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PROTECTION AND CONTROL OF ACTIVE DISTRIBUTION NETWORKS BY ADAPTIVE DC STABILIZER

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Abstract- Smart distribution system automation is the key to realizing a highly reconfigurable, reliable, flexible and active distribution system. Automated network reconfiguration including restoration is the most studied area in distribution automation, and it contributes to power loss minimization, voltage improvement and also can enable the distribution network to respond to contingencies and changes happened in the grid. This project takes a systematic view on the control and protection of medium power DC networks in an active distribution power system considering fault current limiting, system control, and converter design. Reduced terminal capacitance and extra DC impedance are used to limit DC fault current and reduce the required converter current rating for medium power DC networks. The proposed power restoration scheme is based on the coordination among distributed control among relays, load switches, voltage source converters and autonomous operation of multi-terminal DC system. A DC stabilizer is proposed with virtual impedance method to damp out potential oscillation caused by constant power load terminals. A stabilizing method is also proposed to improve system dynamics from the power terminal side by modifying the large constant power terminal impedances. An adaptive DC power stabilizer is proposed to alleviate possible system instability brought by the fault current limiting settings in the presence of constant power load. The effect of the current limiting method and the proposed stabilizer on DC fault current and stability enhancement are validated by MATLAB/SIMULINK simulation studies using a simple two-converter DC network and a multi-terminal DC network in an active distribution power system.

I. INTRODUCTION

Power system were traditionally planned and designed by assuming unidirectional power flows from power stations to loads. Nowadays, several factors (e.g., liberalization of the electricity market, need of increased reliability, and environmental issues) lead to a situation where electricity is produced also downstream the transmission level. Connecting generators to the distribution networks could provide several benefits to the whole system, but also technical and safety problems that must be faced. The traditional electric power system is designed for unidirectional power flow with very limited observability, intelligence and autonomous response. Electricity users are simply waiting for the electric power transferred from power plants through transmission lines and distribution feeders, without any active interaction or demand response.

The limited one-way interaction makes it difficult for the grid to respond to the ever changing and rising energy demands of the 21st century. Besides, concerns about global climate change have increased the penetration of renewable energy resources worldwide. As a result, in order to build a more secure, reliable, efficient and greener power grid, the concept of "smart grid" has been proposed. Generally speaking, there is no specific or unique definition of smart grid. Smart grid technology includes the application of automation and intelligent controls to power systems, and it includes several significant characteristics, including: 1) increased use of digital control and information technology with real-time availability; 2) dynamic optimization relating to grid operability; 3) inclusion of demand side response; 4) demand side management strategies; 5) integration of distributed resources including renewable and energy storage; 6) deployment of smart metering; 7) distribution system automation; 8) smart appliances and customer devices at the point of end use.

It is envisioned that the trend of using more DC systems will grow over time and some point in the future may even dominate over the conventional AC systems. DC distribution systems a number of advantages such as reduced losses, higher power quality, compactness, fast and accurate control of power flow, as well as controllable transient response to disturbances and faults in the system. Modern DC distribution systems increasingly use switching-mode power converters for energy transformation and power distribution. Specifically, power distribution in aircraft, vehicular systems large ships, and even buildings require modular and efficient high bandwidth power devices to satisfy critical system requirements on flexibility of control, high power density, as well as robustness with respect to outages and component failures. The measure taken for fault current limiting using increased DC inductance and reduced DC capacitance can further

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tense up the instability problem along with considerable distribution length, which has rarely been investigated before. And the stabilization of a more expanded DC system, typically up to a few kilometers, with autonomous variable load has rarely been explored with DC protection simultaneously considered.

In this paper, a systematic view on protection, stability control and converter design is taken to enable the application of medium power DC system with considerable distribution length. An adaptive stabilizer is proposed to compensate local negative impedance based on its own local detections hence no need for high bandwidth global information acquisition. The proposed adaptive control is also independent from both the constant power terminal and the grid side conditions, and the flexibility of being able to incorporate into CPL terminal control if required.

II. ACTIVE DISTRIBUTION POWER SYSTEM

The main objective of the electric power grid is to supply loads with adequate capacity, voltage, frequency and reliability. In the last two decades, advancements in automation devices, communications and controls have been progressively adopted in power grid to improve reliability, efficiency and sustainability as part of the ongoing smart grid efforts with improved management & control strategies. Researchers perform studies that facilitate application of smart grid technologies, and assess the benefits for grid operation. Coincident with growing of advanced metering infrastructure (AMI) and adopting appropriate communication technologies in power systems, distribution systems have become more important with an active role. The proliferation of renewable energy sources (RES) and other types of distributed generations (DG) together with load growth, energy storage technology advancements, increased penetration of AMI and increased consumer expectations have significantly changed the approach to planning, design and operation of distribution systems. These new approaches are facing new challenges in distribution systems such as handling large scale data, dealing with uncertainty in information and securing cyber-physical system. Around the globe, distribution companies, equipment manufacturers, electrical engineering consultants, research institutions, regulators and stakeholders are dealing with these issues. As part of this new paradigm, it is possible for the distribution system operators (DSOs) to control, operate and thereby integrate distributed energy resources (DER) into the network with appropriate supporting infrastructure, directly or indirectly. This vision requires the evolution of electricity distribution systems from *passive* to *active* distribution systems (ADS). Figure (1) shows the data flow between the different components of the cyber-physical ADS. As shown in this figure, communication happens in bidirectional way between different end-user and generation/supply resources.

