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FLEXIBLE VOLTAGE CONTROL STRATEGY CONSIDERING DISTRIBUTED ENERGY STORAGES FOR DC DISTRIBUTION NETWORK

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Abstract- Widespread penetration of Renewable Energy (RE) sources in distribution networks may introduce new technical challenges for the distribution network. These issues include voltage rise, voltage unbalancing, voltage regulation problem, thermal overloading, frequency fluctuation, flicker and harmonics. Consequently, the traditional operation of distribution networks limits the penetration level of RE sources and need to be revised to incorporate new control and protection strategies. In this project, a flexible voltage control strategy, which takes good use of the distributed energy storage (DES) units, is proposed to enhance the voltage stability and robustness of DC distribution network. The characteristics of AC/DC interface in network are analyzed, and the virtual inertia and capacitance are given to demonstrate the interactive influence of the AC and the DC systems. The control strategy for DES which is located at the AC microgrid or at the network terminal bus is designed based on the interactive characteristics, enabling the DES to respond to both voltage variation of DC network and frequency change of utility AC grid. A cascading droop control strategy is proposed for DES in DC microgrid to relieve the pressure of voltage deterioration of DC network buses which connect the DC microgrid. The proposed comprehensive flexible control strategy for DESs at different interfaces features independence of communication as well as enhancement of system robustness, and reduces the impact of DC distribution network on utility AC grid. The performance of the proposed control strategy is validated under different operating conditions of the DC distribution network by matlab/simulink simulation results.

***Index Terms*—All-electric ship (AES), hybrid energy storage system (HESS), superconducting magnetic energy storage (SMES), pulse load.**

INTRODUCTION

In recent years, the structure of the electrical power system has changed, and power generation has shifted towards Distributed Generation (DG). Although the increase in the demand for energy and environmental concerns about traditional power generation have been mentioned as reasons for this shift, another crucial motive is the large amount of energy lost in traditional methods: when power is generated from fossil fuels, 40%–70% of the energy present in the resource is lost as heat. Another 2% and 4% is then lost in transmission lines and distribution, respectively. Solar energy (photovoltaic cells) and wind turbines are the most popular of the Renewable Energy Sources (RESs) that can be integrated into the main network in the form of DGs or Microgrids (MGs). Indeed, MGs consist of a number of such DG systems organized together in a way that increases the system capacity and improves the power quality. There are three different types of benefits associated with MGs: technical, economic, and environmental.

From the technical point of view, DGs can support the power of remote communities and give higher energy efficiency while lacking the vulnerability of large networks and helping to reduce blackouts. Economically, DGs reduce emissions, line losses, and interruption costs for the customer while minimizing the cost of fuel, ancillary services, and so on. The environmental benefits of MGs are discussed, and include lower emissions of pollutants and greenhouse gases, a generation system that requires a smaller physical footprint, an increase in the number of clean energy sources incorporated in the grid; and decreased reliance on external fuel sources. MGs may be found in low voltage (LV) and medium voltage (MV) distribution networks, and can operate in grid-connection mode or island mode. The switching between these operation modes is controlled through a circuit breaker at the Point of Common coupling (PCC). Moreover, MGs can be categorized as AC microgrids or DC microgrids.

The general configuration of a hybrid (AC–DC) MG is shown in Figure 1.1. Indeed, the power output by most of the DGs is DC, while the DG sources outputting AC have high levels of variation in frequency and voltage, and thus cannot be directly connected to the AC bus. A power electronic interface is thus needed to implement the MGs. The main control objectives in an AC MG are voltage stability, frequency synchronization, loads sharing considering inverter ratings, and managing power to create ancillary services for the main grid. On the other hand, there are some advantages to DC MGs over AC MGs: they are highly efficiency because of the reduction in conversion loss; frequency and phase control is not required, and there is no need for synchronization. Indeed, the main control objectives in DC MGs are adjusting the DC voltage to the acceptable value, sharing power based on the rate of conversion, and regulating the current flow to or from an external DC source. However, the AC MGs are still dominant, especially in island applications, because of their similar intrinsic characteristics to traditional distribution systems. Since the present research has focused on load sharing and power management in an island MG, it is only AC MGs that have been considered in this doctoral dissertation.

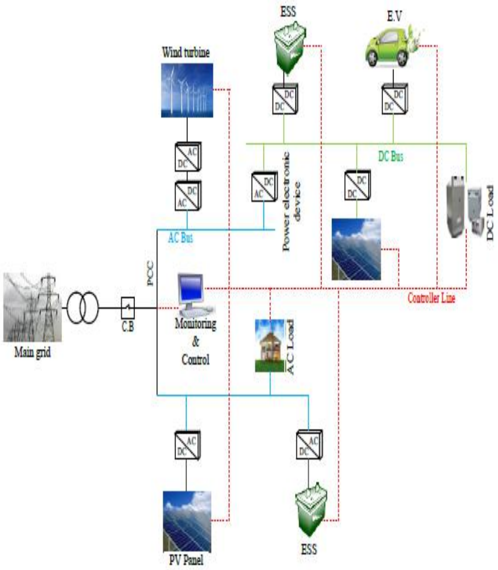

Fig:1. General view of a Hybrid MG

Without the doubt, in modern grids, power management and stability assurance are critical because of the variables involved on the generation and demand sides. Using energy storage to absorb and inject energy as needed can be the best solution to managing this issue. In fact, energy storage systems (ESSs) are crucial in both AC and DC MGs. Due to the benefits it brings DG has been rapidly growing in number in the last years, becoming an important component of the worlds future power systems. DG has the advantage that it may be connected closer to the end user thus reducing transmission losses. Moreover, it can be separated into two general categories: controllable and uncontrollable. The first one refers to generators that can be started whenever the user requires it. The latter to the ones that depend on the weather conditions to generate energy; most of the Renewable Energies Sources (RES) fall into this category. Some of the benefits of changing to a decentralized power system include:

