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Centralized Reactive Power Controller for Grid Stability and Voltage Control

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ABSTRACT- The integration of renewable energy sources like solar and wind energy into the transmission and distribution grid has increased gradually for quenching the increasing demand for alternative sources to fossil fuels. However, due to the intermittent nature of the renewable sources primarily solar and wind, the injection of the renewable power generation into the grid shall also be fluctuating which in turn will impact the voltage profile of the transmission and distribution grid. Also, in case of any major load disconnection or generator tripping in a weak grid, the voltage profile will be severely impacted in a weak grid. The aim is to control the sudden major voltage profile disturbance of a weak grid in case of variation of power injected into the weak grid from solar and wind energy and also due to sudden load tripping or generator tripping in the weak grid by controlling the reactive power in the weak grid. In this paper, a centralized reactive power controller has been proposed to control reactive power injection or absorption in the grid. By controlling the reactive power sources and sinks centrally via the centralized controller, any contingency can be met to prevent major disturbance of the voltage profile in the weak grid. This controller shall aim to control the connected reactive power sources & sinks based on the voltage profile of the transmission grid and it shall also engage the Line Commutated Converter (LCC) High Voltage Direct Current (HVDC) Reactive Power Controller. Various cases have been analyzed in this paper for implementation of the centralized reactive power controller for voltage control in the transmission grid.

Keywords: Centralized Reactive Power Controller, Voltage Profile, Reactive Power, Weak Grid.

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1. INTRODUCTION

In an ac transmission grid, the paramount requirement for facilitating smooth power transmission without any element tripping and damage to equipment is optimum voltage profile. The voltage profile of the grid is primarily impacted by the reactive power injection and absorption. Without adequate loads, the active power required is also reduced. But in this case if reactive power is still being injected into the grid without any connected bus reactors to absorb the reactive power, then the grid will collapse due to overvoltage.

Normally, the reactive power sources like capacitor banks connected to the grid are of fixed size. So even if a small quantum of reactive power is needed for facilitating the active power flow, still the entire capacitor bank is switched when the minimum requirement threshold is reached. The excess reactive power which was not required when injected to the grid shall lead to significant rise of voltage in a weak grid. Similarly, if a small voltage rise is required in the grid, then the disconnection of the shunt reactor may lead to significant rise of voltage in the grid due to the fixed step size of the reactor. This kind of grid condition shall be prevalent in various nodes of the entire centralized grid due to the fixed sizes of the capacitor banks and bus reactors. The problem of fluctuating voltage profile in a grid is primarily due to the connection and disconnection of generation available in the grid and the connected loads. Due to tripping of connected transmission lines or generators, there is massive over voltage in a weak grid.

As more solar and wind renewable energy sources are being integrated into the grid, the challenges that are being faced by the electrical system are control of active power and reactive power, voltage frequency support [1]. The massive integration of new decentralized generators in distribution grid has led to voltage problems especially in low voltage (LV) grid [2]. The integration of renewable energy sources can also lead to increase in voltage oscillations in a weak grid. This is primarily due to the intermittent nature of the renewable energy sources like solar and wind energy sources. The renewable energy sources primarily solar and wind are not available consistently throughout the day as they vary with the changing weather and atmospheric conditions. At certain times for wind energy sources, the generation will suddenly ramp up and at certain times the generation will come down based on the wind direction. If suddenly the generation ramps up and there is not adequate loads connected to absorb the generation, it may lead to over voltage in the grid. Sudden major quantum of load or generation variations in the grid shall introduce significant voltage disturbance in the grid which needs to be controlled immediately to prevent cascade tripping and grid failure. The only possible solution is swift and automated control of the reactive power available and connected in the grid. To solve it, immediate reactive power absorption is required as reactive power affects the operating voltage profile of the electrical grid significantly [3].

Reactive power compensation is a crucial issue in controlling the quality-of-service level in electric power grids [4]. Electric vehicle (EV) is an area in which extensive research is being carried out. Electrification of the power train in EVs lead to new variances and allows research in several new directions [5].Nowadays, detailed studies are undergoing for injecting of generation by electric vehicles into the grid whenever possible and if generation is available with the electric vehicle. In future most of the vehicles will have this possibility of injecting of power into the grid. But the cause of concern from the overall grid perspective is that if massive power generation is injected into the grid simultaneously by a significant number of electric vehicles in the grid, then there is possibility of overvoltage in the grid if there is no adequate load connected to absorb the generated power.