Fig:1. Data flow for cyber-physical ADS.

The International Council on Large Electric Systems (CIGRE) developed a shared global definition of active distribution systems (ADS) defined as: “Active distribution systems (ADSs) have systems in place to control a combination of distributed energy resources (DERs), defined as generators, loads and storage. Distribution system operators (DSOs) have the possibility of managing the electricity flows using a flexible network topology. DERs take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement.”

Distributed energy resources (DERs) are the critical components to make the distribution system “*active*”. There are many types of distributed resources that must be considered.

- Traditional distributed generation (DG) will be more widely deployed. Localized generation can defer investment requirements to meet local load growth, reduce distribution losses, and even support microgrids for special reliability requirements of local systems.
- Renewable energy sources (RESs) are special cases because these are usually variable and intermittent. Both wind and solar generations are becoming more common on distribution systems, and future distribution management and control tools will need to consider the impact of higher penetration layers.
- Energy storage systems (ESS) will help smooth the impacts of the variable generation and can also reduce losses and defer investment requirements.
- Plug-in hybrid electric vehicles (PHEV) could be a special case of distributed storage but with much more control requirements that will depend on consumer choices and behavior.
- Demand response (DR) will be widespread. Smart customer loads and demand response systems will be a resource for local distribution systems as well as the Distribution

Management Systems (DMS) and Energy Management Systems (EMS) level.

With the increasing penetration of renewable generation on the distribution power system, the growing intermittent power could potentially give rise to over-voltage or under-voltage at the "last-mile" feeders of a distribution power system. Medium power DC links can therefore be placed in between these weak feeders to improve their voltage profile and provide more flexible power flow regulations as is shown in Fig 2. As the possible increasing load demand of EV charging may arouse further load mismatching, one option is to integrate the charging station (and other renewable generations) on the DC link side as shown in Fig. 2. In this way the charging load flow and intermittent renewable power can be managed in a more flexible way. Such a system could further benefit from emergency power supply from the charging station along with renewable sources when there is an outage on the AC utility grid side.

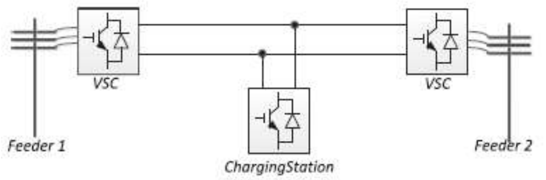

Fig:2. DC network in an active distribution power system.

For a multi-terminal DC network within an active distribution power system, the AC/DC converters may be located some distance away from the loads including CPL (e.g. charging station) and for economical reasons existing overhead line paths may be used for DC distribution. As a result, possible DC fault has to be considered. Protecting the converters from DC faults and, meanwhile, ensuring DC system stability when there is considerable distance between the loads and AC/DC converters have to be dealt with.

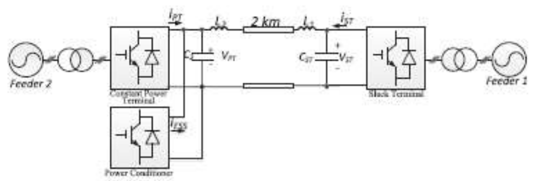

Fig:3. Sample system with single power terminal and conditioner.

Reduced DC capacitances with extra impedance on the DC terminal can effectively reduce the DC fault current. However, such arrangements can potentially cause system instability especially when connecting to a remote constant power terminal. To tackle this problem, an adaptive DC power stabilizer is proposed for stabilizing the DC power system with small DC capacitance and additional DC terminal impedance. In this section, the dynamic effect brought by the extra impedance for DC fault current limiting is analyzed first to show how the FCL configuration can deteriorate system stability when there is CPL in operation. Based on the analysis, an adaptive DC power stabilizer is then proposed and installed at the CPL terminal to avoid potential system instability. A single constant power terminal based DC power network is established as shown in Fig. 3. Two-level VSCs and additional DC impedances for extra fault limiting capability are employed to integrate the DC system to the AC utility grid.