- Avoid the need for building new infrastructure in the network
- Reduce the distribution network power losses
- Increase the systems flexibility
- Provide service support improving the continuity and reliability
- Help in "peak load shaving" and load management programs.

However, DG may also create problems in the grid operation if new Distributed Energy Resources (DER) are installed without previous planning. As already mentioned, DER are usually installed close to the end user making the distribution network their main market. On the rural and suburban areas there is more available space for DER installation, but on the other hand the load density is much lower than in a urban setting. Furthermore, DER connected in the distribution network have been shown to provoke reverse power flow and hence raise the voltage level in the feeders leading to over voltages. Throughout the converters required for grid connection of solar and wind energy ancillary services may be included in their control in order to avoid the negative impacts of DER in the LV network.

SYSTEM MODELING

Topology of DC Distribution Network

Similar to the AC distribution network, the DC network can be classified into three typical types: 1) the radial structure; 2) the ring structure; and 3) the dual or the multi-terminal structure. Fig. 4.1 shows the typical dual terminal DC network studied in this project. To acquire good fault ride-through capability, the substations at the terminal are connected to 4 kV DC network via the isolation transformers and the voltage source converter (VSC), which feature the electric isolation capability and work together to step down the voltage and transfer AC power into DC format. The following three different elements are inter-faced into the network via DC cables.

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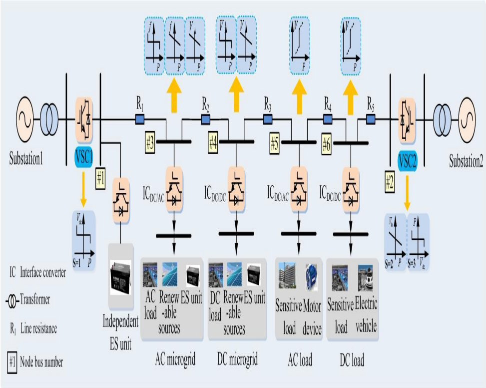

Fig:2. Dual terminal structure of DC distribution network

1) AC/DC microgrid- This type of element usually consists of distributed generators (DGs), ESs and local loads, the power of which is varied periodically in accordance with the change of natural environment factors such as wind speed or photovoltaic irradiation. When there is a shortage in power demand, the microgrid adjusts the power amount absorbed from the DC network. Sometimes, the microgrid can be used to adjust the voltage of distribution network.
2) AC/DC loads- The aggregative loads feature unidirectional power flow and can hardly be taken into consideration for voltage control. Except for some emergency condition, the loads can be shed in a passive way to release the burden of network.
3) Independent ES unit- It can be installed at any node, and offer an ancillary or backup support for DC voltage. The signal of node voltage is collected as the input for ES unit controller to compensate the voltage variation.

Conventional Control Strategy for Network Bus Voltage

According to the classification of network elements mentioned above, the nodes connected with different types of elements show different operating characteristics. Fig. 4.1 shows the control strategies of different types of nodes in the DC distribution network. More specifically, in this section, the voltage control of the nodes with different elements will be investigated.
1) Terminal nodes- At the terminal of DC network, the AC/DC converters are utilized to offer an access to AC grid for the network. These converters work under one of three control strategies, namely, the constant voltage control, the droop control (V-P) or the constant power control, as shown in Fig. 4.2. No matter which topology the DC network adopts, at least one of the terminal converters should adopt the constant voltage control to ensure there is a slack terminal in the system.

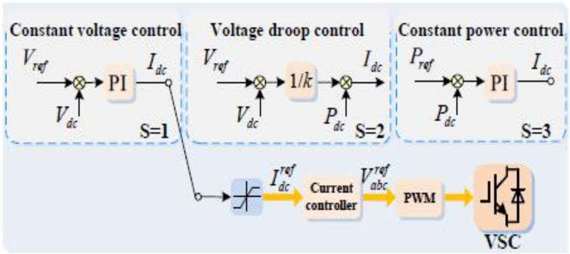

Fig:3. Different voltage control strategies for terminal converter of DC distribution system

2) The nodes connected with aggregating loads- These nodes work in a constant power consuming mode. In some emergency cases, some loads may increase the power demand within a narrow range.
3) The nodes connected with microgrids- The microgrids connecting to DC distribution network can output power if the distributed generators have more power that the local loads cannot be consumed, and the interface converters (ICs) are controlled in the similar way as the terminal VSC.

