The impact of Active Distribution Network Cell (ADNC) on Power System Oscillations

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Abstract- Introducing distributed generators (DGs) into power system has changed the distribution system configuration and shape. Nowadays, distribution systems are no longer passive systems. DGs installed within the distribution system can inject active and reactive power to the grid and change the system dynamics. Adding DGs to the passive cell that consist of different types of loads has formed a new terminology; Active Distribution Network Cell (ADNC), might impose some problems to the power system stability, such as the system oscillations and damping. This paper analyzes and quantifies the impact of (ADNC) on the power system oscillations.

The well-known Two-Area System benchmark is adopted in this paper. The system simulations are conducted using MATLAB/Simulink software and power system analysis toolbox (PSAT). It is found that passive cell reduce the system damping and may cause system instability. By utilization the capability of the converter-based DG, as a part of ADNC, it is shown that back-to-back voltage-sourced converters synchronous generator-based (VSC-SG) can be used to maintain system stability by providing a certain level of damping through modulating its active or reactive output power. Two damping methods using active and reactive fast functionality of ADNC namely; P-method and Q-method has been proposed and verified.

Keywords— Active Distribution Network Cell (ADNC), back-to-back voltage source converter, system damping, inter-area oscillation mode, power system stabilizer, system oscillation, time domain simulation.

1. Introduction

Electric power systems are connection of many individual elements together to construct massive and complex systems that generate, transmit and distribute electricity over large areas. A large variety of dynamic interactions are possible because of this interconnection of a large number of elements, some interactions will only impact some of elements, others will influence parts of the system, while others may affect the total system[1]-[3]. Most electric power systems are AC with a frequency that is nearly equal over the entire system. This is obtained by employing synchronous AC generators. As extra loads increase over the transmission lines, the generators need to depend more heavily on their excitation systems to preserve synchronism, and to some extent, the synchronizing oscillations become unstable if the supplementary control is not provided. Therefore, damping, from other resources, of oscillations is an important in power systems to maintain system stability and increase transmission capability [1]- [4]

With the development of the electric power systems, as the demand increases, various types of loads are connected to the system, and the system becomes more complicated. These loads can be conventional loads, induction motors, constant impedance, constant current and constant power loads (known as ZIP loads) and converter based loads[5]. Additionally, the current power systems infrastructure has received many pressures due to many factors, such its environment and economical impacts. One of the best solutions is moving toward distribution generations (DGs). The most common

DGs types nowadays is back-to-back voltage source converters based occupied either power source; synchronous generator, induction generator, or DC generator (Photovoltaics) [6]. The introduction of DGs is a dominant factor that causes a new evolution in the electrical system. The fast growth of various types of DGs has introduced many challenges to the power system[7]. The wider integration of DG into the distribution network increases requirements for operation and control of the network due to the complexity and variety of the new technology devices. Considering a large-scale deployment of DGs and promoting the power quality, a robust active distribution network is required to change the passive and less intelligent systems. A study of the sensitivity functions for system frequency to power changes produced by renewable energy sources is shown in[8]. The grid Subsynchronous control interaction with variable speed wind turbine is discussed through modified frequency impedance scanning tool[9]. In[10]a new approach is proposed for distributed generations (DGs) planning by partitioning the original distribution systems into several separate zones. The optimized output reactive power of the DGs where have been placed at the operation stage. The impact of tie-lines connecting different areas of power system and the location of wind farms on the small signal stability of a power system was analyzed in [11]. In [12] the impact of power system stabilizer (PSS) and static synchronous compensator (STATCOM) on transient stability of multi-machine power system connected to PV generation was studied. An improvement of transient response for islanding control of microgrid was proposed in [13]. The proposed control was based on utilizing the functionally of bidirectional inverter, active and reactive power can be regulated. The battery system was used to provide support during the system voltage sag. A control scheme of voltage source converter to establish an offshore AC hub to integrate several wind power plants at multiple onshore grids was proposed in [14]. In [15] control scheme and measurement results for a four-quadrant converter control basing on the Pole Restraining concept which allows fast instantaneous-value-based control is presented.

The contribution of this paper is to study, analysis and quantify the impact of active distribution network cell (ADNC) on the power system oscillations. Then, two damping methods using active and reactive utilization the fast functionality of VSC are proposed. The well-known Two-Area System benchmark is adopted in this paper.

2. Active Distribution Network Cell (ADNC) Modeling

Figure 1 represent the active distribution network cell, which consists of composite load model, induction motor (IM) and back-to-back converter-based synchronous generators all are connected in parallel.[16]

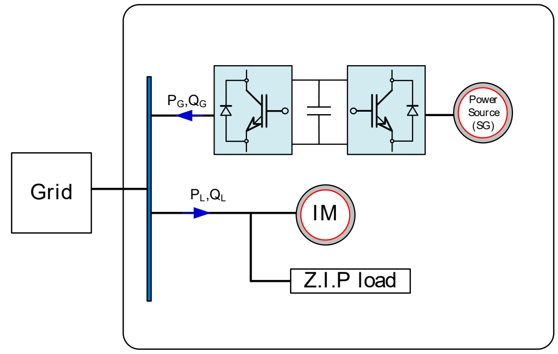


Fig. 1. Schematic diagram of Active Distribution Network Cell (ADNC).

2.1 *ZIP load and Induction motor (IM) Modeling*

In[17] , a general description for load representation for power system dynamic performance and analysis are overviewed. However, the standard load model structures of ADNC for dynamic study are still unavailable [16]. In [18], the standard load model for power flow and dynamic simulation programs were recommended. The widely used composite load model is adopted in this study[19][20]. The composite load model is represented by the combination of constant-impedance (Z), constant-current (I) and constant-power (P) known as Z.I.P model [17][19], and the general mathematical expression can be expressed as in Eq. (1)

$$\begin{aligned} P_L &= P_Z \left(V/V_0\right)^2 + P_I \left(V/V_0\right) + P_n \\ Q_L &= Q_Z \left(V/V_0\right)^2 + Q_I \left(V/V_0\right) + Q_n \end{aligned} \tag{1}$$

where P_L and Q_L are the active and reactive power of the ZIP model, respectively; P_Z and Q_Z are the constant impedance part of the ZIP model; P_I and Q_I are the constant current part; and P_P and Q_Q are the constant power part, P_n and Q_n active power, reactive power, respectively. The third order model has been adopted to represent the induction motor within the ADNC. Typically third-order model is sufficient for dynamics simulations for the aggregated motors in large power systems. Detailed for the model can be found in [3][18], [19].