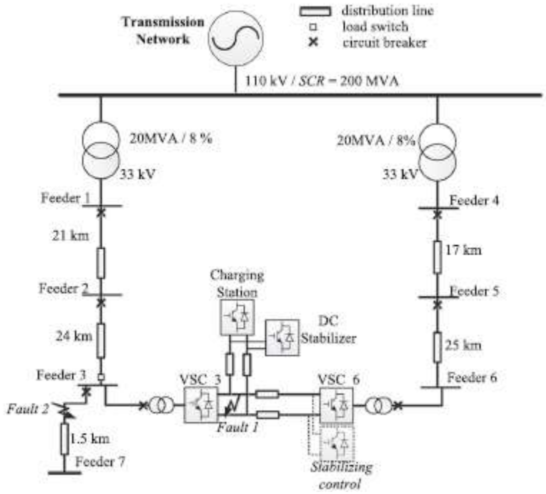

Fig:4. Active distribution power system configuration.

To further examine the effectiveness of the DC current limiting capability and stability enhancement of the proposed system configuration and power stabilizer concept, a 7-feeder active distribution power system is established as Fig.4 shows with its parameters. One VSC operates as the constant power terminal and the other is the slack terminal controlling the DC voltage. The distance between the two converters is 2 km. A small DC–DC converter with super capacitor based energy storage system (ESS) is placed at the constant power terminal side as the power stabilizer. A three-terminal medium power DC network is inserted between Feeder 3 and Feeder 6 with an EV charging station incorporated. VSC 6 (at Feeder 6) is designed to be the main constant power terminal within the DC power system whose internal control is typically accessible by the system operator for illustration. On the other hand, a charging station is incorporated in the DC system operating as an inaccessible/independent constant power terminal. VSC 3 operates as the slack terminal throughout the tests in this section. A virtual DC stabilizer is incorporated within the accessible constant power terminal side (i.e. VSC

6) as shown by the dotted diagram in Fig.4 and an actual DC stabilizer is installed at the inaccessible power terminal of the charging station in Fig.4. All the DC terminals are designed with extra fault limit capability and the charging station is assumed to be able to isolate the DC fault current with galvanic isolated topology.

III. SIMULATION RESULTS

The effect of the current limiting method and the proposed stabilizer on DC fault current and stability enhancement are validated by simulation studies using a simple two-converter DC network and a multi terminal DC network in an active distribution power system.

CASE A: SIMULATION DIAGRAM OF DC NETWORK IN AN ACTIVE DISTRIBUTION POWER SYSTEM

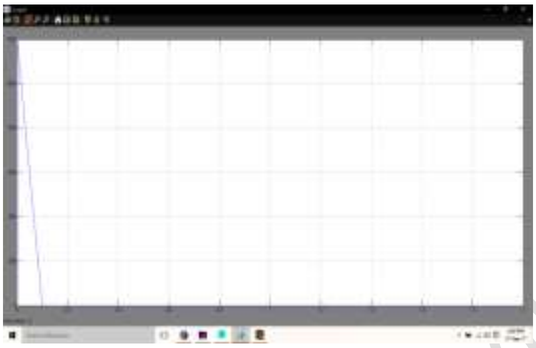

Fig:5(a)

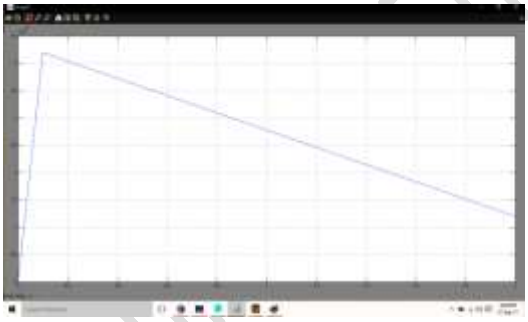

Fig:5(b)

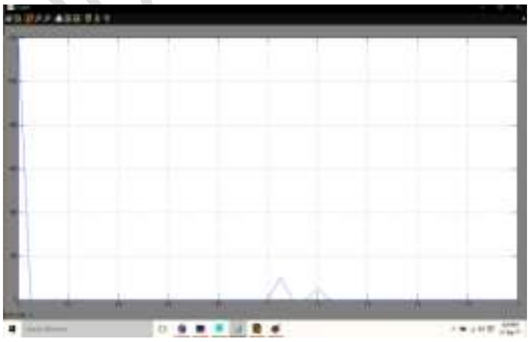

Fig:5(c)

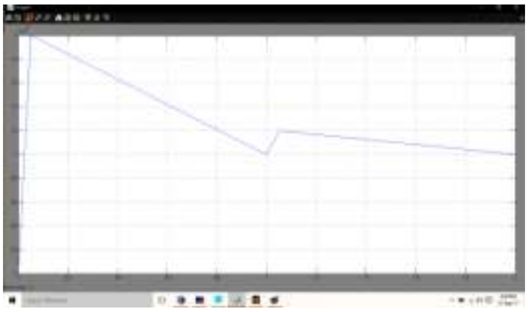

Fig:5(d)

Fig:5(e)

