MODELING AND SIMULATION OF HYBRID AC/LVDC MICRO GRID BY USING ACMC

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ABSTRACT: This paper proposes the detailed modeling of a automatic centralized micro-grid controller (ACMC)-based hybrid AC/low-voltage DC (LVDC) micro-grid network, capable of off-grid and on-grid operation of the system with a coordinated control. using a bi-directional AC/DC/AC converter we can interconnect very large AC and LVDC networks. The AC and the LVDC networks consist of different feeders with loads connected at various voltages. For controlling the real (P) and reactive (Q) power from the sources based on load requirement and voltage control of the LVDC network The ACMC design is proposed and It enables the system to have a plug and play feature. The proposed ACMC has been implemented on a test system consisting of AC and LVDC radial distribution networks designed, with a bi-directional converter. A doubly fed induction generator-based wind turbine and solar photovoltaic array with maximum power point tracking have been used as the sources. The system has been simulated in Simulink. The results show the ACMC successfully performs the four quadrant operation of P, Q in the system for various system conditions.

1. INTRODUCTION

Sustainable energy sources are playing a significant role in satisfying current as well as future energy demand. Renewable energy sources installed at houses supply their loads while having the capability of autonomously injecting their excess energy to the main grid. This leads to a reduction in the power flowing in connecting lines. Such system will increase the grid security and decrease its power losses [1]-[3]. However, renewable energy has some disadvantages due to its dependency on nature's conditions. In case of PV and wind, the amount of power they can provide at a specific time cannot be predicted [4]. It is crucial to inject the maximum power generated by each renewable energy source at any instant of time to either the local loads or back to the main AC grid. It is expected that distributed generation (DG) will play a more vital role in electric power systems [5]. It allows residents and businesses that have the potential to generate electrical energy to sell surplus power to the grid. The variation of grid voltage due to power flow causes the power quality to decay. Consumers may suffer from the quality of power that is generated and transmitted via the AC grid. This reduction in power quality occurs due to poor switching operation in the network, voltage dips, interruptions in the grid, transients and network disturbances caused by loads. The use of on-site power generation equipment will provide consumers affordable power at high quality. With a non-radial system configuration due to the presence of DG units, the power control complexity for a micro-grid is substantially increased, and the “plug and play” feature is the key to insure that the installation of additional DG units will not change the control strategies of DG units already in the micro-grid [6]. On the other hand, DC distribution systems have been suggested lately as a better method for electrical power delivery [7]. This concept is inspired by the possibility of efficient integration of small distributed generation units which attract the attention of researchers all over the world. Moreover, there are other advantages having electrical power transmitted through DC distribution systems like the relatively higher efficiency, absence of reactive power component and the fact that many appliances operate using a DC voltage. The feasibility of using DC distribution systems instead of AC ones is being investigated by many researchers. Their researches have resulted in a number of publications in which certain aspects of the subject are developed [8]. In [9] the feasibility of the low and medium voltage DC systems is investigated. Authors concluded that if DC is used the total system losses will decrease if the semiconductor losses due to switching in converter are reduced. The use of DC power systems to supply sensitive electronic loads was discussed in [10]. Authors carried out their experiments on a scaled laboratory system. They concluded that low voltage (LV) DC distribution systems may well be used to supply electronic loads compared with ac. In [11], protection of LV DC micro grids is investigated. In [12], the opportunities and challenges associated with adopting a DC distribution scheme for industrial power systems have been investigated. This paper has shown that the challenges associated with the dc distribution can be addressed by proper system design. The results, based on simulations performed on a prototype dc system, clearly show that converter interactions can be minimized with proper filtering and control on the converters. Bi-Directional AC-DC/DC-AC Converter for Power Sharing of Hybrid AC/DC Systems A. Mohamed, Member, IEEE, M. Elshaer, Member, IEEE and O. Mohammed, Fellow, IEEE Energy Systems Research Laboratory, Department of Electrical and Computer Engineering Florida International University Miami, Florida, USA

On the basis of the extensive literature survey performed the following grey areas were identified in the existing literature:

- The issue of increased DC penetration has been addressed with the proposal of separate DC micro-grids but the presence of AC sources again poses the problem of redundant conversions.
- The development of a hybrid AC/DC micro-grid has been proposed to counter the problem of redundant conversions. However, due to the rapid penetration of renewable energy sources as well as the dominating development of LVDC systems in the DC part of the micro-grid, the problem of redundant conversions resurfaces along with the requirement of a whole new system control. In an attempt to address these identified potential issues, this paper proposes the following:
- Modelling of a hybrid AC/LVDC subsystem which comprises of an AC network interconnected to an LVDC network. The proposed micro-grid design has no limitation on the number of buses on either the AC or LVDC network.
- Interconnection of both these networks by a bi-directional power converter. This converter is responsible for real and reactive power transfer in all the four quadrants.
- An LVDC network consists of feeders at the voltage levels 326, 230, 120 and 48 V each supplying a different consumer group.
- A novel automatic centralized micro-grid controller (ACMC) is responsible for the control and monitoring of the entire micro grid. It is responsible for monitoring the stable addition of new load buses or generator buses to either side of the micro-grid, ensuring plug and play feature. It also schedules the appropriate power dispatch to the various buses in the grid by control of the converter. The power generation present in any part of the micro-grid is controlled according to the requirements and appropriate control steps are taken to ensure stability of the micro-grid.
- The AC network generation is simulated by different capacities of doubly fed induction generator (DFIG)-based wind turbines and the DC network generation utilizes solar PV arrays with maximum power point tracking (MPPT) mechanism. The offgrid mode of the system is simulated in this paper.

2.SYSTEM DESIGN AND MODELLING

This section deals with the layout of the proposed system as well as the modeling of the renewable sources present in the system. The renewable sources considered for the proposed test system are DFIG-based wind generator and solar PV array and their respective modeling aspects have been discussed subsequently.

2.1 System configuration

The schematic representation of a typical hybrid AC/DC micro grid can be seen from Fig. 1. The micro-grid consists of separate AC and DC buses. They are interconnected by a bi-directional converter which is responsible for power flow between two buses. Various AC sources such as DFIG, diesel generator are connected to the AC bus, whereas sources such as fuel cell, PV array have been connected to the DC bus. The individual grids have their corresponding loads and energy storage elements connected. The conventional AC grid is connected through a breaker to the AC bus of the micro-grid.

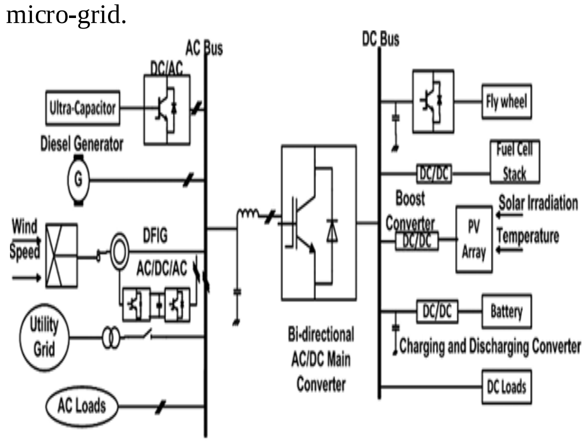

Fig. 1 Typical hybrid AC/DC micro-grid

Fig. 2 shows the proposed layout of hybrid AC/LVDC micro grid. The AC part of the micro-grid is capable of handling an AC network with n number of buses. The number of buses on either of the networks can increase or decrease during the operation of the micro-grid. The DFIG is modeled with the AC/DC/AC converter to the rotor which is responsible for the reactive power control of the machine. The machine is also equipped with pitch control mechanism for real power control. The PV array is designed along with the MPPT mechanism implementation. The perturbation and observation (P&O)-based MPPT technique has been used in this paper. The design of an ACMC is proposed in this paper, whose modeling is discussed in detail in later sections. It is responsible for the central controlling of all the generations in the system as well monitoring for any modifications to the network structure. A bi-directional converter of 250 kVA capacity has been modeled which interconnects both the networks. The proposed ACMC senses the load currents and voltages as well as the source currents and source voltages and implements the control and monitoring algorithms.