2.2 *Modeling of Back-to-back Converter*

The converter-connected generator is composed of a synchronous generator model and a back-to-back full converter model[21][22]. The synchronous generator interfaces with the grid via a back-to-back full converter as shown in Fig. 2 below.

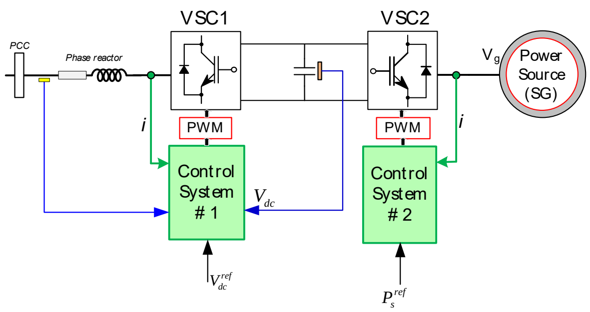


Fig. 2. Synchronous generator-back-to-back full converter schematic diagram

In stability model of back-to-back VSC it is not realistic to include a detailed model of power electronics converter and high frequency switch, therefore representing them as a simple voltage or current sources will be sufficient from the stability standpoint and to observe the response with the respective time frame.

For back-to-back VSC the interface with the grid is a power converter (the generator exchange the power with the grid via the power converter).Therefore it is acceptable , to some extent, that the detailed models of the generator side components behind this interface (power converter) is not needed, and further simplification will be beneficial. The transient response can be shown through simple model.

As a result, and from the stability point of view, the most important part to be appropriate modeled is the grid side converter. Because the back-to-back VSC interact with the grid through the converter and it is the connection between the grid and the other parts. Modeling the grid side converter should be performed in such away to represent all the conditions and states of back-to-back VSC.

The power source is this kind of distributed resource could be controllable (dispatchable) and non-controllable: controllable sources such as inverter based synchronous generator governed by conventional source (diesel, gas, hydro), further controllable sources could be PVs and wind (with storage devices; batteries), while, the uncontrollable can has a structure for PVs and wind (without storage devices)

Figure 3 shows the model used in this study, it is known as *phase model*. The current regulators and the voltage sources have been replaced by a current source as shown in the figure. This model is usually utilized to simulate the low frequency electromechanical oscillations for long periods of time (tens of seconds to minutes). This model is suitable for transient stability simulation; it also has been used in MATLAB/Simulink simulation tools. This model is the most common used to model stability studies. The data for this model is shown in Appendix.

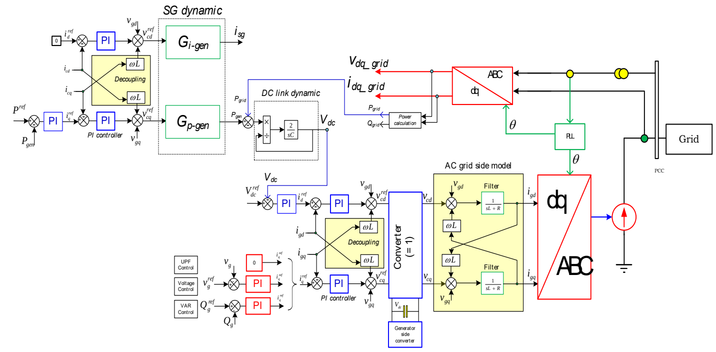


Fig. 3. Current source model (phasor Model) for back-to-back converter.

3. Simulations and Analyses

The impact of active distribution network cell on the power system oscillations is analyzed and quantified in this section. The most common system in the literature for understanding and studying, and performing a particular power system oscillation studies is Two-Area System benchmark (Kunder's system) for this reason it is adopted[3]. Fig. 4 below shows the Two- Area System benchmark with connected ADNC.

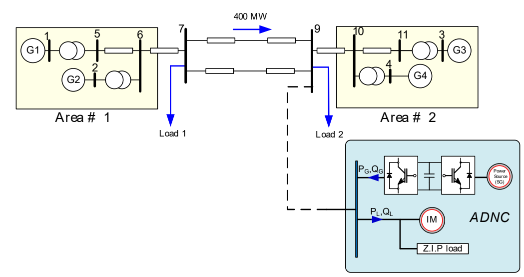


Fig.4. Two-area system with ANDC

3.1 *Two-Area System with Passive Networks (ZIP and IM)*

A. *Simulations for studied system with induction motor and regular load*

In order to perform a fair comparison and to identify the impact of passive cell on the oscillation the load (L2) at area 2 is reduced by the same amount of added passive cell load, to maintain the same transferred power over the tie-lines, the size of IM is 100 MW. Three different cases are simulated:

- **Case #1** 100 % regular (ZIP) Load: 100 MW and 10 MVAR refer to normal load.
- **Case #2** 100% IM: 100 MW and 50 MVAR refer to IM.
- **Case #3** 50 % IM and 50% of load refer to both.

Fig. 5 shows the connection of the passive cell to bus#9. The system response under large signal variation (three phase fault at line 7-9 as pointed in Fig. 5) is created. Fig. 6 shows the system the generators speed response. As it is clearly observed the system is stable, (i.e., the system reaches a new bounded output), under this disturbance.