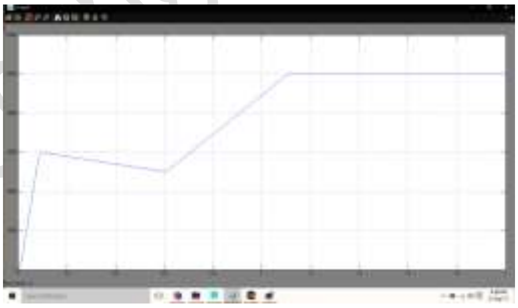

Fig:5(f)

Fig:5 System performance with dc network in an active distribution power system,(a)V_{ST} (b) I_{ST} (c) V_{PT} (d)I_{PT} (e) P_{PT} (f) I_{PT}

The DC fault behavior is depicted in Fig. 5 where the DC fault occurs at t = 0 ms. No current limiting measure is taken and the IGBTs are assumed to be blocked immediately after the fault. As a result the DC voltage *V*dc drops to 0 and the fault current *i*LDC reaches as much in less than 1 millisecond. This peak current is mainly produced by the discharging of the terminal capacitor. The discharging current in Stage 1 and the subsequent circulating current in Stage 2 are the main fault current components after the fault. This is due to the fact that a smaller terminal capacitance has reduced the total capacitor discharging energy at Stage 1 shown in Fig. 5. The fault current decays and circulates through the diodes after the DC voltage reaches 0. The extra inductance further reduces the fault current rising rate during stage 1 and the peak discharging current has been suppressed to less than 4 p.u. when the DC voltage drops to 0.

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CASE B: SIMULATION DIAGRAM OF SINGLE CONSTANT POWER TERMINAL WITHOUT ADAPTIVE POWER STABILIZER

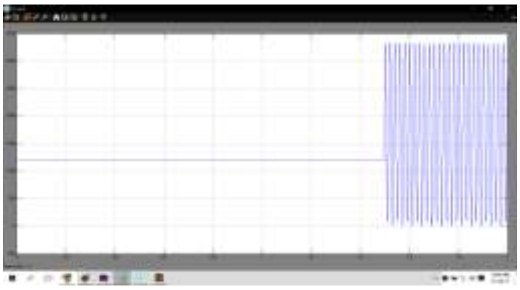

Fig:6(a)

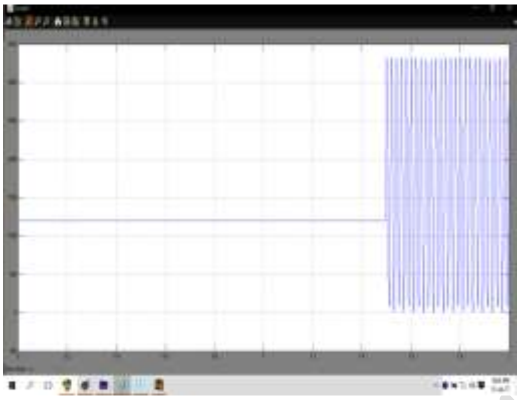

Fig:6(b)

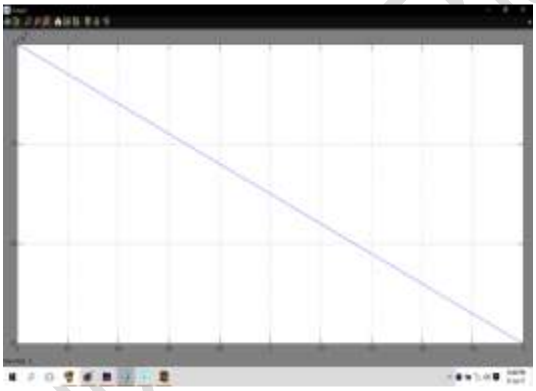

Fig:6(c)

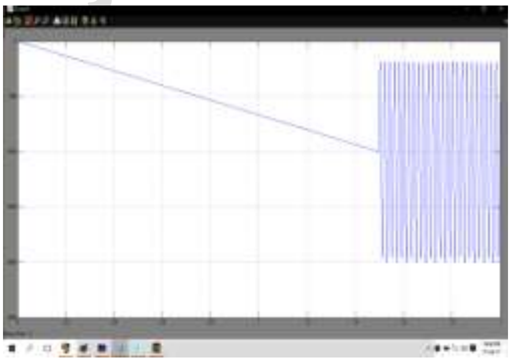

Fig:6(d)

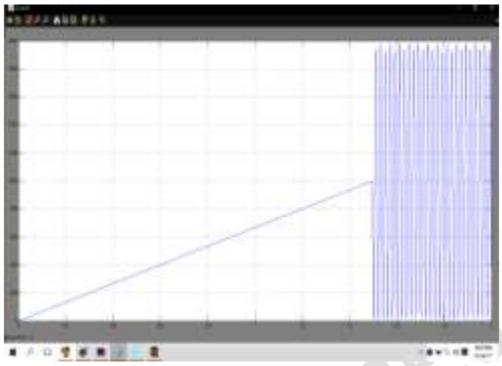

Fig:6(e)

Fig:6. System performance with single constant power terminal without adaptive power stabilizer,(a)V_{ST} (b)V_{PT} (c)P_{PT} (d)I_{PT} (e)I_{ST}

By deactivating the power stabilizer, the system is tested with a defined power ramp from the constant power terminal. The simulation results are shown in Fig.6. It can be seen that when the power terminal starts to drain power from the DC network, the current are balanced by the slack terminal accordingly.