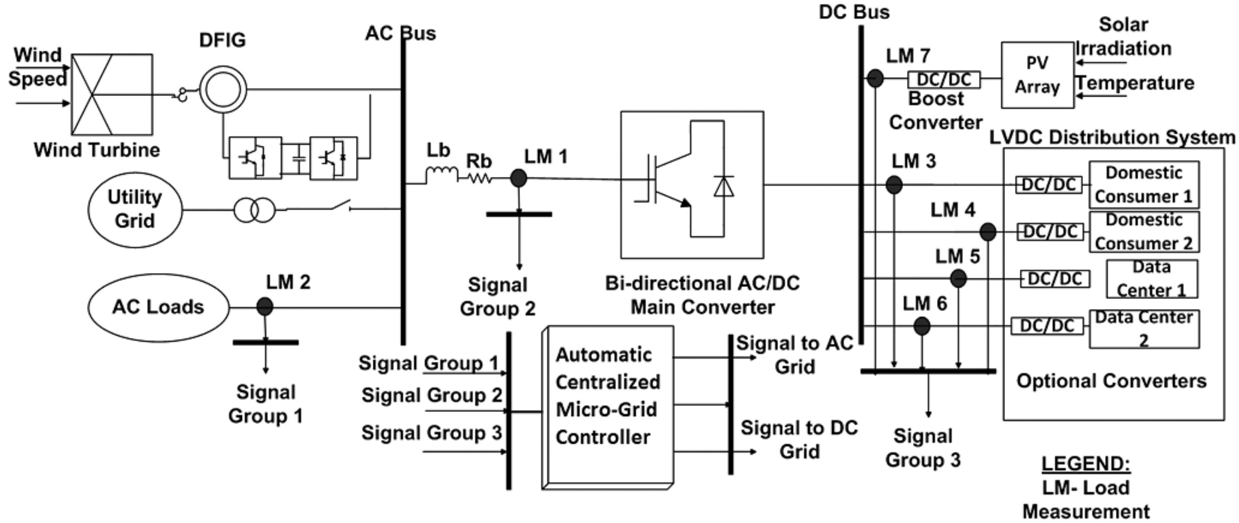

Fig. 2 Schematic representation of the proposed hybrid grid

2.2 Modeling of the sources in the system

The modeling of DFIG-based wind generator as well as the solar PV array is carried out by the existing conventional approach. The modeling of the PV array has been done using one diode model of PV cell. The DFIG has been modeled electrically by using a fifth-order model of induction generator. The mechanical model of the machine has been done using the one mass lumped model. The output of the mechanical subsystem acts as the input to the electrical subsystem. The modeling of the electrical subsystem of the machine has been done in d–q-axis in an arbitrary frame of reference.

3. MODELLING OF CONVERTERS

The proposed system has three types of converters. A boost converter is connected to PV array to track MPP. The terminal voltage is regulated by continuous tracking of the operating point of the characteristic power versus voltage curve of the module. An AC/DC/AC converter is used in the rotor circuit of the DFIG. It interconnects the rotor to the grid and is used for reactive power control as well as operating the machine at MPP. There is a bidirectional converter which is responsible for the control of real and reactive power flow in the four quadrants between the AC network and the DC network of the micro-grid. The converter is also responsible for the maintenance of DC-link voltage in the micro-grid. The following section discusses briefly about the modeling of these converters.

3.1 Modeling of boost converter

An averaged state-space model has been used to model the converter. This boost converter designed is used in implementing the P&O-based MPPT algorithm.

3.2 Modeling of DFIG controllers

Different control strategies for modeling of DFIG have been discussed in detail in. A pitch control mechanism as well as a rotor side converter is designed for the DFIG.The pitch angle is computed continuously and is controlled as required by the system. The pitch angle is continuously recorded and compared with the reference value. The deviation or the error signal is sent through an appropriately tuned proportional–integral controller to get a control signal as output. The rotor of the machine contains an AC/DC/AC converter through which it is coupled to the grid. Since the machine is modeled in d–q reference frame, the modeling of controllers becomes easy. This allows a decoupled design of the controllers which allows the control of real and reactive powers independently.

3.3 Modeling of bi-directional converter

The main bi-directional converter interconnects the AC and DC networks of the hybrid micro-grid. The major tasks of this converter are:

• To convert power between AC and DC as required for facilitating power exchange between the networks.

• Maintaining constant DC-link voltage of the micro-grid. The converter is modeled in the d–q reference frame for the ease of developing a decoupled control loop for both active and reactive powers as discussed in. The block diagram of the converter can be seen in Fig. 3. The two major control loops present in the controller are discussed briefly.