The control strategy for ES unit of microgrid can be classified into two modes. In Mode I, ES unit will not be activated during connection, all the net power demands will be satisfied by absorbing energy from distribution grid, and ES units should take part in power adjustment only when the microgrid is isolated from grid, or in the situation that power flow is beyond the capacity limitation. In Mode II, it features that ES unit is assigned to track the net power variation of microgrid. The ES unit is utilized to absorb high-frequency power variation, and the rest of power vacancy is compensated by the DC distribution net-work. In some cases, the ES unit is responsible for all of the power vacancy which is not beyond the operational limits of ES converter, and DC network will only take part in the power adjustment when the power burden is too much for ES to handle. For Mode I, ES units are of high vacancy rate. For Mode II, the capability of power support of distribution network is not fully utilized, which means the ES units are of high pressure on power adjustment. Besides, the conventional control strategy for DC distribution network mainly focuses on the voltage quality by tuning the terminal VSCs, which means the DC network has no response to the frequency variation of AC network. Therefore, the conventional strategy is not friendly to the utility grid and indirectly deteriorates the frequency stability, and it would be become harder and more complex to keep the global voltage quality when the scale of DC distribution net-work enlarges and more nodes are included.

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FLEXIBLE VOLTAGE CONTROL WITH DESS

In this project, the comprehensive demands of the operating characteristics and control aims for different interfaces are taken into account. The power flowing from microgrids or AC utility grid to the DC network is considered in the condition of charge, and thus the inverse power flow is in the discharge state. The inner traits describe the variation of the electrical characteristics of elements interfaced to the DC network, such as the frequency of AC grid and the voltage of DC grid. The control objectives of this paper are described in this Table, where the absolute frequency deviation |Δf| is limited within 1%, and the DC voltage variation is within 5%. ΔVdc and ΔV bus represent the voltage variation of DC microgrid and DC distribution network, respectively. It should be noted that when some severe power events occur and the power quality cannot be guaranteed, which means the above delta values are beyond their limits, the common emergency measures like load shedding or microgrid disconnection will be activated to keep the stability of the DC distribution system.

Interactive power balance analysis for AC&DC grid

When the power is transferred from DC grid to AC grid, the IC can be treated as a virtual synchronous machine seen from AC side, providing the frequency support; similarly, when the power is absorbed from AC grid to DC grid, the IC can be treated as a virtual capacitor, providing the voltage support. Such interaction of power balance is illustrated in Fig. 4.3,

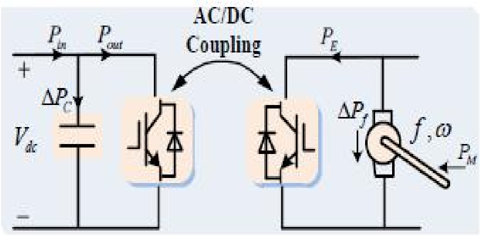

Fig:4. Equivalent power relationship for AC/DC interface

4.3.2 Voltage control strategy for AC/DC interface

When there is lack of power in AC microgrid, the power vacancy will be compensated by the DC network. When the DC network is under the extreme condition such as isolation and power limitation, the net power of AC microgrid should be compensated in part or all by its local ES units. When there is a voltage variation of DC bus, resulted from the power compensation for AC grid, the ES unit of AC mi-crogrid will be activated to output power to the local microgird, and to support the DC voltage. As can be known and the definition of kb, the output power of ES unit is determined by virtual inertial constant Hvir and the DC voltage variation ΔV. The capacitance Cdc and the droop coefficient kac are set as the fixed values, so they have no influence on the output power. Based on the general control structure of VSC, the control diagram of DC/AC converter for the ES unit in AC microgrid is developed as shown in Fig. 4.4. The hysteresis controller is adopted to avoid the frequent activation of the ES unit when the DC voltage changes near the boundaries of dead band, which can protect the ES unit and prevent the voltage oscillation due to the power compensation. Note that the droop control method described will not change the trend of voltage variation of the DC network, thus no power flow disorder will be caused.

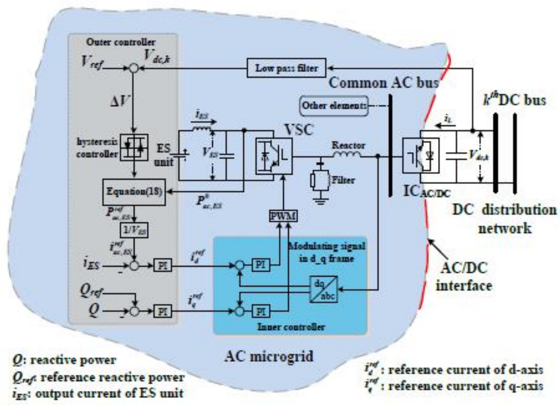

Fig:5. Controller configuration for the ES unit in AC microgrid

By adopting the aforementioned control strategy, the ES unit in AC microgrid is able to respond to the voltage variation of the bus where the microgrid accesses. The output power of ES unit is proportional to the voltage deviation. Since the voltage deviation is traced and compensated, the stability of DC net-work can be enhanced. When the voltage fluctuation of terminal bus appears, the utility grid will transfer power through VSC to the DC network according to the predefined voltage droop or the constant voltage control strategy. Meanwhile, the independent ES unit, used to regulate voltage in emergency condition, is activated to track the voltage deviation component ΔVdc_f. The reference output power of the independent ES unit is determined by ΔVdc_f and added as the supplementary control input of the terminal VSC signal, serving as a modified term to regulate the power absorbed from the utility grid. By using this control method, the DC network is able to respond to the frequency variation of the utility grid via the ES unit, without influencing the effect of voltage control strategy for the DC network. Thus, the DC network can perform as a

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friendly load to the AC utility grid. Fig. 4.5 shows the comprehensive control diagram for the terminal AC/DC interface.