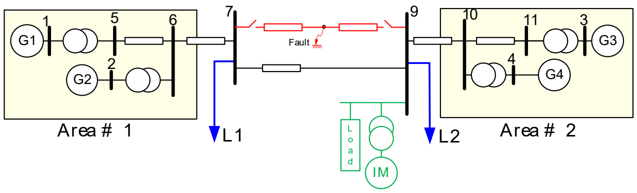


Fig. 5. Connection of the passive cell to the system

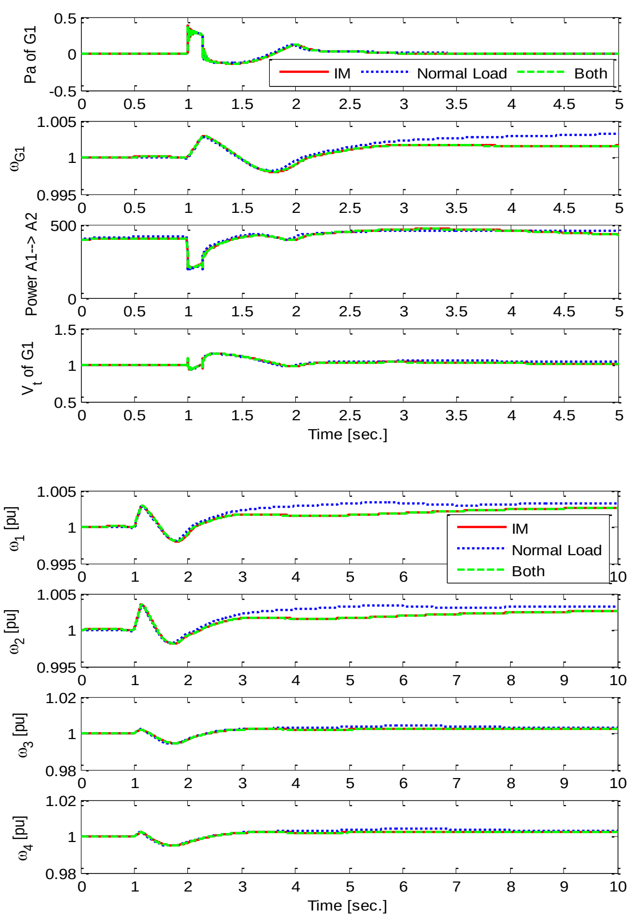


Fig. 6. Generator no. 1 response Accelerated power, generator speed, Generator speeds responses, terminal voltage and the transferred power over the tie-line.

B. Large Signal Stability under different locations of the Passive Cell

In this subsection the impact of the location of the passive elements, both the load and IM, on the system oscillation is studied. As presented in Fig. 7 the passive cell is installed in three different locations: at bus7, at bus9 and at the mid-point of the tie line between buses 7 and 9. Figs. 8, 9 and 10 show System responses at different bus locations Generator no. 1 response, Accelerated power, generator speed, terminal voltage and the transferred power over the tie-line, and generator speeds responses. As is observed that, the system is unstable in case of installing the passive cell at the mid-point of the tie line.

In order to figure out what is the reason for the instability in this case, the system will be further studied in small signal analyses. To do so, the power system analysis toolbox (PSAT) software[23] is used to perform the small signal stability, which is presented in the following subsection.

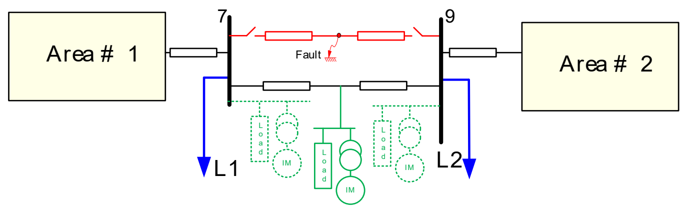


Fig. 7. Different locations of passive cell.