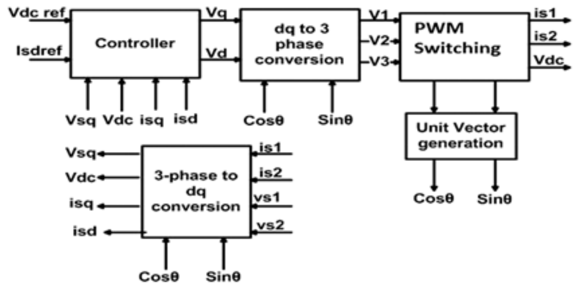

Fig. 3 Block diagram of the bi-directional converter

3.3.1 Power control loop:

The real and reactive powers, after a power invariant transformation in the d–q reference are calculated, as this operation facilitates the decoupling of control individually in both the axes. From the decoupled equations, it is shown that qaxis current is used to control real power and d-axis current controls the reactive component of total power. Two separate loops similar to each other are designed for the same .

3.3.2 DC-link voltage control loop:

An outer voltage loop is designed for the regulation of the DC-link voltage to the reference value. The converter has feedback control designed to make sure to maintain the nominal bus voltages during all conditions.

4. MODELLING OF ACMC

The micro-grid designed consists of distributed control systems. The ACMC is intended to provide a secondary control, i.e. coordinated control and monitor the overall functions of the micro grid. The major functions of the ACMC are as follows:

•To provide the real and reactive reference values for the bidirectional converter discussed in Section 3.3.

• To monitor and control power flow and schedule required flow as necessary in micro-grid by appropriate generation control of the converters discussed in Sections 3.1 and 3.2.

• To monitor and control the LVDC-link voltages.

• To monitor plug and play feature of load and generator buses on any part of network in the micro-grid.

The load and source currents and the bus voltages at each point in the network are metered and the computed power is processed by ACMC. The amount of power to be dispatched by the generators present either on the AC network or on the DC network depending on the requirement. After the schedule has been prepared, the generations of the respective AC and DC sources are controlled so that the power balance criterion is met. If the generation exceeds the demand or vice-versa, then the appropriate generator dispatch is modified according to the economic analysis algorithm. The control is achieved practically by varying the number of cells in series and parallel in the PV array for subsequently changing the generation. In the DFIG, the signals obtained by the ACMC are sent to the real power control block of the machine, thus changing the real power reference as required. If the load is greater than the capacity of the micro-grid, then appropriate loads will be shed. Concurrently, any addition of a new load bus or generator bus is first preceded by an input to the ACMC which allows it to record the modified network structure to its database. The basic flowchart of the working of ACMC has been presented in Fig. 4. The flowchart explains the implementation of the automatic power control which is performed by the ACMC. The economic criteria used for power transfer algorithm is based on the distance of the source load from the link buses, as it is a radial network, unlike a mesh network and losses are directly proportional to the transmission distance.

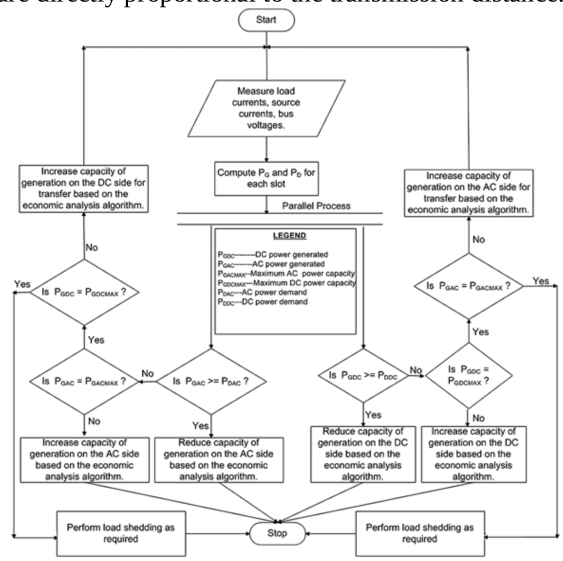

Fig. 4 Automatic power generation control flowchart

The algorithms used by the ACMC are discussed below.

4.1 Plug and play algorithm

Step 1: Calculate and store the equivalent Thevenin resistance and impedance of the DC and the AC networks separately.

Step 2: Sense the change in equivalent impedance to observe the request of addition or removal of any new bus to either of the network.

Step 3: Sense the voltage level of new feeder added or removed.

Step 4: Update the network map with the modifications done.

Step 5: Go to step 1 and continue the same process.

If the micro-grid is incapable of meeting the excessive load demand with either of the network generation at their maximum capacity, then certain amount of load shedding needs to be done to keep the system in a stable operating state. The algorithm used to programme is discussed as follows.