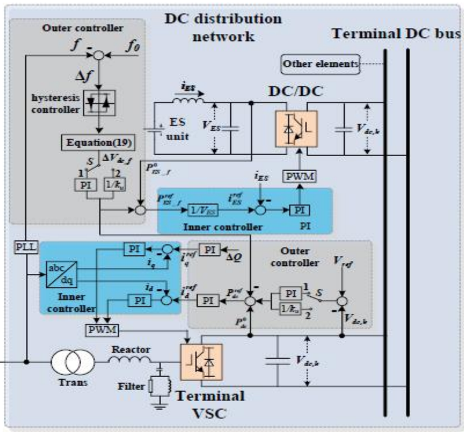

Fig:5. Comprehensive control diagram for the terminal AC/DC interface

Voltage control strategy for DC/DC interface

The bi-directional DC/DC interface is located between the DC distribution network and the DC microgrid, where the high-power bi-directional DC/DC converter is installed as IC. For simplifying the analysis, it is assumed that voltage droop control method is adopted to regulate the DC microgrid voltage. Unlike the conventional control strategy, the ES is assigned to track the voltage of DC network side bus where the DC microgrid is located, rather than the voltage of DC microgrid itself, and thus a cascading power compensation method is developed.

SIMULATION RESULTS

Case-1: Dynamic Performance on Power Variation

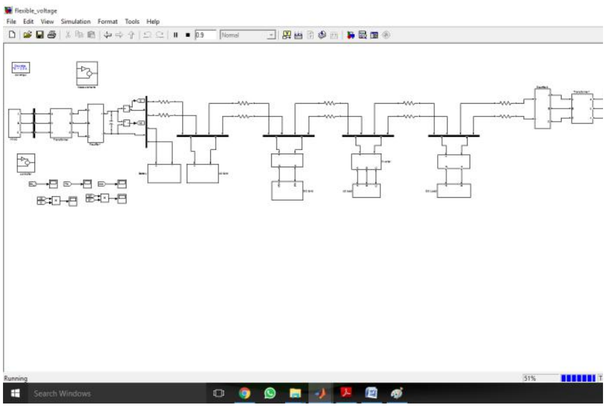

Fig:6.. simulation diagram of Dynamic Performance on Power Variation

In order to validate the proposed voltage control strategy, a comprehensive simulation model of DC network based on Fig. 5.1 is developed. The independent ES unit is installed at the terminal bus denoted #1 of the DC network, and the microgrids are also equipped with ES units. To acquire a good balance between energy density and fast power response, the Li-on batteries are chosen as the ES units in the simulation cases. Aggregating AC/DC loads are substituted by a constant power load, since they play no significant part in the following simulation.

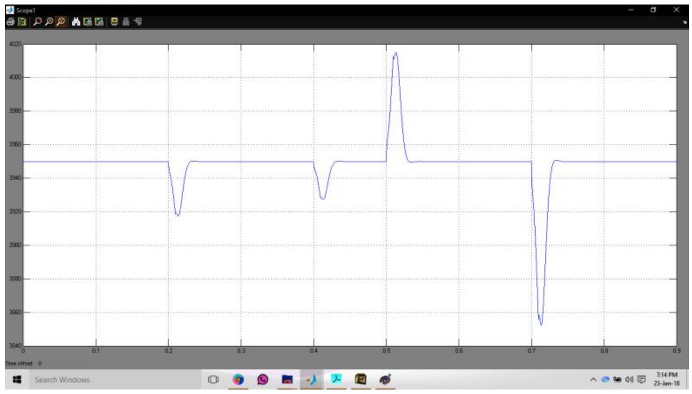

Fig:7.a)

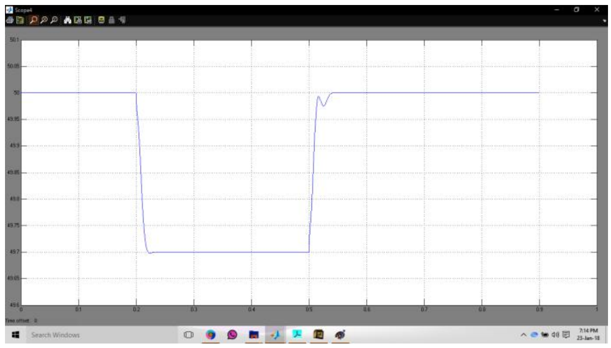

Fig:7.(b)

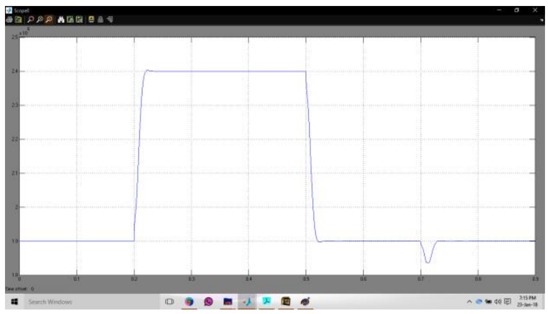

Fig:7.c)

Fig:7.(d)

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Fig:7.(e)