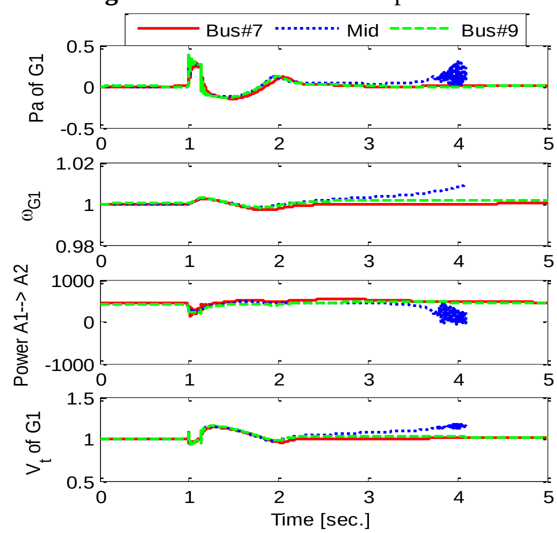


Fig. 8a. Response of generators No.1 and Tie-power

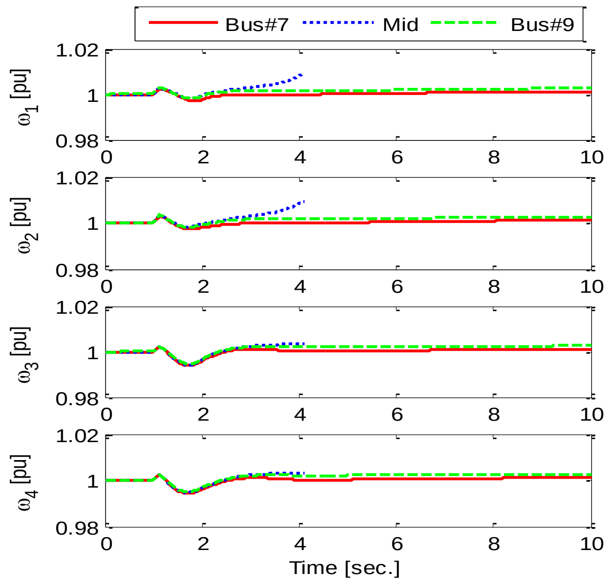


Fig. 8b. Response of generators speeds

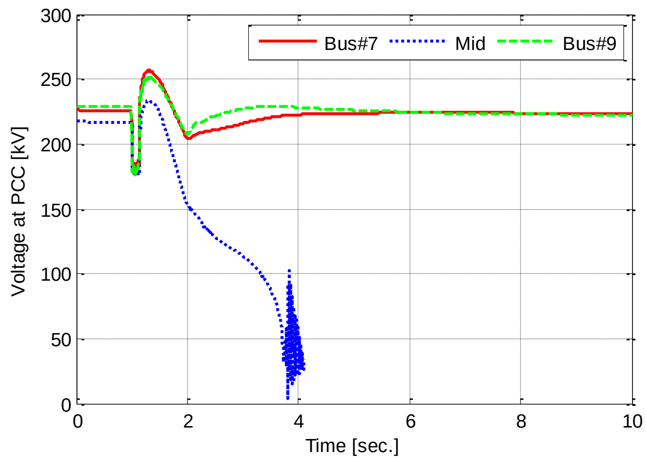


Fig. 9. Voltage responses at the connection points of passive cell

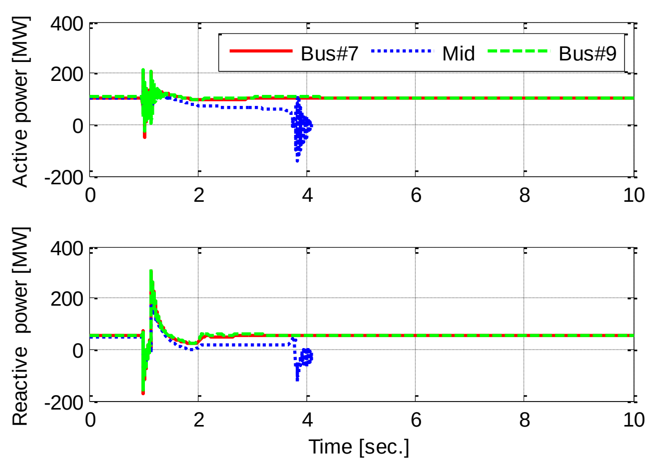


Fig. 10. Active and reactive power of passive cell

C. Small Signal Analysis Under different location of the Passive Cell

For further understanding for what causing instability in previous cases, small signal analysis can reveal some useful information and identify the key factors that has the impact on the system oscillation, for this purpose, the studied system (Two area system with added passive cell) is implemented in PSAT (Power System Analysis Toolbox). MATLAB-based software (PSAT) is powerful software that can provide both small signal analysis, frequency domain using eigenvalues analysis, as well the time domain.

Table 1 shows the associated eigenvalue of the induction motor where the passive cell at the mid-point cause system instability, it is obvious that the one of induction motor eigenvalue has negative real part, which could be the main source of instability.

Fig. 11 and Fig. 13 show the PSAT time domain results when the passive cell installed in the three locations. The damping where the passive cell installed in area I in slight higher than that installed in area 2, this is easily observed by comparing Fig. 11 with Fig. 12, at area1 generators 1 and 2 oscillate together against generators 3 and 4, where the magnitude of the speed variations are higher and takes long time to settle down. For the case where passive cell is installed at mid-point, as shown in Fig. 13, the system become unstable, which matches the result for the eigenvalue analysis shown in Table 1.

Table 1. Domian Eigenvalues

Location	Eigenvaule	Freq[Hz]	Damping
Area II (Location 1)	-52.0781± 7.4841 -0.66162	5.963 --	0.8116
Middle (Location 2)	-49.5407± j49.11 **0.19165**	7.813 --	0.7102
Area I (Location 3)	-51.9719± j 5.433 -0.8186	5.639 --	0.8262

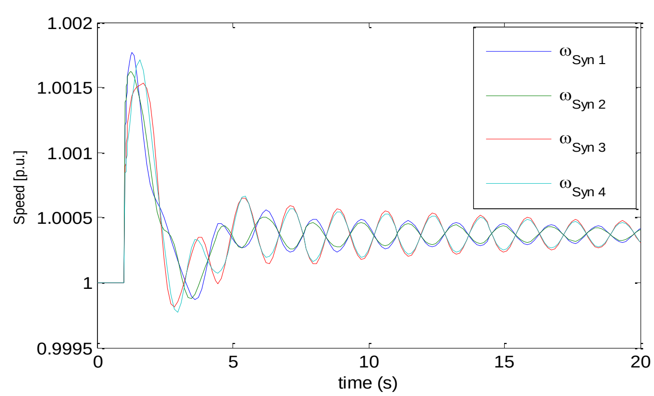


Fig. 11. Time domain response of rotor speed of machines – location of passive cell at the Area I. *Stable system*

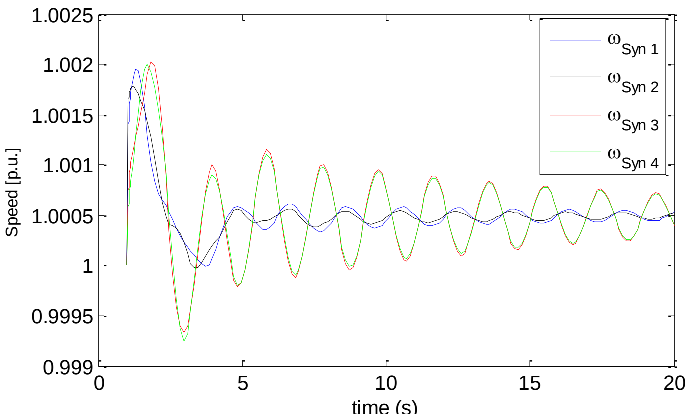


Fig. 12. Time domain response of rotor speed of machines – location of passive cell at the Area II**.** *Stable system*