To solve the problem of reactive power management in the transmission grid, a centralized RPC is proposed in this paper for maintaining a balanced reactive power and voltage profile in the grid. In this paper, the centralized RPC model is proposed for the transmission grid involving the RPC of LCC HVDC for voltage control and reactive power balance. Further, several cases are simulated showcasing the need of the centralized RPC in the transmission grid.

2. LITERATURE REVIEW

Stability of power system is the key for secure and uninterrupted grid operation. Power system stability is defined as the ability of the grid to restore the operating balance after enduring a physical disturbance. To maintain a balanced electrical grid, the power demand and supply has to be balanced without curtailing of load. Taking into account the increasing penetration levels of renewable energy sources such as wind and solar power, the electrical grid has to be flexible to adapt to the variable and hardly predictable renewable energy sources [6].

For power system stability, maintaining the reactive power balance is very critical. Reactive power management is a vital tool for smooth and uninterrupted operation of the electrical grid [7].

To achieve the optimum utilization of the reactive power sources and sinks, an effective tool is the Optimal Reactive Power Dispatch (ORPD) [8].

Literature reviews have highlighted that OPRD is an effective tool due to the increased provision for monitoring of parameters like real time voltage profile, real and reactive power flow and active power losses in the network lines. Modern features like Advanced Metering Infrastructure (AMI), and Phasor Measurement Units (PMU) available in smart grid network helps to enhance the grid monitoring capability and optimize the reactive power balance over the grid [9], [10].

For maintaining optimum voltage level in the grid, simultaneous active and reactive power management is proposed to be carried out with active and reactive power management unit (ARMU). In the proposed method, measurement units communicate with the ARMU in each bus and share real time grid parameters. Based on it, ARMU determines and sets the operating points of active and reactive power sources connected in all the buses and all the controllable units contribute to online voltage and power control[11].Research work has also been carried out for reactive power sharing in an islanded microgrid using the concept of virtual impedance[12].An advanced renewable energy based smart grid model involving Artificial Neural Network (ANN) has been proposed for maintaining a balanced reactive power profile across the grid using DSTATCOM which injects/absorbs the reactive power on the grid network based on feedback from the ANN algorithm for maintaining the reactive power profile as per set operating points. This method utilizes all the controllable elements of the grid for attaining reactive power balance [13].

For voltage control in a weak grid, voltage source converter (VSC) HVDC technology can be an effective tool as it has the feature of swift and independent control of active as well as reactive power. VSC-HVDC provides voltage support during disturbance in the connected electrical AC grid. This voltage support boosts the restoration of AC grid voltage and helps to operate the AC grid in a stable manner [14].

In line commutated converter (LCC) HVDC, reactive power controller plays a significant role in matching the reactive power requirement with the increase in dc power flow level. Study has been carried out aiming to look at the inverter side of LCC HVDC with customizable capacitors, reactive power and accurate management of the AC voltage. The generally used AC voltage control and PI controller utilized for reactive power control has been replaced with an injected controller that increases reaction speed and control [15]. In an islanded microgrid, research has been carried out for reactive power sharing control strategy which engages central controller. The central controller is proposed to increase the accuracy of reactive power sharing in the grid [16].

With the advances in the modern grids, the concept of micro grids has gained momentum. However, there are a lot of challenges in the operation of a microgrid. For effective sharing of reactive power between distributed generation units in a microgrid, the concept of novel multiagent moving average estimators has been proposed to utilize the participating nodes of the microgrid to share active and reactive power among themselves [17].In a microgrid, inclusion of renewable energy sources to match the increasing load requirement has been a significant development. In a microgrid, a decentralized control strategy proposed. The proposed control strategy includes droop control technique along with virtual impedance. It includes PI controllers to control the voltage and current for two Voltage Source Inverter (VSI) distribution generation units

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which are connected in parallel combination via a Point of Common Coupling (PCC) [18]. In a microgrid, the concept of Power-Frequency Droop Control (PFDC) is introduced to bring back the grid frequency perfectly and also share the reactive power in an isolated microgrid with the application of virtual power plant (VPP). The power processing capacity of each VPP has been upgraded to operate as an active generator to attain better results in this decentralized control technique [19].