Fig.7. Simulation results of the AC microgrid for case 1, (a) voltage of DC bus #3; (b) frequency variation; (c) change of net power; (d) output power of the ES unit; (e) SoC of ES unit (with DESs)

Fig:8(a)

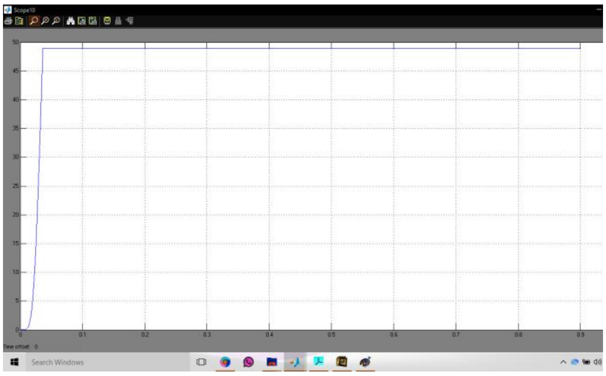

Fig:8(b)

Fig.8 Simulation results of the AC microgrid for case 1, (a) voltage of DC bus #3; (b) SoC of ES unit.(without DESs)

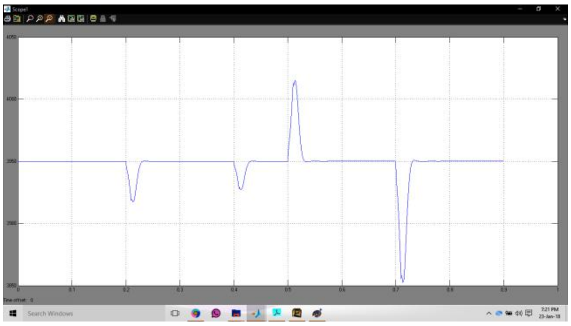

Fig:9(a)

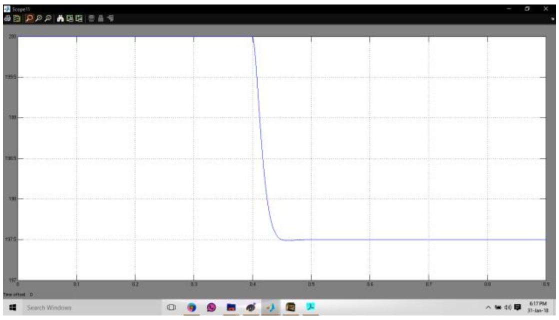

Fig:9b)

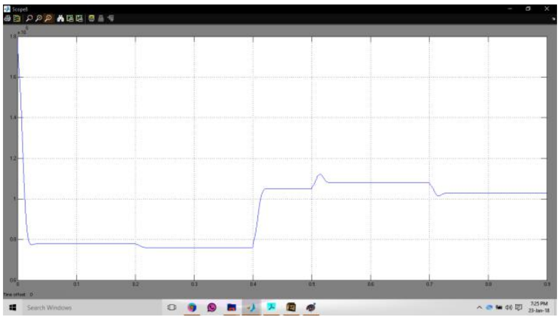

Fig:9.(c)

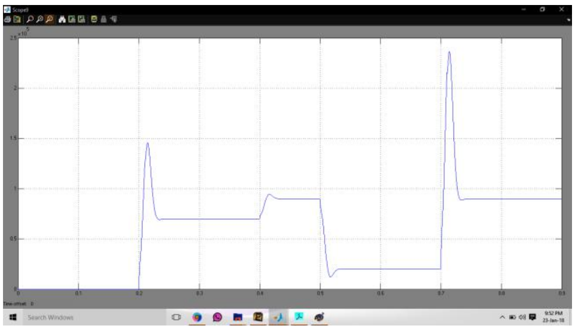

Fig:9.(d)

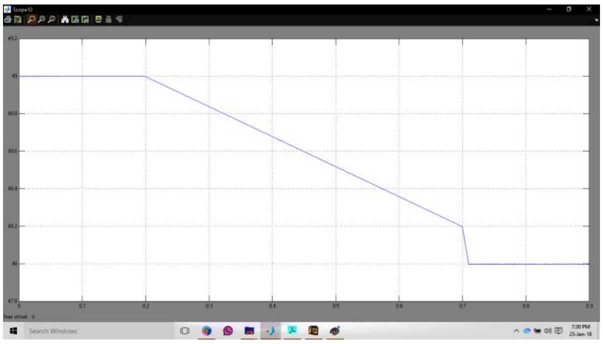

Fig:9.(e)

Fig.9. Simulation results of the DC microgrid for case 1, (a) voltage of DC bus #4; (b) voltage variation; (c) change of net power; (d) output power of the ES unit; (e) SoC of ES unit (with DESs).