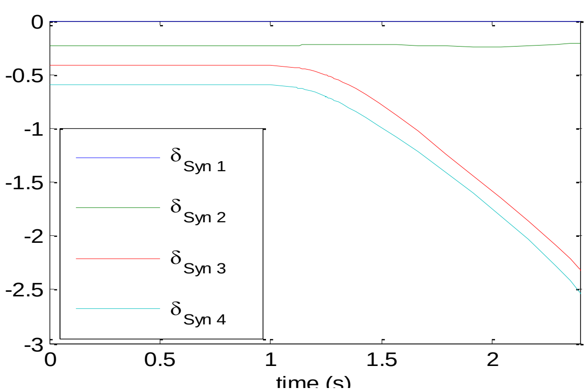


Fig. 13. Time domain response of rotor angle of machines – location of passive cell-Midpoint *unstable scenario*

D. Impact of Passive Cell Loading on System Damping

The impact of system configuration is further investigated in this subsection. Fig. 14 and Fig. 15 below show the damping profile as well as the frequency of the inter-area mode as a function of loading level of the passive cell under one of tie-lines is tripped. It is clear that as the loading increases the damping decreases, with 116 MW loading the system become unstable, the loading level has slight impact on the frequency of the mode, as shown in Fig. 15. The results from small signal analysis are proved by time domain simulation, Fig. 16 and Fig. 17 show the time domain simulation for two loading conditions (107 and 110 MW), by investigating these figures it can be seen that with high loading the oscillation increase (i.e., less damped), while with less load is relatively damped.

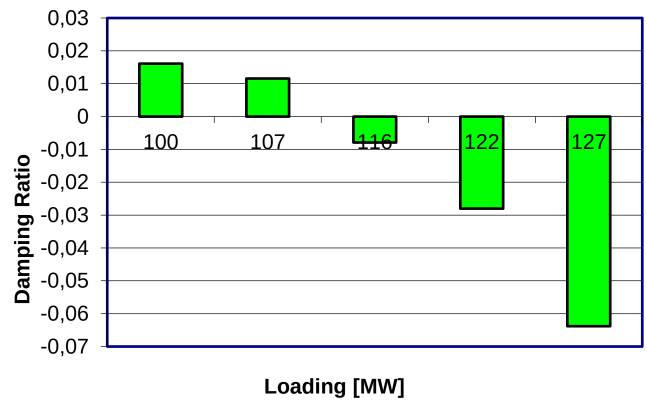


Fig. 14. Damping profile under different loading level of passive cell.

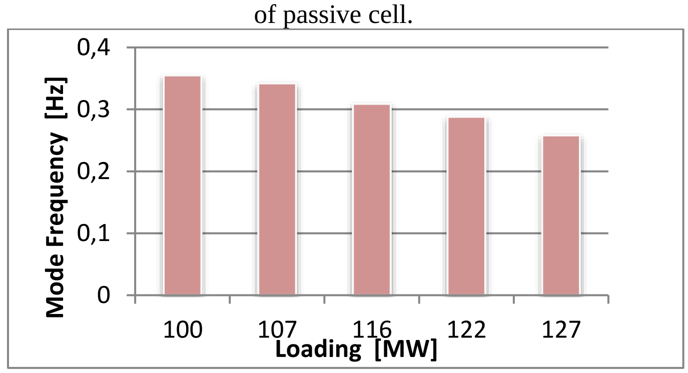


Fig. 15. Inter area mode frequencies under different loading level of passive cell.

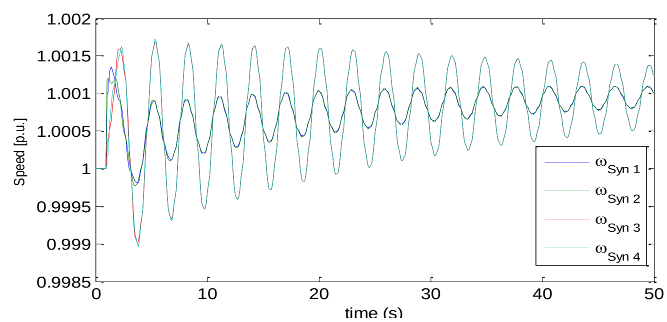


Fig. 16. Time domain response of rotor speed of machines – location of passive cell at the Area II [107 MW].

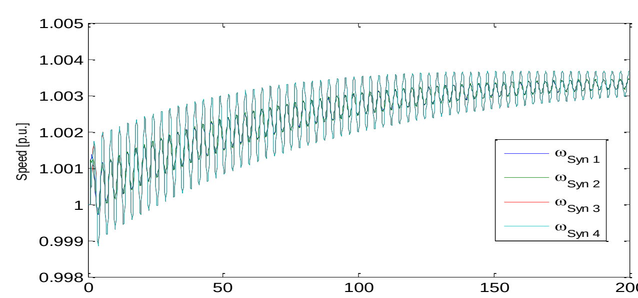


Fig. 17. Time domain response of rotor speed of machines – location of passive cell at the Area II [110 MW].

3.2 *System Simulations with overall ANDC cell*

The entire Active Distributed Cell is analyzed in this section, which is consists of the passive cell (IM and load), and SG-VSC based. The overall system has been implemented in MATLAB/Simulink software.

Figure 18 and Fig. 19 show the system response under a three phase fault at the tie-line (the fault is cleared after 3 cycles). By zooming the plot of the accelerating power Pa, in Fig. 20. It is obvious that adding the VSC-SG to the passive cell increase the damping where the power becomes more damped compared with case where there is no VSC-SG. This improvement can be attributed to that VSC-SG reduces the stress on the tie-line which made the system more damped.

