

VSCs can rapidly control the active power exchange by controlling the phase angle of the produced voltage as well as control the reactive power at each terminal by controlling the magnitude of VSC voltage independent of the Direct current power transmission. Due to this property VSCs can be installed anywhere in the AC grid irrespective of the short circuit current capacity. Moreover to change the direction of the power flow in its DC link, VSC does not need to reverse the voltage polarity. This power reversal is observed by changing the direction of the current. Many attempts have already been made to conceptualize the formation of the meshed grids using classic HVDC or CSC technology. However due to the high amount of complexity involved the projects were thereby limited to a maximum of 3 nodes. On the other hand the VSC-HVDC provides the most suitable conditions for a multi terminal system which is the basis for the deployment of a super grid because of the fact that the number of nodes and the kind of grid topology utilized does not have any limit with regards to VSC-HVDC.

B. VSC- HVDC Functional Principle

The working of a VSC converter is based on the synchronous functioning of a 6-pulse bridge circuit of IGBT's (power transistors) controlled by a clocked control signal generating pulses in the range of KHZ frequencies. Provision has to be provided for the serial switching of the multiple semi conductors in order to account for the limited reverse voltage capacity of the power electronic elements. Intelligent control techniques can introduce a very high flexibility in the output voltage control in order to obtain the desired active and reactive power [9]. AC voltage is formed by the use of PWM modulation in case of PWM VSC converters and DC voltage is smoothened by the use of DC capacitors. There is a higher precision of synchronism if a higher clock frequency is used. PWM technology has been in use for nearly a decade now and two and three level VSC converters are now available.

Constant research into upgrading the ratings and the frequency of VSC converters has led to the use of a modular construction based on the use of multi-level technology. Sub-modules consisting of half bridges having two valves and a module capacitor are at the heart of sub module architectures. Partial voltages of the sub modules combine to the complete voltage of the branches and thereby branches act as controllable voltage sources.

Using Modular circuits VSC technology coupled with a complicated control process can decrease the operating frequency of the converters and thereby directly affecting the losses at the converter station which can amount to about 1 percent. AC voltages are generated by a cumulative process consisting of step functions with hundreds of voltage steps. This directly affects the harmonic components in the voltage sinusoids which are directly reduced and thus improving the overall THD of the voltage wave. In HVDC technology based on VSC converters reversal of power depends on the reversal of current unlike the LCC HVDC in which reversal of power depends on the reversal of voltage. Polarity of DC voltage thereby always remains the same and hence makes the use of XLPE- DC cables possible.

C. Application of VSC Based Multi-Terminal HVDC

Multi terminal Direct Current systems (MTDC) hadn't been deployed in practical power systems until 1987 when the first MTDC system was introduced by installing a third terminal in Corsica to the already existing link between Sardinia and Italy. Another landmark achievement was the completion of the first large MTDC system by ABB in 1992 which again was a three terminal HVDC system. While as earlier the MTDC systems used to be based on the LCC converters, because of huge advances in the field of VSC converters and their subsequent advantages the shift is gradual towards using the VSC

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converters for MTDC system deployment. In India itself POWERGRID corporation of India (PGCIL) is installing +/- 800 kV, 6000 MW HVDC multi-terminal system of approx length of 1728 km from North Eastern Region to Agra which will consist of one rectifier station in Biswanath Chariali (in North Eastern Region), second one in Alipurduar (in Eastern Region) and Inverter station at Agra (in Northern Region). This is the first multi terminal system in India consisting of VSC converters.