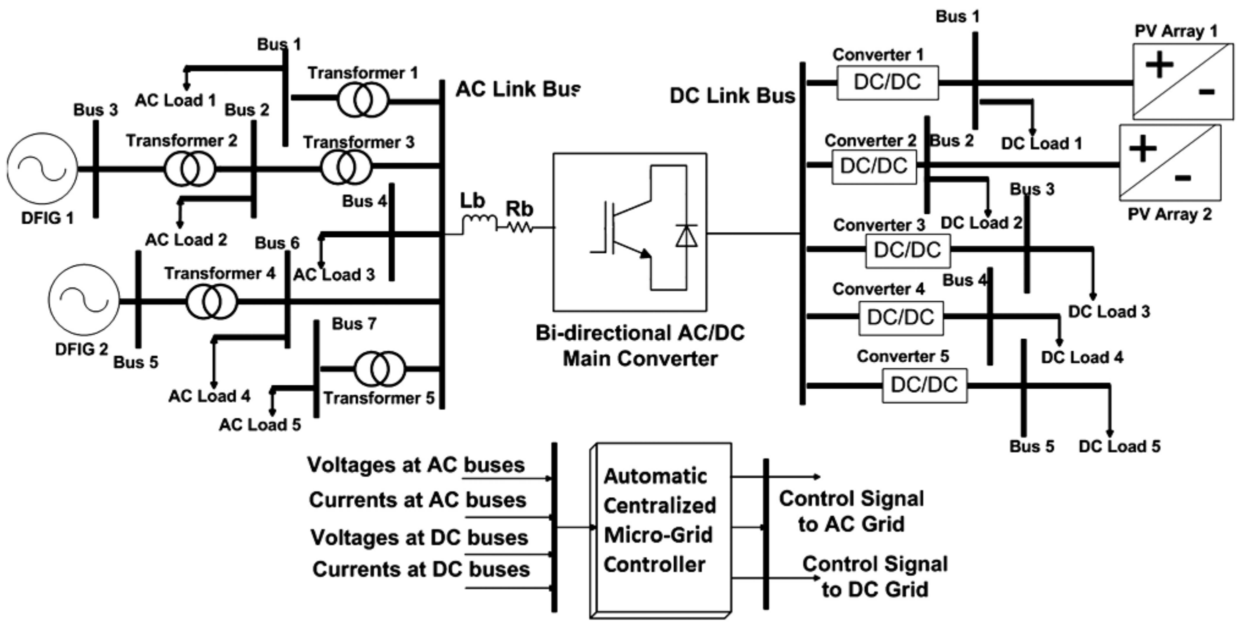

Fig.5 Test system used for case study

4.2 Load shedding algorithm

Step 1: Collect and store the data for critical load demand on each feeder on both AC and DC networks.

Step 2: Supply the critical loads uninterrupted during a power unbalance.

Step 3: Prioritise the non-critical loads based on a predefined criterion.

Step 4: Supply the loads based on the priority and disconnect the lesser priority loads.

Step 5: If the systems power generation matches the demand go to step 6 else go to step 3.

Step 6: Stop.

The priority is predefined by the user and set before the operation. The ACMC is designed to implement the algorithms and to achieve the desired four quadrant operation in the micro-grid as well as control of the DC-link bus voltage in the system.

5. CASE STUDY

A test system has been designed for the analysis and simulation studies of the proposed hybrid micro-grid design. In this system, an AC network of seven buses and DC network containing five buses have been considered. The system is designed to have a radial distribution network on either grid. The layout of the system considered for case study has been presented in Fig. 5. The load data and the bus data as well as the parameters of the elements used for the modeling in the AC as well as DC network are given in Tables 1 and 2, respectively. A total AC generation capacity of 1250 kW has been considered and a 500 kW capacity on the DC side.

The bi-directional converter was designed for a power of 250 kVA.