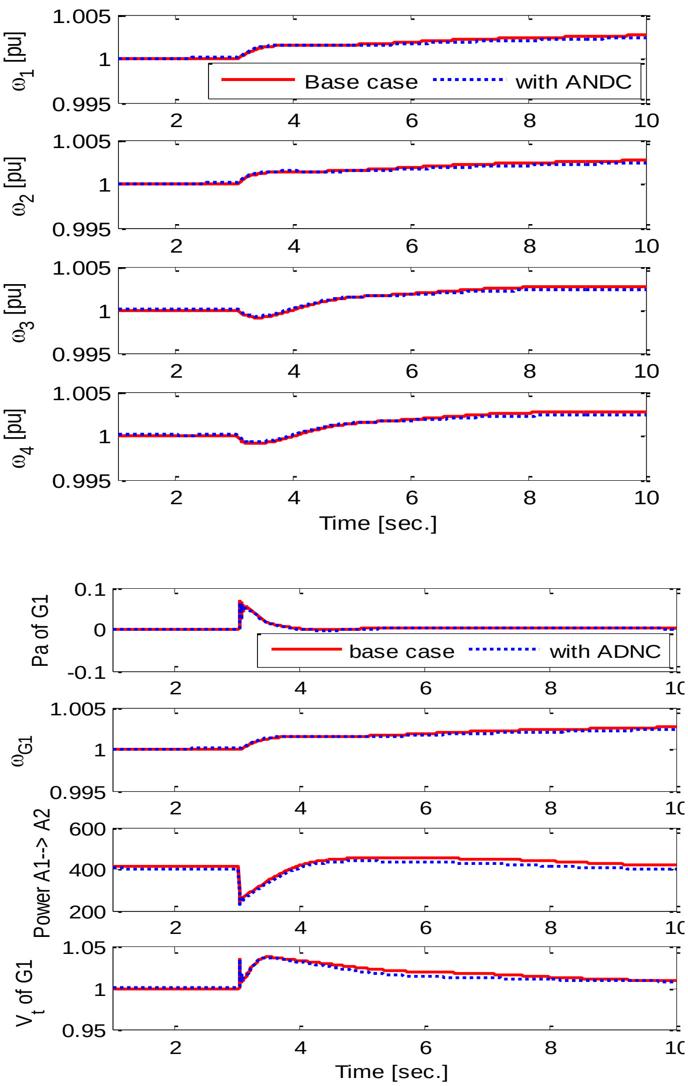


Fig. 18. Time domain response of rotor speed of machines (Upper plot) and generator 1 variables – location of ANDC at the Area2 [110 MW] and VSC-SG=0

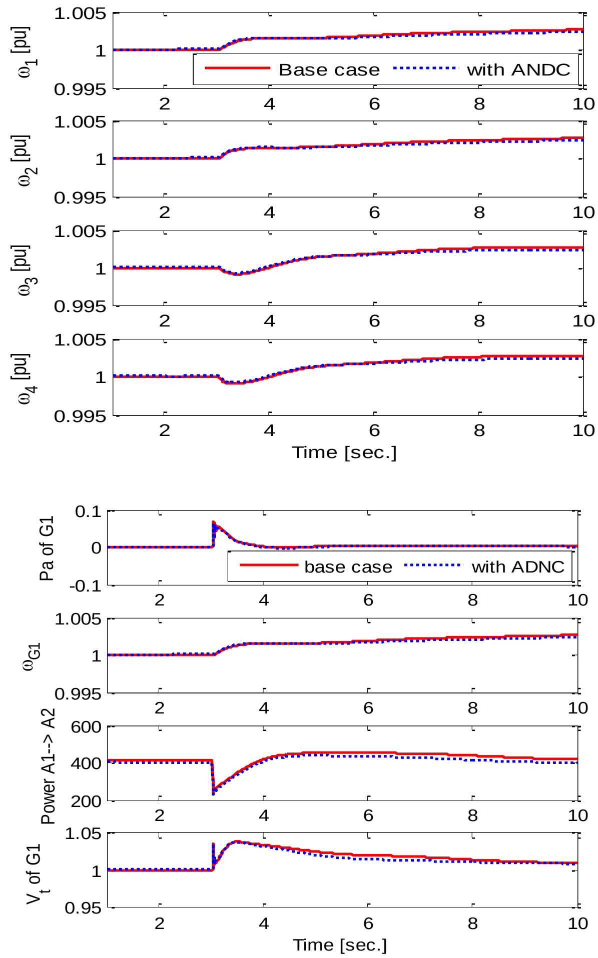


Fig. 19. Time domain response of rotor speed of machines and generator 1 variables – location of ANDC at the Area2 [110 MW] and VSC-SG, P=20 MW

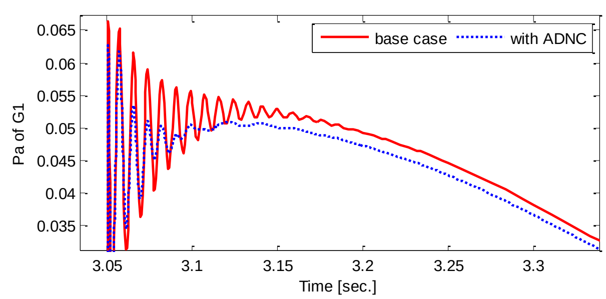
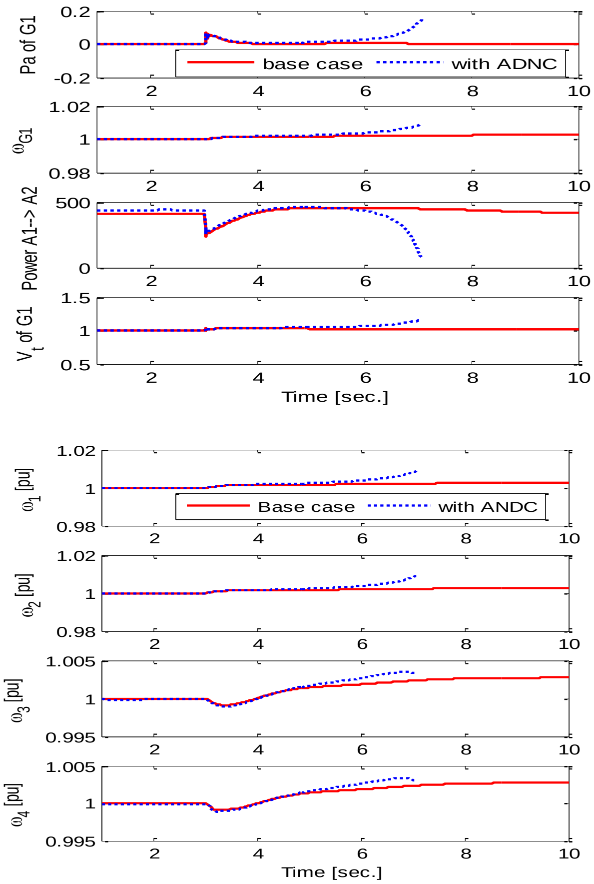


Fig. 20. Zoom-in of accelerated power plot [Pa**]**.