For the deployment of MTDC system two types of configurations are possible such as the parallel connection and the series connection. While as the parallel connection allows the DC terminals to operate around a single rated voltage VDC, the series connection involves a single converter that controls the current around a common current rating and the rest of the converters control the power. The series connection is more suited for CSC MTDC systems as the CSCs on the DC side provide the same functions of a voltage source and thus can be introduced in series connections without any subsequent need for special switching control. Among other drawbacks of this configuration the most significant in the HVDC applications is its inability to control the losses and the use of complicated insulation. More importantly if due to certain circumstances one of the DC lines is disconnected which may be due to fault conditions; the power flow in the entire DC grid is affected. Hence only parallel configuration is recommended by power engineers to be used in the MTDC systems. Consequently if CSCs are used for the parallel connection of an MTDC system, a complicated and special switching arrangement has to be made to overcome the precise voltage balancing between the converters which arise because of the voltage source nature of the CSCs. This cumulates into a more serious technical issue of the converter stations are far away which is highly probably in case of a super grid MTDC systems since an inherent need of fast communication channels is needed. However the presence of Smart Grids in each of the participating country can to a large extent mitigate this technical problem because of a presence of a very fast and reliable communication highway. Thus formation of more than 5 terminal MTDC system based of CSC converter stations is highly discouraged. On the contrary if VSCs are used to form a parallel configuration because of their functioning as an ideal current do not pose any serious technical difficulties.

As already concocted, reversal of power in case of VSCs can occur by reversing the direction of current keeping the polarity of the DC voltage unchanged. This capability of the VSCs is quite suited for the construction of an MTDC system. For the construction of a bulk power system such as a super grid VSC based MTDC system having parallel connected converters have a great potential. The DC super grid is a direct consequence of the possibility of such connections which can not only connect many unsynchronized grids but also provide a definite medium to integrate the renewable energy from various distributed resources around the subcontinent. This proposition of the formation of a DC super grid is a direct consequence of the compatibility of VSC converters with a basic parallel connection for the construction of a reliable DC grid integrated into the conventional AC grids. Investigative research has to be conducted though to observe the effect of the MTDC systems on a large power system since such proposition is a relatively newer one. The Super Grid for the Indian sub continent has to be dynamically connected with a very high flexibility to address the different requirements of the countries taking part in such a project. Not only should the super grid provide a stable power flow depending upon the demand and supply difference at different times of the year it should also be able to absorb the intermittent and highly variable renewable power from energy sources that are scattered all over the sub continent. The renewable energy sources an intermittent nature and can thus prove to be hazardous to the normal functioning of a large inter connected grid because of the fluctuations endangering the stability of the system. The Dc super grid based on the VSC converter systems can allow non conventional energy from different renewable energy sources in the subcontinent feed electric power into the common DC super grid thereby providing all the participant countries a steady access to a reliable and stable source of electricity generation.

D.VSC-HVDC Station Modeling

The need to understand the underlying structure of the VSC station model arises because of the presence of several VSC stations in the VSC based MTDC systems. The figure shows the elements constituting a VSC station. While as the model consists of AC buses, series reactance, AC filters, coupling transformers and converter blocks on the AC side, it consists of the DC bus, the DC filter and the DC line on the DC side. A single line represents the DC side of the model.

The point of common connection acts as a medium from where the VSC station is connected to the AC grid. The PCC is connected to the AC side of the VSC through a converter transformer, shunt filter and a phase reactor while as on the other side the DC bus, at which a shunt DC capacitor is connected to the ground, is connected to the DC line on one side and the VSC on the other side.

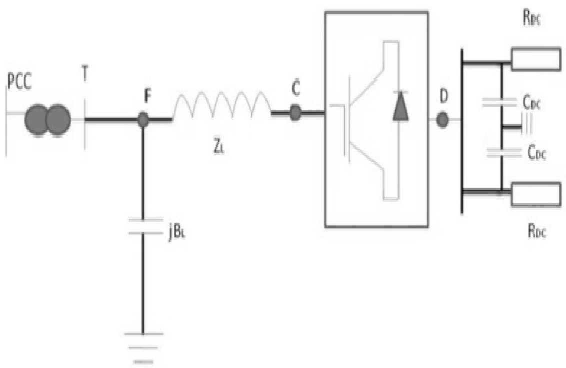

Fig. 2 Modeling of VSC HVDC stations

IV. Power Flow Analysis

A meshed grid topology is assumed for the subsequent discussion on the power flow analysis. Different methods and calculation algorithms that have been proposed for the power flow or load flow analysis of three-phase AC systems are have been refined. The power flow analysis of DC meshed grid depicts a much simplified and exceptional case of the AC power flow analysis. In case of DC grids, for stationary conditions the reactive power and the reactive network devices are nonexistent because of the inherent zero frequency operation of the DC and hence the voltage can be influenced by the active power flow. Quality of power supply is thus a function of voltage and not frequency and thereby only voltage active power control is observed as a control system for DC grids.