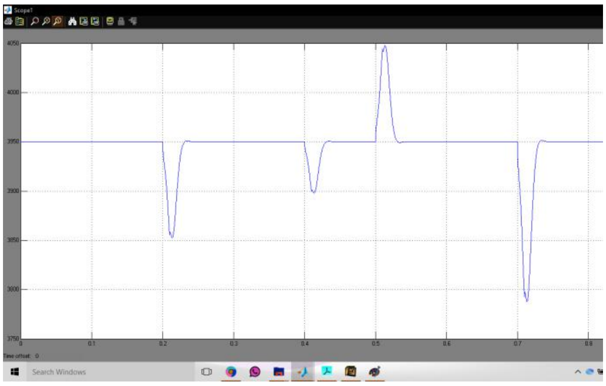

Fig:10.(a)

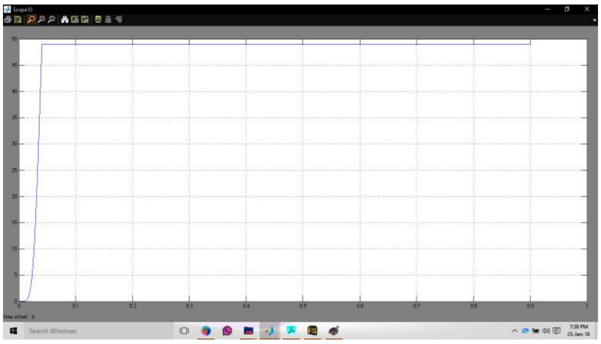

Fig:10.(b)

Fig.10. Simulation results of the DC microgrid for case 1, (a) voltage of DC bus #4; (b) SoC of ES unit (without DESs).

Fig:11.(a)

Fig:11.(b)

Fig:11.(c)

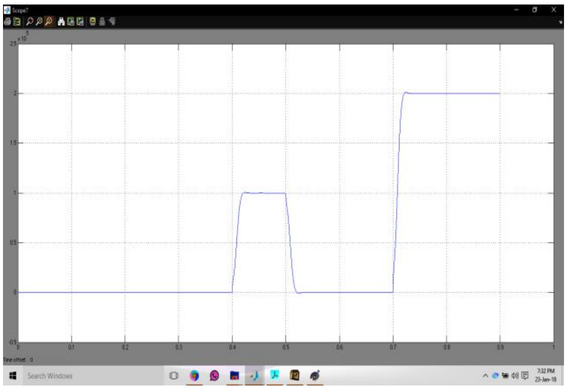

Fig:11.(d)

Fig.11. Simulation results of DC bus #1 for case 1, (a) voltage of DC bus; (b) frequency variation of the utility grid; (c) active power of VSC1; (d) output power of the independent ES unit (with DESs).

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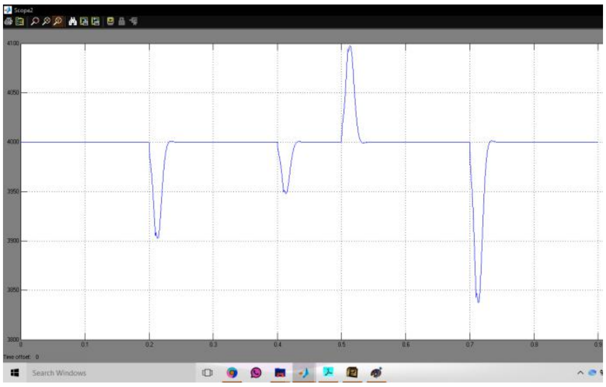
Fig:12.(a)

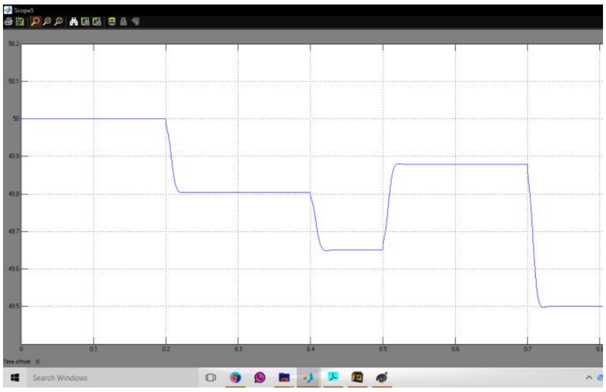
Fig:12.(b)

Fig.12.Simulation results of DC bus #1 for case 1, (a) voltage of DC bus; (b) frequency variation of the utility grid (without DESs).

This case is used to test the proposed control strategy on the power variation appearing in DC network. The simulation results are shown in Figs. 5.2-5.6, and the DC voltage changes of terminal VSCs. It should be noted that, *with DESs* scenario means the proposed strategy is adopted, whereas *without DESs* corresponds to the strategy of Mode I, as illustrated in Section II.B, in which the ES unit will not be ac-tivated during the connection of microgrids. Besides, *Full-DESs support* represents Mode II, in which the whole variation of net power is compensated by ES units based on the precise load prediction, thus no significant variation of DC voltage will be caused. When the net power increment of 0.6 MW is started at t=2 s, which leads to the decrease of frequency approaching 49.8 Hz, the IC transfers more power from the DC network to retain the stability of the AC microgrid. Instant DC bus voltage decrease of 130 V (0.0325 p.u.) is detected, as shown in Fig.5.2 (a), and the ES unit in AC microgrid outputs 0.25 MW active power to compensate the voltage variation. With the stabilization of bus voltage, the output power of ES unit is reduced to 0.1 MW, as shown in Fig. 5.2(d). When the net power increment of 0.3 MW is started at t=4s, the voltage of DC microgrid drops from 200 V to 197.5 V, and the active power is compensated via the IC by absorbing more power from the capacitor at the DC side, resulting in the sudden de-crease of bus voltage. The DESs in the AC and DC microgrids are controlled by the proposed strategy described to regulate the voltage of respective DC bus. It should be noted that, as the frequency of utility grid connected to VSC1 drops under 49.8 Hz, the independent ES unit is activated to respond to the frequency change, as shown in Fig. 5.6(d). When the net power reduction of 0.6 MW in AC microgrid is started at t=5 s, the frequency of AC microgrid returns to near 50 Hz. Due to the decrease of power demand, the voltage of every DC bus is increased, and those ES units which correspond to the voltage variation reduce the output power accordingly, as shown in Fig. 5.2 (d) and Fig. 5.4 (d). The external utility grid at the terminal VSC2 is disconnected from DC network at t=7 s, which means that the distribution network is only sup-ported by the terminal VSC1. As shown in Fig. 5.2(a) and Fig. 5.4(a), the DC voltage is down to the lower limit 3.6 kV. The frequency of utility grid connected to VSC1 drops to nearly 49.5 Hz, as shown in Fig. 5.6(b). If some unexpected disturbances are brought to utility grid, the DC network may be isolated to guarantee the security of the external power grid. In comparison, with the proposed DESs control strategy, the voltage only drops to approximately 3.9kV, and the frequency margin is increased effectively for the utility grid. It can be seen from Figs. 5.2(e) and 5.4(e) that, with the proposed strategy, the DESs are supposed to output fewer active power than that of Mode II, corresponding to smaller change of state of charge (SoC), which not only contributes to the dynamic power quality, but also prolongs the ES service life.