Electrical distribution network aims to distribute the energy received from transmission grid to supply passive loads. However, with the advent of increasing distributed generation integration in the grid which is intermittent in nature and demand of power requirement for electric vehicles in the distribution grid is increasing, the distribution grid is facing a lot of challenges. To effectively manage the distribution grid, centralized control techniques are analyzed to mitigate the challenges of the distribution grid [20]. In distribution grids, a two tier real-time voltage control technique is proposed for voltage control. It consists of a local controller and a centralized controller for reactive power control. The controller at local level looks for swift response after a disturbance thereby damping the impact of the disturbance in the voltage profile. The controller at central level aims to restore the voltage to normal level by utilizing real time measurements accumulated from the network [21]. For overcoming the challenge of voltage control in the electrical distribution grid due to the increased dependency on distributed generation sources, flexibility in reactive power management is the need of the hour. A reactive power control methodology is proposed which guides the grid operators with reactive power flexibility in the grid within the permitted limits [22].

The advantage with centralized reactive power control strategy is that with all the grid real time data available centrally, the reactive power control problem may be identified as optimal power flow which in turn will reduce system operation costs such as system losses and voltage fluctuations [23]. The present industry practice is to install capacitor banks locally for decentralized reactive power control which is quite expensive. As a part of centralized reactive power control, all the capacitor banks connected in the grid are integrated in centralized controller for coordinated reactive power control of the entire grid [24]. An online centralized control technique for distribution networks has been created which combines a proportional integral (PI) controller with a corrective control unit (CCU), based on Model Predictive Control (MPC) principle. This controller is designed to adjust to the increasing penetration of distributed generation and continuously managing the reactive power requirements of the grid, with an aim for maintaining a stable voltage profile in the connected grid [25].

3. CENTRALISED RPC CONTROL STRATEGY

There is a requirement of a centralized RPC to control the reactive power of the electrical grid due to the significant increase in penetration of the distributed generation sources in the grid gradually [27]. In case there is higher renewable energy generation – namely wind and solar generation being injected into the grid than the available loads at a particular node, then the centralized RPC shall prohibit any further injection of the generated power into the grid at that particular node and allow voltage injection at power nodes of the grid if there is margin for voltage rise at that particular node. Electric vehicles in the future can travel to a nearby node in the grid and start injecting power into the grid if RPC prohibits further injection of power at a node and directs them to the nearest node for voltage injection if required by RPC for grid voltage stability.

To control this sudden rise or fall of the voltage, a centralized RPC is required for the transmission grid level as shown in *figure 1*. The primary aim of this RPC shall be to maintain the transmission grid voltage within the set band of voltage level. All the connected loads, generators, shunt reactors and capacitor banks including LCC based HVDC RPC shall be monitored and controlled by the centralized level RPC. This centralized RPC shall control the loads connected to the transmission grid and also control the active power flow from the generators within an allowed margin which shall be set by the operator to control the grid voltage level [28]. Also, this centralized RPC shall connect and disconnect the shunt reactors, capacitor banks which are located at different parts of the grid to keep the grid voltage at different nodes of the region within the specified limits [29]. The real time voltage measurement feedback for the centralized RPC can be taken directly from the bus voltages of different transmission grid nodes in a region. The real time measurement and feedback has to be very fast and accurate as the centralized RPC controller will have to assess the difference between the voltage reference and measured voltage and issue a trip/close command to shunt reactors and capacitor banks or issue a power order up/down command to generators and loads. A PI controller is used to design the centralized level RPC [30].

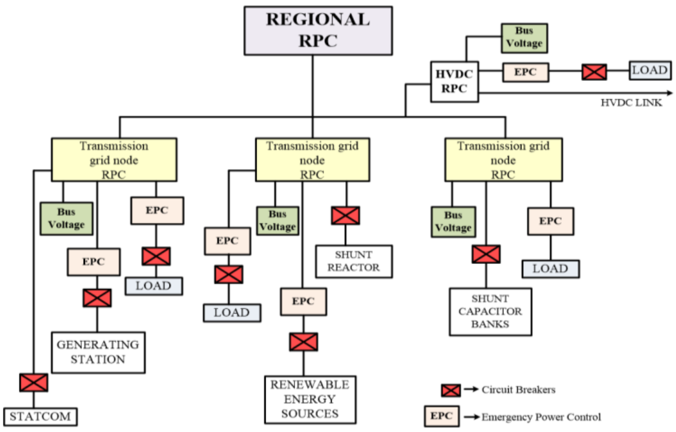

Figure 1: Centralized RPC connection block diagram

4. RPC OPERATION HIERARCHY

In the existing grid operation philosophy, there is no central controller to utilize the available resources in the grid to control the voltage level at the overall grid level automatically. Only localized controllers are available at substation level. which are connected and disconnected manually. Automated immediate response for voltage control to ascertain grid stability is not

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available. The centralized RPC proposed in this paper aims to fix this problem.