The most common practical analysis methods for power flow consist of the Newton Raphson method and the method of joints. The method of joints is based on the principle of current balance and is solved iteratively using the Gaus-Seidel method to obtain the required parameters. The Newton Raphson method uses the power balance techniques of the nodes. Mathematical calculation with a relatively less complexity is observed when the power flow methods were applied to the DC systems than in the three-phase systems because of the crossing over of the complex calculations in the real domain. Consequently the admittance matrix [Y] of the grid converts to the conductance matrix [G]. However the normal step by step process consisting of the creation of the system of equations followed by the analysis of network and the direction arrows depicting the direction of flow of power is determined. For the calculation of the conductance matrix, Kirchhoff's Voltage law is applied at various nodes, i.e. various node equations are formed and the product of conductance and voltage difference replaces the branch currents.

Equations (1) to (8) represent the Kirchoff's current law at various nodes of the Supergrid which are technically referred to as "supernodes" i.e., nodes of the Supergrid. i_x is the current flowing into a node x, i_{xy} refers to the current flowing from node x to node y, U_x represents the voltage maintained at a particular node x, g_{xy} refers to the conductance of a particular edge of the graph and is a function of distance.

$$i1 = i21 + i41 = {(U2-U1)}/{g12} + {(U4-U1)}/{g14} \quad (1)$$

$$i2 = i12 + i32 = {(U1-U2)}/{g12} + {(U3-U2)}/{g23} \quad (2)$$

$$i3 = i23 + i43 + i73 = {(U2-U3)}/{g23} + {(U4-U3)}/{g34} + {(U7-U3)}/{g37} \quad (3)$$

$$i4 = i14 + i34 + i54 = {(U1-U4)}/{g14} + {(U3-U4)}/{g34} + {(U5-U4)}/{g45} \quad (4)$$

$$i5 = i45 + i65 = {(U4-U5)}/{g45} + {(U6-U5)}/{g56} \quad (5)$$

$$i6 = i56 = {(U5-U6)}/{g56} \quad (6)$$

$$i7 = i37 + i87 = {(U3-U7)}/{g37} + {(U8-U7)}/{g78} \quad (7)$$

$$i8 = i78 = {(U7-U8)}/{g78} \quad (8)$$

The conductance matrix is arranged after the formation of the network equations and replacing the branch currents by the product of conductance and the node voltage difference. In the complete analysis efforts have always been made to replace the current by its equivalent quantities (product of conductance and voltage) depending on the network state.

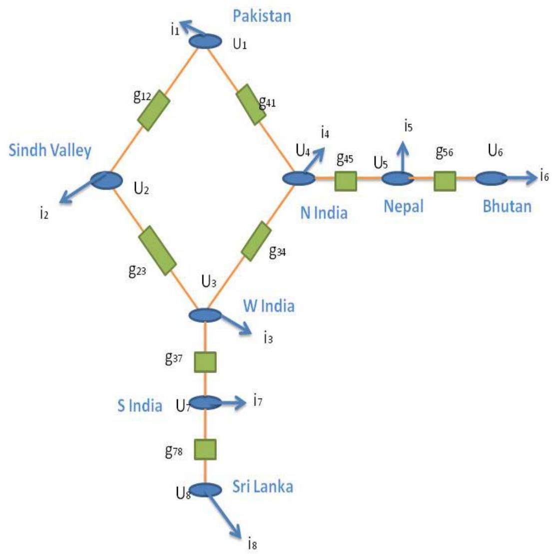

Fig. 3 Analysis and Definition of quantities and arrows in the network

The Gauss Seidel method is the most common iterative method that is used to solve the system of linear equation as it involves the least complexity. Another possibility consists of using the Jacobian method based on the node equations. For solving the equations of the grid based on various bus voltages which are chosen based on the known and unknown values there is a strong need to choose a slack bus which acts as a reference bus and is often the bus consisting of the largest generation capacity. The system of equations is thus modified with the provided slack voltage U_{sl}.