Table 1 AC network parameters

Sl. no	Element description	Parameter value
1	bus 1	230 V
2	bus 2	11 kV
3	bus 3	690 V
4	bus 4	415 V
5	bus 5	690 V
6	bus 6	415 V
7	bus 7	230 V
8	DFIG 1	1 MW, 690 V
9	DFIG 2	250 kW, 690 V
10	transformer 1	415 V/230 V, 10 kVA
11	transformer 2	690 V/11 kV, 800 kVA
12	transformer 3	11 kV/415 V, 1 MVA
13	transformer 4	690 V/415 V, 10 kVA
14	transformer 5	415 V/230 V, 10 kVA
15	AC-link bus voltage	415 V

Table 2 DC network parameters

Sl. no	Elements	Parameter values
1	bus 1	120 V
2	bus 2	48 V
3	bus 3	120 V
4	bus 4	326 V
5	bus 5	230 V
6	PV array 1	250 kW, 48 V
7	PV array 2	250 kW, 120 V
8	converter 1	400 V/120 V, 1 kW
9	converter 2	400 V/48 V, 1 kW
10	converter 3	400 V/120 V, 1 kW
11	converter 4	400 V/326 V, 500 W
12	converter 5	400 V/230 V, 500 W
13	DC-link bus voltage	400 V

The AC and DC side bus voltage levels have been chosen to cater the needs of majority of customers. The AC consists of 230 V feeders for supplying single-phase domestic loads and has 415 V feeders for supplying the three-phase loads. Similarly, an 11 kV feeder has been considered to supply the industrial load requirement in the area. The appropriate loads and transformers have been connected with reference to the designed bus voltages. The DC side voltage levels have been designed with respect to various utilities. The 120 V feeder is mainly dedicated to cater to the office and commercial needs, whereas 48 V has been designed for domestic needs as was observed optimal in [25].

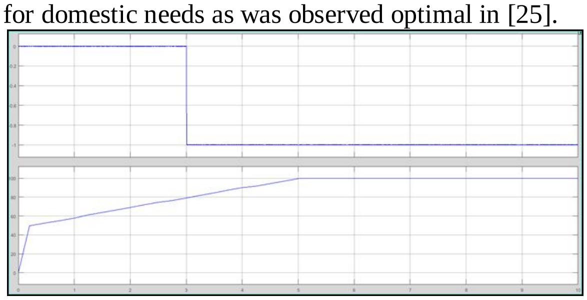

Fig. 6 Power generation of renewable sources in the test system (a) PV output power versus irradiation, (b) DFIG output power versus time

6. PROPORTIONAL RESONANT CONTROLLER

Proportional resonant controller the current controller can have a significant effect on the quality of the current supplied to the grid by the PV inverter, and therefore it is important that the controller provides a high quality sinusoidal output with minimal distortion to avoid creating harmonics A single phase feedback current loop is used to regulate the grid current. A proportional resonant control strategy is used as compensator to track a sinusoidal current reference frame. The basic control loop diagram [4] with PR control is as shown in figure 3.

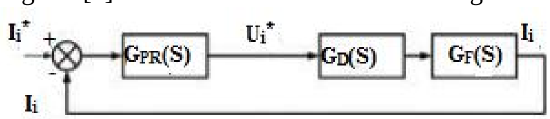

Fig.7 control loop diagram with PR controller

Transfer function of the ideal PR controller is as below:

$$G_{PR}(S) = K_P + K_R \frac{S}{S^2 + W_0^2} \quad (1)$$

Where

$Kp -$ proportional gain of the controller

$KR -$resonant gain of the controller

$wo-$ resonant frequency of the controller in general which is frequency of the grid Unfortunately, the ideal PR controller acts like a network with an infinite quality factor, which is hard to implement the PR controller in reality. Firstly, the infinite gain introduced by PR controller leads to an infinite quality factor which cannot be achieved in either analog or digital system.

Secondly, the gain of PR controller is much reduced at other frequencies and it is no adequate to eliminate harmonic influence caused by grid voltage. Therefore, an approximating ideal (non-ideal) PR controller, is given by

$$G_{PR}(S) = K_P + K_R \frac{2\omega_C S}{S^2 + 2\omega_C S + \omega_0^2} \quad (2)$$

Where ω_c - bandwidth around the ac frequency of w_o the frequency response of (2), where the resonant peak now has a finite gain of 40 dB which is satisfactorily high for eliminating the voltage tracking error. In addition, a wider bandwidth is observed around the resonant frequency, which minimizes the sensitivity of the controller to slight grid frequency variations. At other harmonic frequencies, the response of the non-ideal PR controller is comparable to that of the ideal PR controller

7. SIMULATION RESULTS AND DISCUSSION

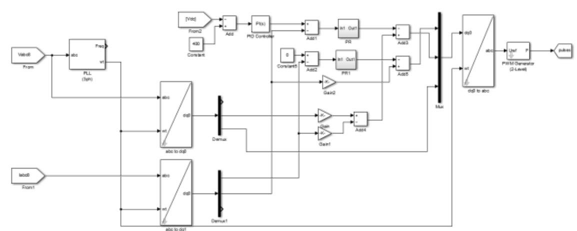

Fig.8 Simulation diagram for the controlling of Bi-directional converter

The case study was simulated in MATLAB/Simulink environment. Various cases were considered to simulate the transfer of real and reactive powers based on the requirement of either grid. The controlling action of the ACMC is validated and can be observed from the results in Table 3.