The control flowchart of centralized RPC for a weak grid is shown in *figure 2*. This figure represents the model for hierarchy of connecting or disconnecting the elements of the weak grid for controlling any major deviation in the voltage profile of the weak grid. The priority of connecting or disconnecting the elements is defined in this flowchart. It is the mathematical model for the centralized RPC for the weak grid. The very first point is to set the reference voltage level required by the operator. Based on it, the PI controller shall aim to connect/disconnect the grid elements automatically until the reference voltage is attained.

The priority for control of the grid voltage automatically by the centralized RPC is to be in the following order.

1) The first priority is issuing command to STATCOM devices connected to the centralized grid (if available) for absorption or injection of reactive power into the grid based on the command received from the centralized RPC.
2) If STATCOM devices are not available or unable to arrest the voltage rise /fall, then connection or disconnection of available shunt reactors are to be done as second priority. If all the shunt reactors in that particular node are connected, then reactors in the adjacent node are to be connected.
3) The third priority for voltage control in the transmission grid is by connection and disconnection of the shunt capacitor banks available in the grid for reactive power injection.
4) The fourth priority is using the RPC available in LCC based HVDC converter station for controlling the reactive power absorption and injection into the grid. In a thyristor based HVDC system, the RPC control is facilitated to connect and disconnect the filters based on the requirement of reactive power to facilitate the HVDC power transmission. The primary aim of the RPC is to supply the reactive power requirement from the filter sub banks available within the converter station for facilitating dc power flow as per the set order. The reactive power required is directly mapped with the dc power and filter sub banks shall get connected by using the dc power flow level.

The last priority should be using an emergency power control (EPC) action in the grid by the RPC. An EPC controller shall come under the RPC. Only as a last resort or final contingency plan, the RPC shall communicate with the generating station to reduce the generated power so as to prevent high reactive power injection into the grid. The EPC shall also disconnect loads if there is sudden increase in loads which will cause the voltage level to fall below the minimum operable limits and cause grid disturbance.

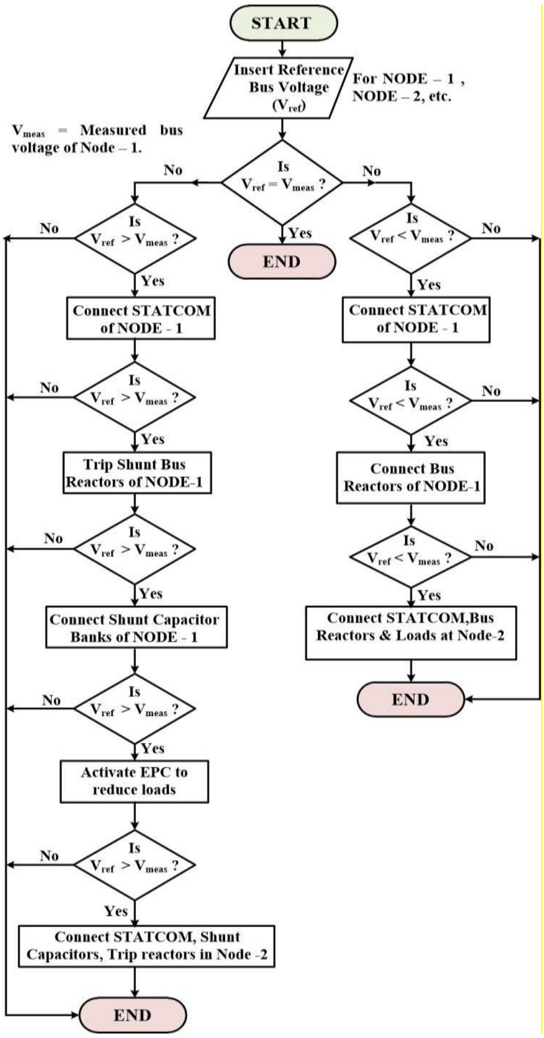

Figure 2: Flowchart for connecting and disconnecting of grid elements for centralized RPC