Case-2: Dynamic Performance on VSC Mode Change and Cable Fault

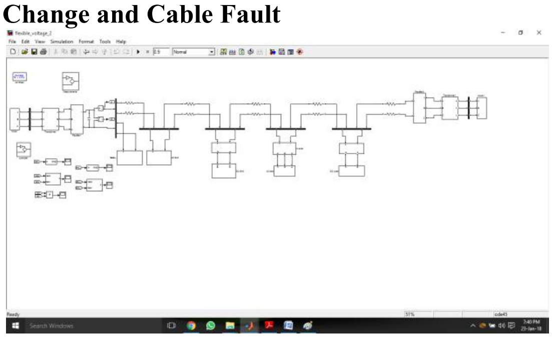
Fig:13.. simulation diagram of Dynamic Performance on VSC Mode Change and Cable Fault

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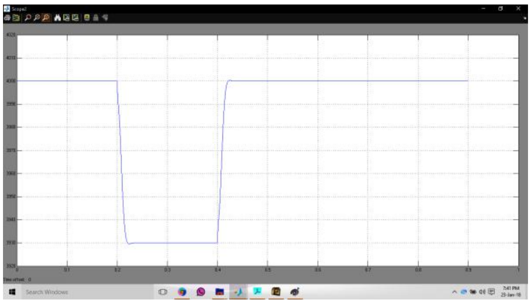

Fig:14.(a)

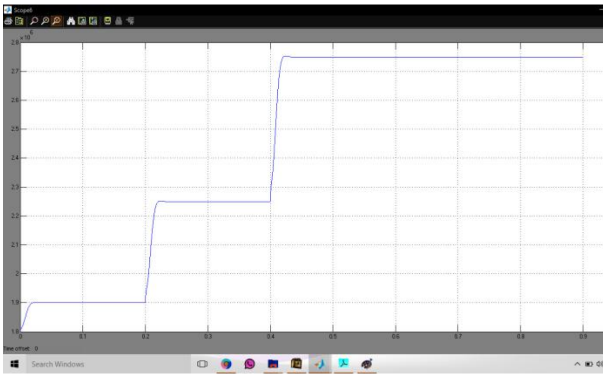

Fig:14(b)

Fig.14. Simulation results of DC bus #1 for case 2, (a) voltage of DC bus; (b) active power of VSC1 (with DESs).

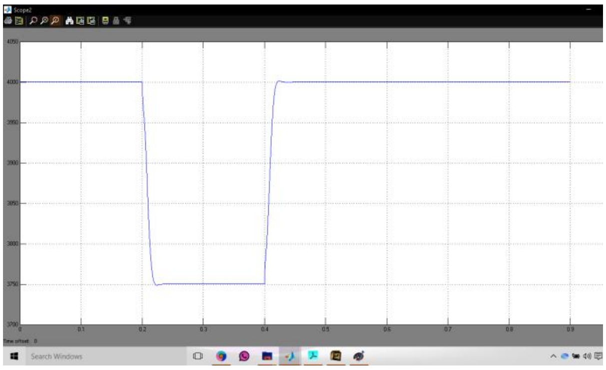

Fig: 15.(a)

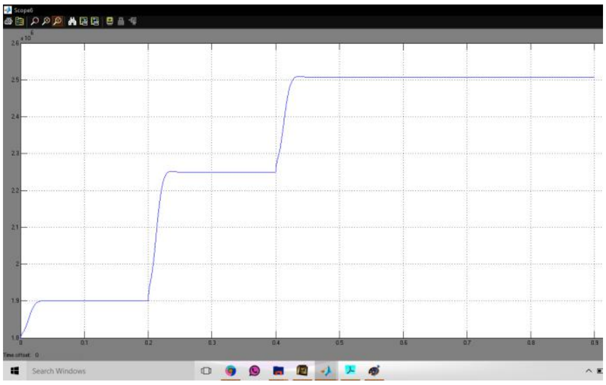

Fig:15(b)

Fig.15. Simulation results of DC bus #1 for case 2, (a) voltage of DC bus; (b) active power of VSC1 (without DESs).