CASE C: SIMULATION DIAGRAM OF SINGLE CONSTANT POWER TERMINAL WITH ADAPTIVE POWER STABILIZER

Fig:7(a)

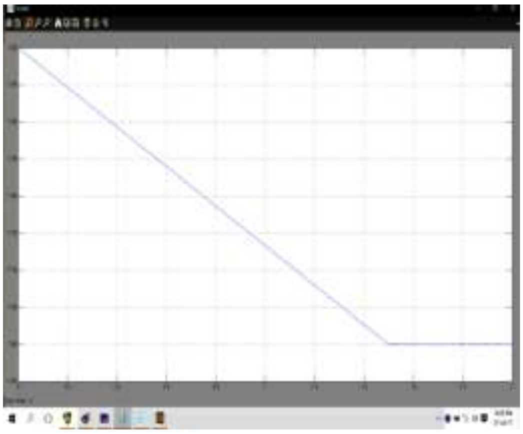

Fig:7(b)

Fig:7(c)

Fig:7(d)

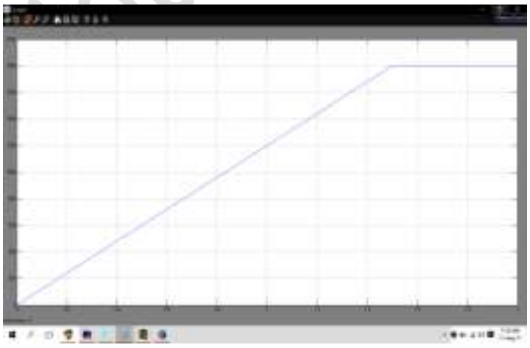

Fig:7(e)

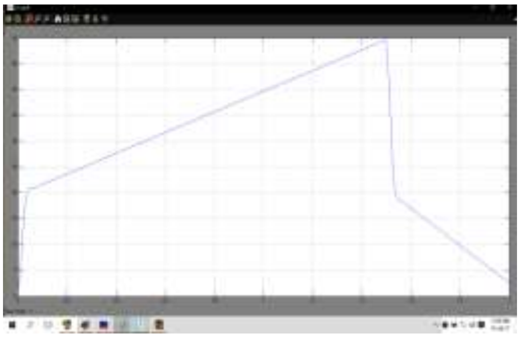

Fig:7(f)

Fig:7. System performance with single constant power terminal without adaptive power stabilizer,(a)V_{ST} (b)V_{PT} (c)P_{PT} (d)I_{PT} (e)I_{ST} (f)I_{ESS}

On the contrary shown in Fig.7, the DC stabilizer is activated and the power ramp of the constant power terminal The DC voltages are well regulated throughout. The power stabilizer only consumes 50 A at its peak, which is less than 3% of the rated current of the constant power terminal and gradually drops to zero after the ramp indicating only a small energy and power rating is required for the storage.

CASE D: SIMULATION DIAGRAM OF DC FAULT BEHAVIOR AT VSC3

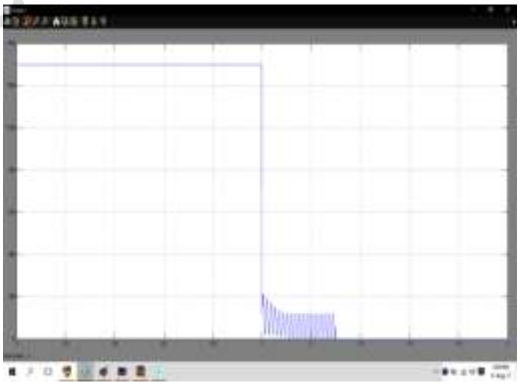

Fig:8(a)

Fig:8(b)

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Fig:8(c)


Fig:8(d)

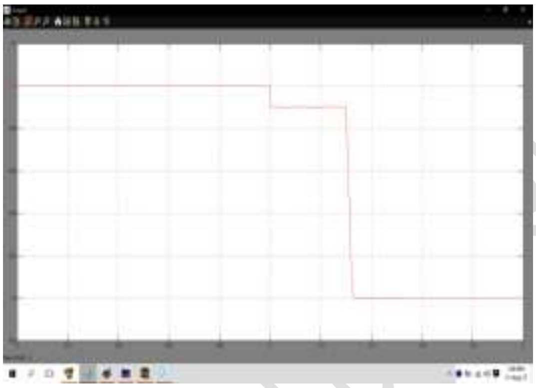
Fig:8(e)