$$[U]_{xy} = [G]_{xy}{}^{-1}\{[I]_{xy} - [G_x]_v - [U]_x - U_{sl}[G]_r\} \quad (9)$$

Separating the nodal conductance $[G]_x$ and voltages $[U]_x$ and obtaining the voltage matrix $[U]_{xy}$. Using the iterative solution in every step, node currents are first determines using the node power and then the new state vector is defined which is calculated for the node voltage. The power flow, slack power and the power loss can be determined after converging the voltages or node power with the abort criterion after the required convergency is obtained which in most cases is reached after a maximum of ten steps. It is of course an inherent characteristic of applying power flow analysis to DC systems that the PV buses that are analogous to the three-phase system don't exist in the DC systems. This is attributed to the fact that only power or voltage is possible on each node as only a single degree of freedom exists.

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The modification of the Newton Raphson method for application to the DC grids is also possible. This process involves very high complexity and thus this method can be done with at most 4 steps to obtain the same accuracy.

Newtonian directional null method lies at the heart of the Newton Raphson method. Using the Taylor series expansion the node power balance is linearized and thereby resolved in each iteration step which leads to the formation of a Jacobian matrix [J].

Linearized equation:

$$\begin{bmatrix}[\Delta P]\\ [\Delta Q]\end{bmatrix}=\begin{bmatrix}H & N\\ M & L\end{bmatrix}*\begin{bmatrix}[\Delta\vartheta]\\ [\Delta U]\end{bmatrix}=[J]*\begin{bmatrix}[\Delta\vartheta]\\ [\Delta U]\end{bmatrix} \quad (10)$$

and since in DC systems $\Delta Q = 0$ and $\Delta\vartheta = 0$;

$$[\Delta P]=[J]*[\Delta U]$$

and the simplified Jacobian matrix is,

$$[J] = \begin{bmatrix}\partial P1/\partial U1 & \partial P1/\partial U2 & \partial P1/\partial U3 & \dots & \partial P1/\partial Un\\ \partial P2/\partial U1 & \partial P2/\partial U2 & \partial P2/\partial U3 & \dots & \partial P2/\partial Un\\ \partial P3/\partial U1 & \partial P3/\partial U2 & \partial P3/\partial U3 & \dots & \partial P3/\partial Un\\ \partial P4/\partial U1 & \partial P4/\partial U2 & \partial P4/\partial U3 & \dots & \partial P4/\partial Un\\ \dots & \dots & \dots & \ddots & \dots\\ \partial Pn/\partial U1 & \partial Pn/\partial U2 & \partial Pn/\partial U3 & \dots & \partial Pn/\partial Un\end{bmatrix} \quad (11)$$

Accordingly,

$$[\Delta U] = [J]^{-1}*[\Delta P] \quad (12)$$

The state vector of voltages are corrected iteratively until the required convergence is achieved which occurs after a maximum of 5 iteration loops.

Fig. 4 Draft of DC multi terminal grid for the Indian subcontinent

V. Conclusion

The power grids of the future need to be highly adaptive with regards to satisfying the needs of the high growth economies of the future as well as dynamic to balance and effectively transfer the huge quanta of power flow. This flexibility in the grid has been proposed to be achieved by interconnecting several grids in order to form a massive interconnected grid that spans across borders. Interconnection of the grid provides a platform for a need based power flow backed by generation in areas of high potential and consequent transfer where it can be used most effectively. This meshed structure is supplemented with a number of decentralized structures that play a part in load coverage as well as allocate excessive energy for power flow.

This paper proposed that a meshed topology for Supergrid deployment is the most feasible because of its dynamic characteristics to efficiently deal with power flow. This structure was then analyzed through load flow methods adapted for DC grids. This practice thereby leads to an interconnection of transmission networks of various participating countries in the subcontinent and also provides a key seminal concept for integrating the proposed wind power integration from the Sindh valley located in the Southern Pakistan.

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