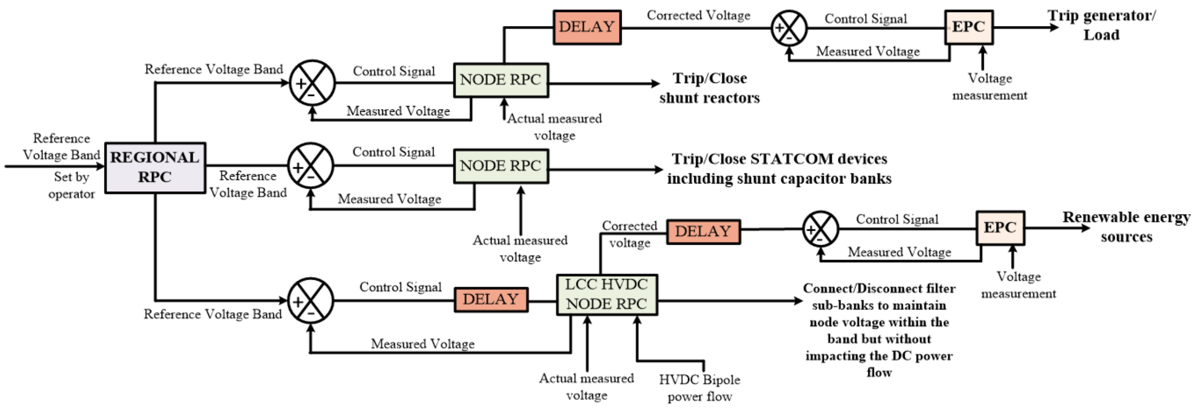

Figure 3: Centralized RPC Control Function Block

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Figure 3 represents the control block diagram for connection/disconnection of elements by centralized RPC as per grid requirement from operational perspective. The control block diagram as represented in *figure 3* is designed for the real time grid voltage control practically. The block NODE represents an electrical substation wherein the elements to be connected or disconnected for voltage control of the weak grid is physically present. Based on the feedback control and priority scheme as defined in *figure 2*, the Regional RPC block shall issue commands to the NODE to connect or disconnect the elements for voltage control. The central controller will always strive to maintain the reference voltage set in the centralized RPC.

The innovative idea for voltage control that can be utilized is by engaging the LCC HVDC RPC controller to use the ac bus voltage as the reference for connection of the filter banks. A minimum reference value (MVAR) equivalent to the smallest size (MVAR) of the filter sub bank has to be set. In case of reactive power required below the minimum reference size for dc power flow, the HVDC RPC can import it from the grid. Only in case the required reactive power exceeds the minimum reference value, 01 no. of filter sub bank shall get connected from the converter station.

The HVDC RPC shall communicate with centralized RPC directly. Centralized RPC can connect and disconnect the filter sub banks in case of sudden change of voltage in the grid. However, the primary aim of HVDC RPC shall be to maintain constant dc power flow as per set order.

5. RPC OPERATION

The operation of centralized RPC shall be based on the inputs received to the controller. The real time node RPC voltage from all the transmission nodes shall be fed to the centralized RPC along with the healthiness status of all the connected elements. Based on the input voltage and healthiness status of all the connected elements, the centralized RPC shall issue an automated command to the node RPC to connect or disconnect the elements so as to maintain the node voltage within the set voltage band. The EPC shall also be controlled by the centralized RPC. In case of any requirement to disconnect the generation or load to prevent grid failure by voltage overshooting, *th* centralized RPC shall issue the trip command via the EPC as shown in *figure 4*.

Figure 5 represents the feedback controller for centralized RPC. In this controller the voltage measured in the node RPC shall be fed as feedback. The difference between the set reference voltage and measured voltage is the error voltage. The sole aim of the centralized RPC is to keep this error value to zero as early as possible.