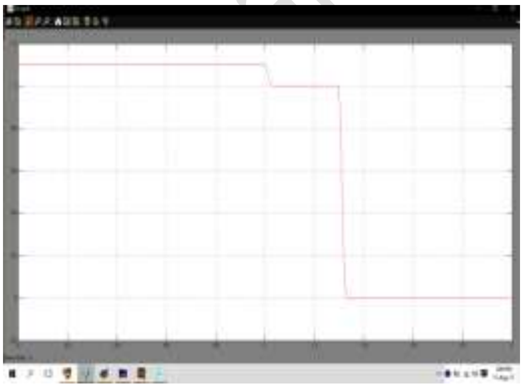
Fig:8(f)


Fig:8(g)


Fig:8(h)

Fig:8 DC fault behavior at VSC3. (a)V_{DC3} (b)V_{DC6} (c)I_{fDC3} (d)I_{fDC6} (e)V_{AC3} (f)V_{AC6} (g)I_{AC3} (h)I_{AC6}

Fig. 8 shows the DC fault behavior at VSC 3 which connects to Feeder 3. The system starts with VSC 6 importing a ramp power of the DC network and the charging station is idle. The circuit breakers at the AC sides of the VSC 3 and 6 are tripped to break the DC fault. As a result, the fault currents at both AC and DC sides are gradually extinguished and DC network is de-energized.

CASE E: SIMULATION DIAGRAM OF SINGLE STABILIZER PERFORMANCE AT THE CHARGING STATION WITH RAMP CHARGING LOAD WITHOUT ANY STABILIZER

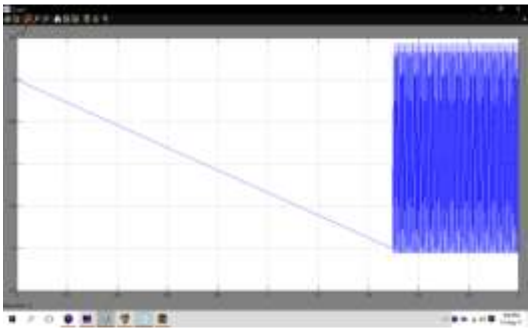
Fig:9(a)

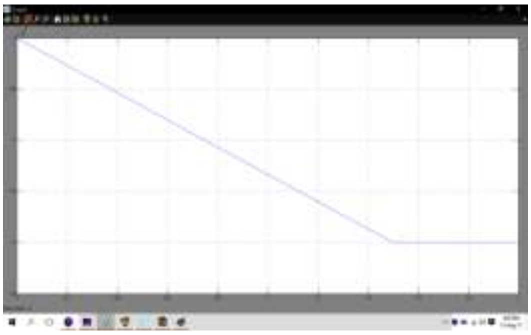
Fig:9(b)

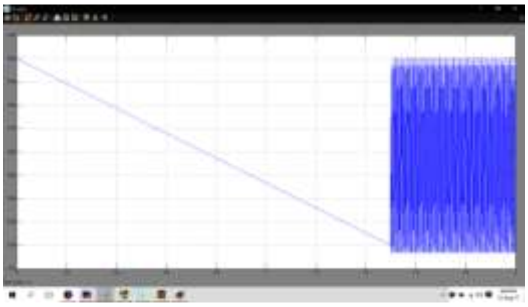
Fig:9(c)

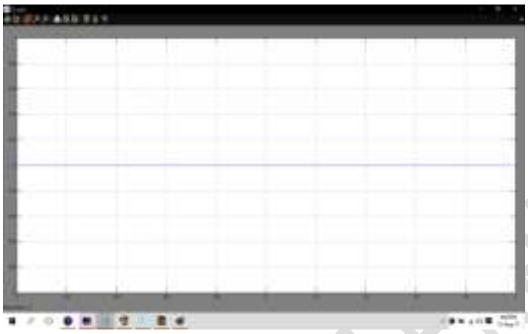
Fig:9(d)

Fig:9. Single stabilizer performance at the charging station with ramp charging load without any stabilizer, (a)P_{DC3}(power consumed by VSC 3) (b)P_{Charg}(power discharged from the charging station) (c)V_{DC}(DC voltage at the charging station bus) (d) P_{Cond} (power discharged by the DC stabilizer).

In Fig. 9, both the stabilizing control in VSC 6 and the charging station are deactivated. A ramp load of 0.5 MW/s is consumed at the charging station from T = 0 s till it reaches its full rating of 2 MW and the power is fully accommodated by VSC 3 as VSC 6 is given zero power order. It can be seen that when the charging power rise up to 1.9 MW, the DC system starts to oscillate. This demonstrates the superiority of the DC link over the AC link, as it does not reduce the equivalent short circuit impedance whereas the additional AC connection does.