Fig. 21 shows the system response under full load of ADNC, 180 MW for both the normal load and IM. The system lost its synchronism after in the 7 sec. The main cause of this instability can be attributed to the additional stress that has been on the tie-line due to increase in ADNC loading level.



(a)
(b)

Fig. 21. Time domain response for the system: rotor speeds of machines

4. Utilization of VSC-SG to Damp System Oscillation

Previous section shows the dynamics response and loading ADNC affect the system stability, as it is found that the system becomes instability after certain level of loading. By utilization the fast response of voltage source converter based devices, in our case, the SG-VSC based the system performance can be improved. In[24] and[25] it is shown that the variable speed wind turbine (DFIG), equipped with supplementary control loops, can contribute to suppress system oscillations. Two control loops are used; active and reactive power loops, using the active power modulation has been found to be more effective. A decentralized reactive/active power control strategy to allow the maximum available active power production from renewable energy resources has been discussed in[26] . In[27], the authors present a control strategy involving both active and reactive power management of the connected plants with Battery Energy Storage System (BESS) and distributed generators (DGs). In[28] , PQ control strategy is applied on distributed generations (DG) to maintain a controllable active and reactive power output in microgrids A Static Synchronous Generators based in Synchronous Power Controller (SSG-SPC) is proposed in [29]. Its capabilities for dynamic stability enhancement in a long AC transmission system are examined. The key results reveal that the proposed controller is effective in providing active damping of power oscillations and reducing small signal instability. A technique aiming for frequency support utilizing the Energy storage systems (ESSs) and large-scale wind generators providing is proposed in[30]. In this paper two damping methods using active and reactive utilization the fast functionality of ADNC namely; P-method and Q-method has been proposed and verified.

4.1 *Utilization of VSC-SG to damp system oscillation Method#1 P-Method*

Previous section shows the dynamics response and loading effect of ADNC on the system stability, as found that the system becomes instability after certain level of loading. By utilization the fast response of voltage source converter based devices, in our case, the SG-VSC based. The active output power can be modulated to support the system stability. Fig. 22 shows the simulation results, where SG-VSC is used to maintain system stability. Fig. 23 shows the output of VSC-SG where its output is changing in steps; this scenario can be implemented for dispatchable generators, however, this technique could be also implemented by utilizing the energy from storages devices and even from the wind farms that occupied with frequency support mechanism.

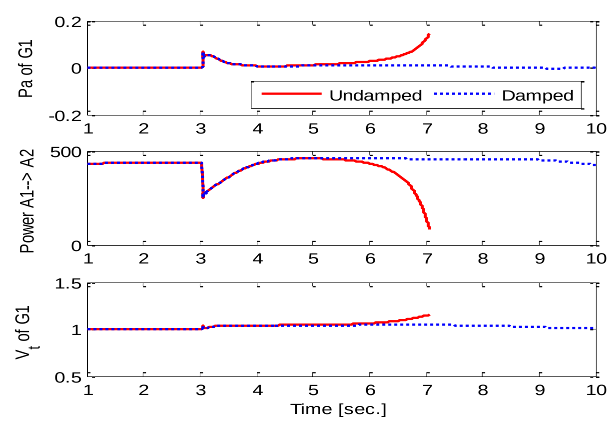


Fig. 22a. Generator#1 Voltage& Power, Tie power: Utilization of VSC-SG for maintaining system stability, *P-method*

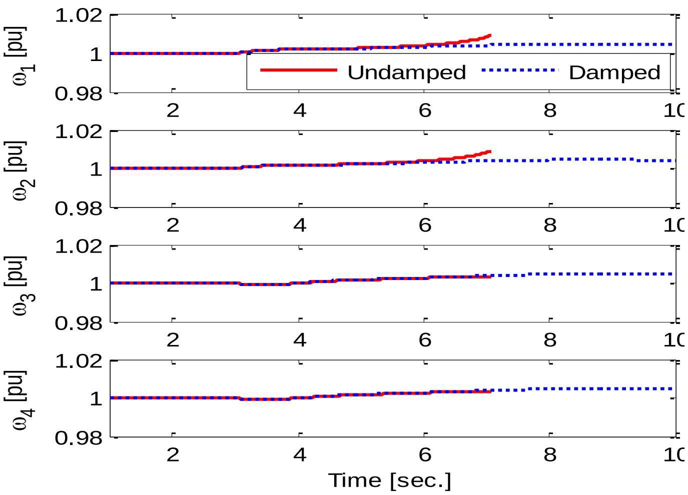


Fig. 22b. Generator speeds: Utilization of VSC-SG for maintaining system stability, *P-method.*

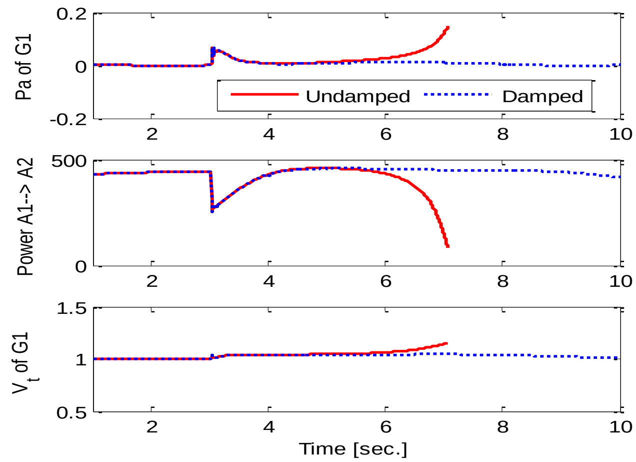


Fig. 24a. Generator#1 Voltage& Power, Tie power: Utilization of VSC-SG for maintaining system stability, Q-*method*