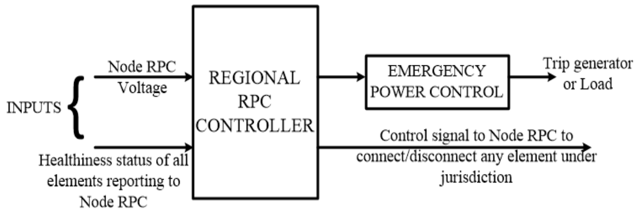

Figure 4: Centralized RPC signals

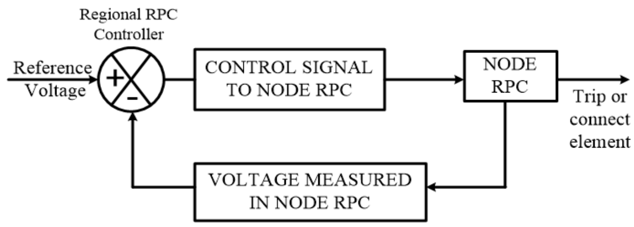

Figure 5: Feedback controller for centralized RPC

Figure 4 and *figure 5* represents the small-scale block diagrams of the input signals and feedback controller of the centralized RPC. The entire centralized RPC is shown in *figure 2* wherein the RPC shall take into account the node voltage of all the nodes simultaneously and issue the control signals to bring back the node voltage within the set voltage band with minimal delay by connecting /disconnecting the existing grid elements.

6. SIMULATION RESULTS AND ANALYSIS

As a part of analysis for implementation of centralized RPC, simulation tests have been carried out and discussed in details for various configurations of a grid wherein the effect of faults and sudden load losses have been carried out with and without centralized RPC. For carrying out the simulation, a network has been considered as shown in *figure 6* with 400kV 3000MVA on node B1 and 400kV 250MVA on another connected node B3. In node B1,100 MW load is connected. In node B3, 1000MW load, 100MVAR Shunt Reactor and 125MVAR Shunt Capacitor. Also, 100 MVA STATCOM is also connected in the grid. To simulate the behaviour of the centralized RPC, the Simulink model of *figure 6* has been used. In this model, various reactive power absorbing and injecting elements links STATCOM, shunt capacitors and shunt reactors are available at various nodes of the model which can be controlled centrally by the centralized RPC. The nodes represent the electrical substations of the grid. As per the defined operational hierarchy of the centralized RPC model, the elements shown in the Simulink model shall get connected or disconnected based on the system requirement for voltage recovery as per set points.

The aim of the simulations are to highlight the swift recovery of the grid voltage profile when the centralized control of reactive power is carried out.

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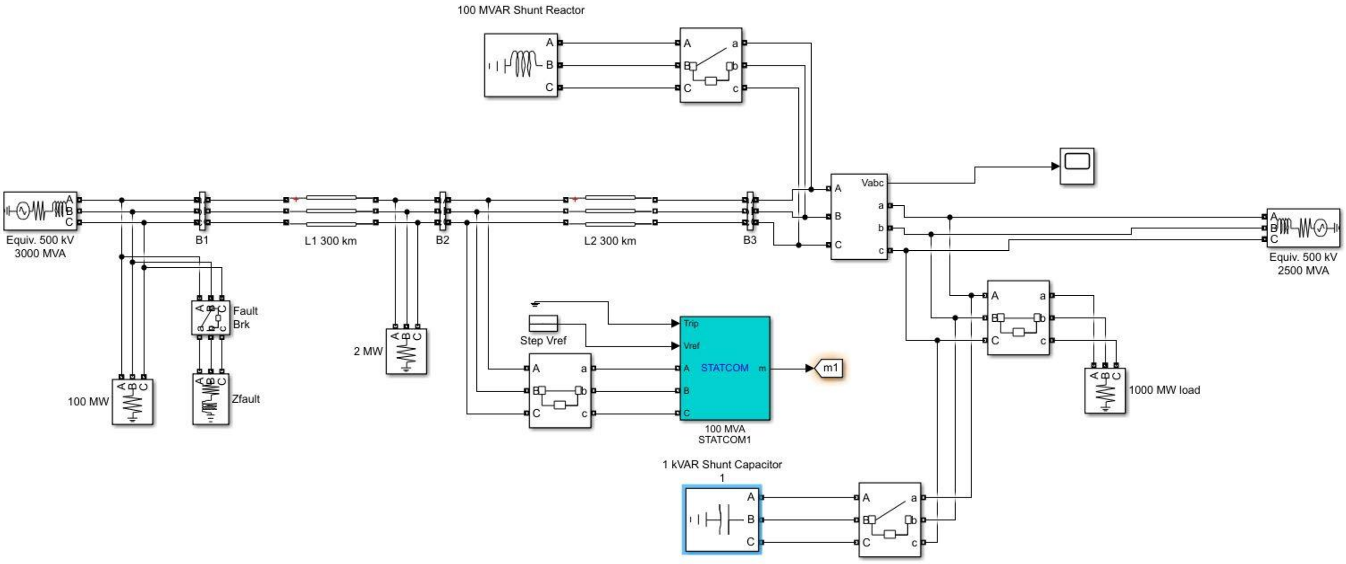