CASE F: SIMULATION DIAGRAM OF SINGLE STABILIZER PERFORMANCE AT THE CHARGING STATION WITH RAMP CHARGING LOAD WITH CHARGING STABILIZER

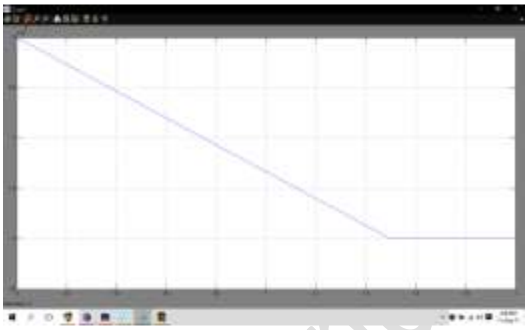
Fig:10(a)

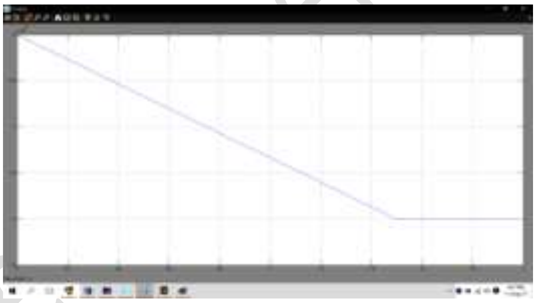
Fig:10(b)

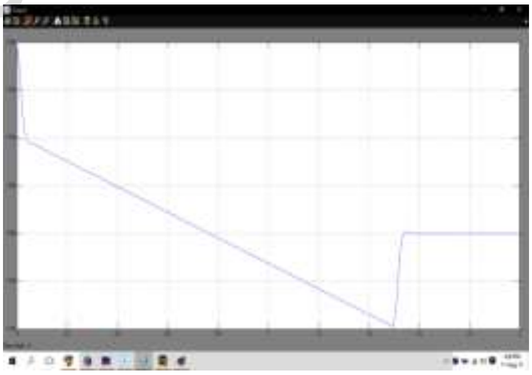
Fig:10(c)

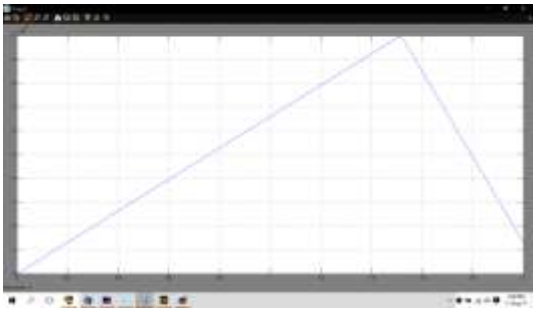
Fig:10(d)

Fig:10. Single stabilizer performance at the charging station with ramp charging load with charging stabilizer, (a)P_{DC3}(power consumed by VSC 3) (b)P_{Charg}(power discharged from the charging station) (c)V_{DC}(DC voltage at the charging station bus) (d) P_{Cond} (power discharged by the DC stabilizer).

On the contrary, the ramp charging load test is performed in Fig. 10 with charging side stabilizer activated. It can be seen that no oscillation is induced throughout this test. The maximum power shared by the stabilizer is less than which is 5% of the load rating. The stabilizing power gradually moves towards, since the stabilizer function only provides dynamic response due to the addition of the high-pass filter design. The proposed stabilizers can effectively eliminate undesirable oscillations caused by additional DC side impedance and constant power load in medium power DC network of an active distribution power system.

CASE G: SIMULATION DIAGRAM OF DUAL STABILIZER PERFORMANCE WITH POWER RAMP AT VSC 6 WITH ONLY CHARGING STABILIZER

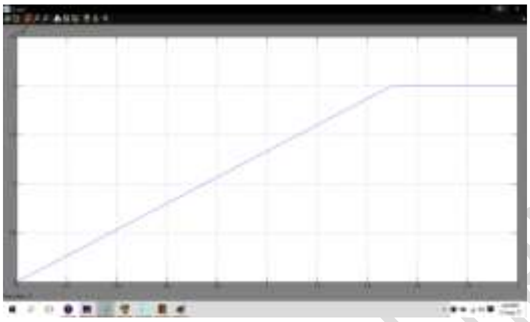

Fig:11(a)

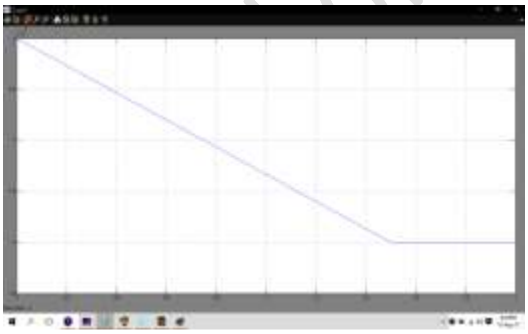

Fig:11(b)

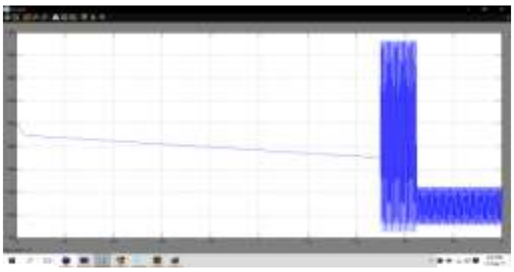

Fig:11(c)

Fig:11(d)

Fig:11. Dual stabilizer performance with power ramp at VSC 6 with only charging stabilizer, (a) P_{DC6} (power consumed by VSC 6), (b) P_{Charg} (power discharged from the charging station) (c) V_{DC} (DC voltage at the charging station bus) (d) P_{Cond} (power discharged by the stabilizer).