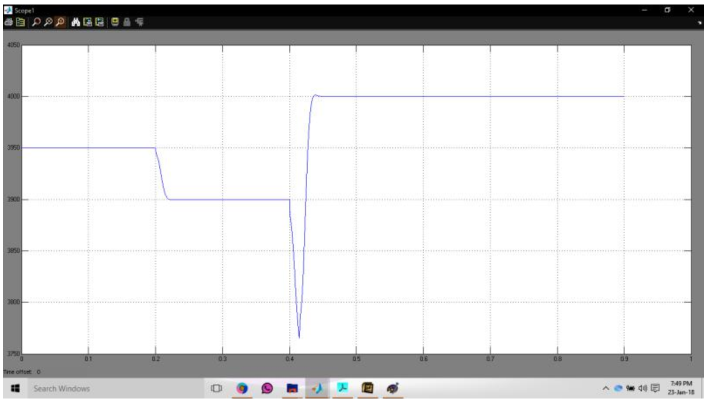

Fig:16.(a)

Fig:16.(b)

Fig:16. Simulation results of DC bus #2 for case 2, (a) voltage of DC bus; (b) active power of VSC2 (with DESs).

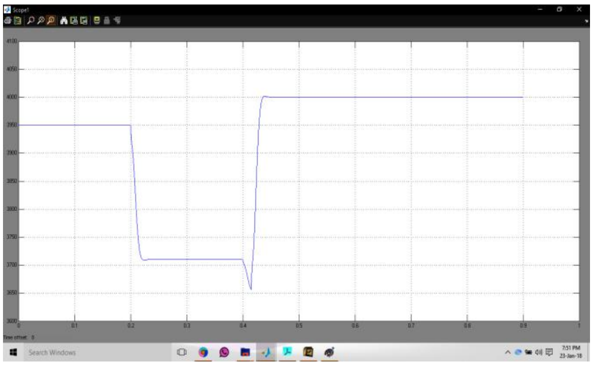

Fig:17.(a)

Fig:17.(b)

Fig:17. Simulation results of DC bus #2 for case 2, (a) voltage of DC bus; (b) active power of VSC2 (without DESs).

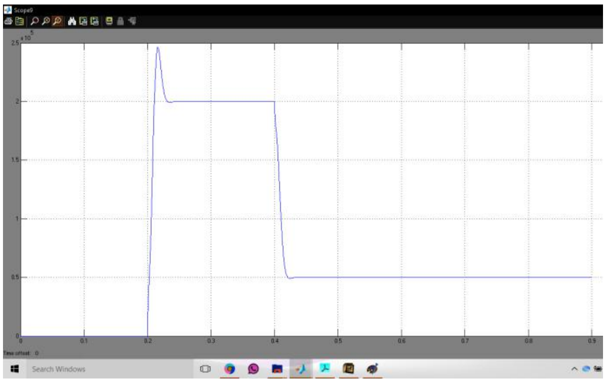

Fig:18. Output power of the ES units in microgrids for case 2

This case is used to test the proposed control strategy on the change of the operating mode of the terminal VSC, and the serious outage fault happens in the network. The simulation results are shown in Figs. 5.9-5.13, and the DC voltages of terminal VSCs are given. When the net power increment of 1 MW is activated at *t*=2 s, VSC1 outputs the fixed active power of 2.3 MW and lacks the ability of voltage regulation. When there is no DES response, VSC2 switches to the droop control mode to respond to the voltage sag, and inject 0.15 MW power into the DC network, as shown in Fig. 5.11(b). In comparison, with the DESs, the operating mode of VSC2 is not changed, since the net power vacancy is compensated by the DESs in microgrids. Besides, the voltages of terminal buses are beyond 3.8 kV during the power change, as shown in Fig. 5.9(a) and Fig. 5.11(a). A disconnection on the DC cable between the nodes of the AC and the DC microgrids occurs at *t*=4 s. The DC network is separated into two individual parts. When detecting the serious fault, both terminal VSCs switch to constant voltage control mode. As shown in Fig. 5.9(a) and Fig.5.11 (a), the voltage variation is smoothed with the participation of DESs. Besides, the power demand by the DC network is automatically adjusted according to the frequency change of the utility grid, as shown in Fig. 5.9(b). Therefore, the stability of the whole system involving DC network and the utility grid can be enhanced.

CONCLUSION

A flexible voltage control strategy, which fully considers the regulation ability of the DES units in DC distribution network, is proposed. The proposed strategy sufficiently utilizes the features of different interfaces in the DC network, and shows good performance in diminishing the voltage variation of DC buses. The relationship between the AC frequency and the DC voltage is identified via the interactive virtual inertia and capacitance, which is used to design the voltage control strategy for AC/DC interface. The strategy enables the DES units in AC microgrid to relieve the voltage variation of DC network, and improves the system stability by the help of in-dependent ES unit to respond to the frequency of the AC utility grid. Besides, a cascading droop control method is involved to provide the power support for voltage stability of the interface between the DC network and the DC microgrid. The performance of the proposed strategy is validated by considering different scenarios in the case studies. In the future works, the hybrid ES system will be considered for the more complex AC/DC distribution networks.

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