Figure 6: Network grid with centralized RPC

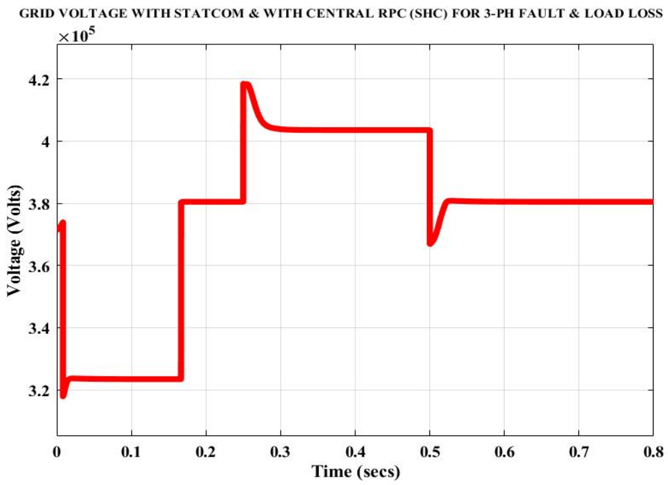

Figure 7: Voltage oscillations during 3-ph fault and load loss

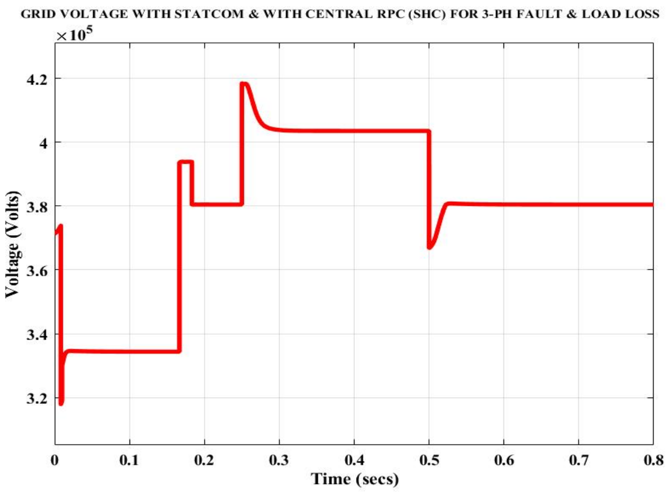

Figure 8: Voltage oscillations during 3-ph fault and load loss

The various cases simulated along with the test results are discussed as below:

A. Case 1: 3-ph fault followed by1000 MW load loss with STATCOM but without centralized RPC (No connected bus reactor and shunt capacitor bank).

For this case, simulation test was carried out and it was observed as shown in *figure 7* that during the 3-ph fault the voltage in B3 node in the network fell to almost 320kV as further dip was arrested by connected STATCOM. Further after recovery from the 3-ph fault when 1000MW load loss was simulated at node B3, the voltage rise was till 415kV but further rise was arrested by STATCOM until the load was restored.

B. Case 2: 3-ph fault followed by 1000 MW load loss with STATCOM and with centralized RPC (only shunt capacitor bank available).

For this case, simulation test was carried out and it was observed as shown in *figure 8* that during the 3-ph fault the voltage in B3 node in the network fell to almost 320kV but it recovered immediately to about 335kV as further dip was arrested by connected STATCOM and also automatic connection of the 125MVAR shunt capacitor bank by centralized RPC when voltage dip was sensed. Immediately after clearing of the fault, the shunt capacitor was disconnected to keep the voltage in optimum range.

Further after recovery from the 3-ph fault when 1000MW load loss was simulated at node B3, the voltage rise was till 415kV but further rise was arrested by STATCOM until the load was restored.

The difference observed with Case 1 above is that in this case due to activation of centralized RPC, the immediate connection of shunt capacitor bank when voltage fell down during the 3-ph fault was arrested. In Case-1, the shunt capacitor bank was not a part of the centralized RPC which did not allow its connection even when voltage fell down during the 3-ph fault.