As shown in Fig. 11 significant voltage oscillation is induced when the VSC 6 load increases to approximately 1.9MW. The maximum power of the actual stabilizer is only 0.01 MW (when system stable) indicating that the remote power terminal and its additional stabilizing control has negligible effect on the stabilizer at the charging station side. This result shows that the proposed stabilizer is not sensitive to remote variations. The required power rating of the stabilizer is very small compared to the power rating of the system and thus the additional cost of the stabilizer is trivial compared to the overall system cost. In addition, this allows the adoption of simple fault current limiting method using additional DC inductance and reduced DC capacitance.

CASE H: SIMULATION DIAGRAM OF DUAL STABILIZER PERFORMANCE WITH POWER RAMP AT VSC 6 WITH BOTH STABILIZERS

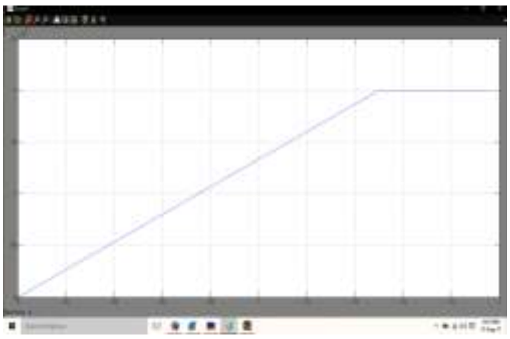

Fig:12(a)

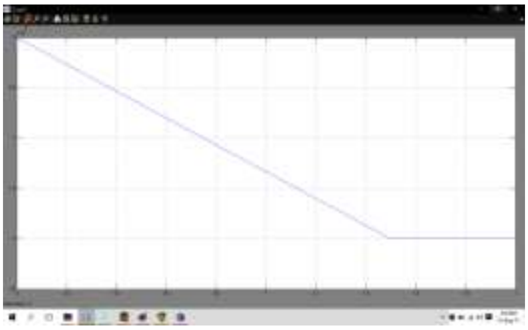
Fig:12(b)

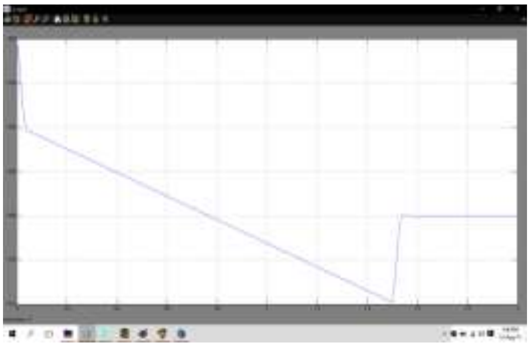
Fig:12(c)


Fig:12(d)

Fig:12. Dual stabilizer performance with power ramp at VSC 6 with both stabilizers, (a) P_{DC6} (power consumed by VSC 6), (b) P_{Charg} (power discharged from the charging station) (c) V_{DC} (DC voltage at the charging station bus) (d) P_{Cond} (power discharged by the stabilizer).

However, when the stabilizing control is activated the oscillation is eliminated and system is completely stable across the whole power range, as can be seen in Fig. 12. In order to effectively stabilize the DC power system, real and/or virtual stabilizers need to be located close to the CPL. It can also be seen that the stabilizer (either physical or virtual) can effectively neutralize instability effect though; it has very little effect on the remote constant power terminal and vice versa.

IV. CONCLUSION

A medium power DC system solution considering DC fault current limiting and stability for active distribution power system has been investigated. By replacing the normal open switch with a DC link, the distribution network achieves improved power distribution control and load ability without increasing AC fault current. Increasing DC inductance and reducing DC capacitance of the DC terminals can effectively reduce VSCs' peak fault current, current rising rate and accumulated diode I^2t before fault current interruption. However, this technique can give rise to instability when there are large CPL terminals within the medium power DC system due to the amplification of CPL's negative impact on small-signal stability by the additional DC inductance and reduced DC capacitance. To overcome the adverse effect on stability and alleviate sensitivity to system operational conditions, an adaptive DC stabilizer with limited power rating requirement is proposed which can either be placed close to the inaccessible CPL terminal or with its control function embedded into an accessible CPL control as a virtual stabilizer. The proposed DC stabilization scheme requires only local measurements and enables the use of simple fault current limiting methods by effectively stabilizing a DC system of considerable distribution length. The stabilizing control has been validated by simulations of a two-terminal DC system and a multi-terminal DC system in an active distribution network.

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