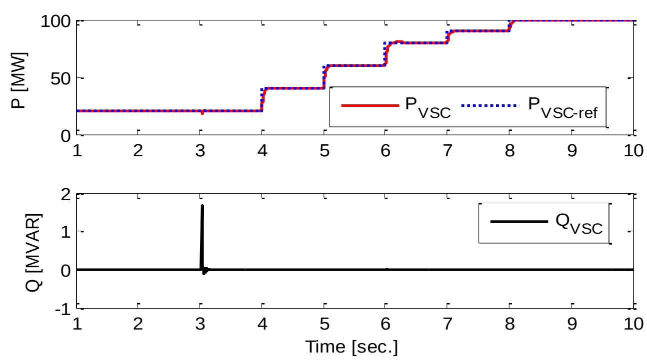


Fig. 23. Changing the active power output of back-to-back SG converter.

4.2 *Utilization of VSC-SG to damp system oscillation Method#2 Q-Method*

Alternatively, the reactive power can also be utilized to help the system and provide damping. By utilization functionally and the inherent fast dynamics of the grid side converter of back-to-back, a certain level of reactive power can be injected to the system and help to maintain system stability. Fig. 24 shows the simulation results, it is obvious that Q-method also helps the system to maintain its stability. The output of SG-VSC is depicted in Fig. 25, the active power was 20 MW and the reactive power is increased to enhance the system stability. However, this method may stress the converter for a short period of time, but and typical converter is designed for 110% operation and other converter can operated up to 125% of its rated

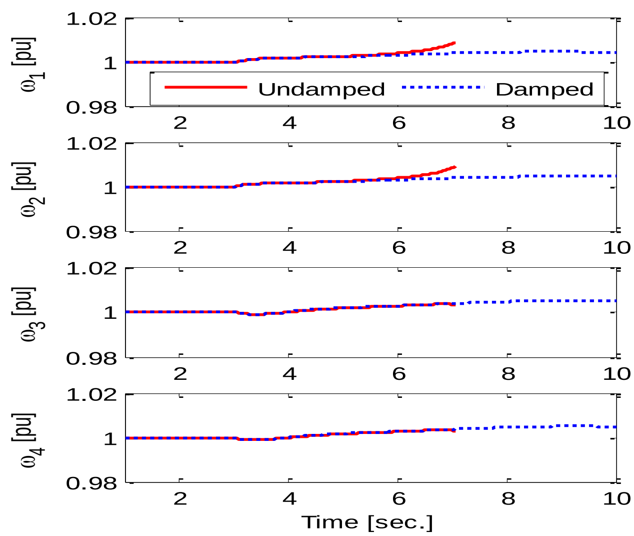


Fig. 24b. Generator speeds: Utilization of VSC-SG for maintaining system stability, Q-method.

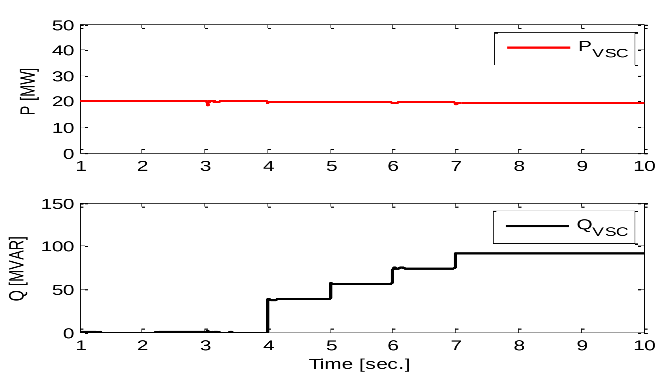


Fig. 25. Active power profile and changing the reactive power output of back-to-back SG converter.

5. Conclusion

A new form of distributed load called active distribution network cell (ADNC) components has been studied and analyzed. The impact of a regular load and induction motor as a passive cell, and different locations, and their impact on the system loading have been analyzed.

The impact of overall the active distribution network cell (ADNC) on the power system oscillation has been investigated. Increasing in the loading level of ADNC is actually reflected as an additional stress on the tie-line that may cause system instability. By utilizing the fast dynamics response and functionality of the back-to-back VSC-SG system a certain level of damping can be injected as a form of active or reactive power modulation to help the system to maintain its stability under an integration of such a system. Two proposed methods has been introduced, namely; P-method, Q-method. It is shown that VSC-SG can help the system to accommodate further increase in the loading level of active cell and help to stabilize the system.

The power source within ADNC could be controllable and non-controllable types: controllable sources such as inverter based synchronous generator governed by conventional source (diesel, gas, hydro) where the both active and reactive power modulations can be utilized to inject damping power to the system, further controllable sources could be PVs and wind (with storage devices; batteries), while, the uncontrollable can has a structure for PVs and wind (without storage devices) where the reactive power modulation can be used to improve the system damping.

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Appendix A: System Data

Table B.4: ADNC data

Item	**Size**
ZIP load	100 MW
Induction Motor	100 MW
Back-to-back SG	100 MW

Table B.5: Back-to-back Modeling

System based: 24 kV and 100 MVA

Exciter no.	**Value [p.u.]**
Grid side inductance	0.22
Grid side resistance	00073
Kp_current controller	0.45
Ki_current controller	15
DC link capacitance	75 mF
DC rated voltage	40kV
Kp_DC voltage controller	0.001
Ki_DC voltage controller	0.001