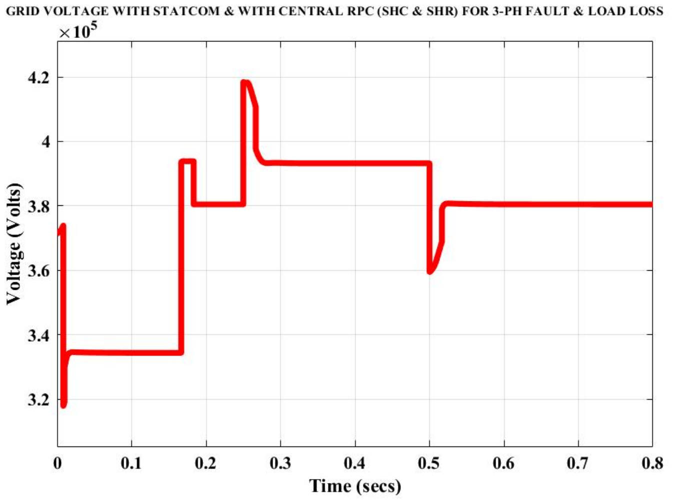

Figure 9: Voltage oscillations during 3-ph fault and load loss

C. Case 3: 3-ph fault followed by 1000 MW load loss with STATCOM and with centralized RPC (Both shunt capacitor banks and shunt reactors available)

In this case, simulation test was carried out and it was observed as shown in *figure 9* that during the 3-ph fault the voltage in B3 node in the network fell to almost 320kV but it recovered immediately to about 335kV as further dip was arrested by connected STATCOM and also automatic connection of the 125MVAR shunt capacitor bank by centralized RPC when voltage dip was sensed. After clearing of this fault, there was a sudden load loss of 1000MW. In previous cases, due to the sudden loss of such huge load, there was sudden significant rise of voltage. However, in this case, due to availability of shunt reactor apart from STATCOM as a part of centralized RPC, the voltage overshoot was arrested immediately. The average voltage overshoot was till 405kV in previous cases. In this case due to the availability of shunt reactors which got connected automatically by the centralized RPC order when voltage rise was detected the average voltage rise was till 380kV. Almost 25kV voltage rise was prevented by the centralized RPC thereby preventing grid failure.

7. CONCLUSION

For understanding the requirement of centralized RPC in a weak grid, the above 03 cases have been simulated. The parameter which is being observed from the grid stability perspective in this paper is only system voltage.

From the above simulations carried out, it was observed that in Case 1, the 3ph fault simulation was carried out without centralized RPC which means that the reactive power sources and sinks of the grid were not controlled by a centralized controller to recover from the fault. As a result, the recovery time taken for the voltage dip when 3-ph fault was simulated is more for Case 1 compared to the similar fault simulated in Case 2. In Case 1, the voltage dip of about 50kV persisted until the 3ph fault was cleared. However, in Case 2, the voltage dip was of about only 35kV due to the activation of the centralized RPC which connected an additional 125 MVAR shunt capacitor bank as the voltage fell down significantly. In comparison of Case 1 and Case 2, an additional dip of around 15kV was observed. For Case 1as there was no centralized RPC available for Case 1.

Further in Case 3, the centralized RPC was active with STATCOM, shunt capacitors and shunt reactors being a part of the centralized RPC.As a result during the simulation of 3ph fault like in Case 1 and Case 2, the voltage fall was arrested immediately due to STATCOM and connection of shun capacitor bank which is similar to the voltage recovery of Case 2. Further, due to availability of shunt reactor as a part of the centralized RPC in Case 3, when sudden load loss of 1000MW case was simulated just like in Case 1 and Case 2, the overvoltage as observed in Case 1 and Case 2 was of about 30kV which restricted to only 10kV in Case 3 due to the connection of shunt reactors in Case 3 by the centralized RPC. From all these simulation cases it can be observed that in Case 3 where all the elements of the grid are controlled by the centralized RPC, the voltage rise/fall during various faulty conditions in the weak grid can be successfully restricted by the immediate response from the centralized RPC by connection/disconnection of reactive power injection/absorption elements connected in the grid.

The centralized RPC aims to utilize all the available resources in a grid to provide automatic swift response based on defined priority to maintain the voltage in the set level in case of any disturbance in the grid.

For a weak grid, voltage oscillation is a major cause of concern, as it leads to severe disturbance in the grid and hampers the power quality. Effective and fast control of reactive power in the grid is paramount as it will allow the grid to be in operation without any major cascade tripping or grid failures. For achieving grid voltage stability with integration of renewable energy resources mainly with solar and wind energy sources, a centralized level RPC has to be implemented which has the automated feature to connect/disconnect any element in the grid including ordering down of generation and disconnection of connected loads for reactive power management of the transmission grid to maintain the grid voltage within prescribed limits.

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