Table 3 Results of different cases performed on the test system

Case number	AC load, kW	AC generation, kW	Power transferred, kW	DC load, kW	DC generation, kW
1.	1000	1000	0	250	250
2.	1250	1250	0	250	250
3.	1250	1250	0	500	500
4.	1500	1250	250	250	500
5.	1000	1250	250	750	500

Cases 1, 2 and 3 show the power generation controlling action of the ACMC. It can be observed that the generations were modified accordingly to the demand. The case 4 shows the transfer of excess real power from DC side to the AC side, whereas case 5 shows the transfer of excess real power from the AC side to the DC side. A transfer of 2 kVA reactive power from DC side to AC side was achieved in case 4 in parallel.

Fig. 6a shows the variations in the irradiation level versus the output power of the module at a constant temperature. The irradiation was 0.2 kW/m2 at t=0. It was increased to 0.4 kW/m2 at t = 4 s and to a final value of 1 kW/m2 at t = 10 s. The MPPT operation of the solar panel can be seen from the hill climbing nature of the graph. Fig. 6b shows the output real power of the DFIG which achieves a cut-in speed at 3 s and remains constant even with wind variations due to the MPPT and rotor converter control. The negative value of power indicates the power delivered and the positive value indicates the power absorbed. The output control signals are given to the AC and DC grid from the ACMC to the various sources.

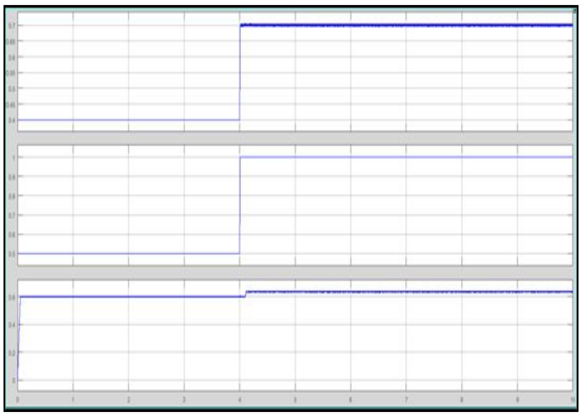

Fig. 9 Generation control signals generated by ACMC (a) Control signal to 1 MW DFIG from ACMC, (b) Control signal given to the 120 V bus connected PV array, (c) Control signal given to the 48 V bus connected PV array

Fig. 9a is the control signal given to the 1 MW DFIG in the system. Figs. 9b and c are the signals given to both the PV arrays connected at 120 and 48 V bus, respectively. The control signal values vary between 0 and 1, where 1 means the maximum generation capability switched on and 0 means the unit completely generating no power as the output. Owing to the continuous measurement and evaluation of the values, the waveform can be found to have continuous high frequency variations depending on the frequency of running of algorithm iterations. The power transfer has been shown in the autonomous mode of operation where a positive load change of 300 kW has been simulated in the DC side.

Fig. 9a shows that a power of around 200 kW has been transferred through the converter pushed by the AC grid as the DC grid was able to ramp up its capacity to give 100 kW of the required power demand. Similarly, in the second case in Fig. 9c, a positive load change of around 600 kW was simulated on the AC side out of which the AC ramped up its generation to 380 kW and the remaining 120 kW was supplied by the DC grid in its capacity through the converter. In addition to this, the reactive power transfer has also been simulated in both the directions which can be seen in Fig. 9b. Initially, it was simulated that the DC grid supplies a reactive power of 2 kVAR, whereas a change in the demand at t = 2 s led to the transfer of 2 kVAR from the AC grid as required. Throughout the operation of the converter, Fig. 9d shows the voltage on the DC-link bus, which was maintained at constant voltage of 400 V by the converter. The dip in the voltage due to start in generation of DFIG at cut-in speed at 3 s and load changes at 4 s can be observed.

8. CONCLUSION

In this paper a smart hybrid AC/LVDC micro-grid was proposed and the design was simulated in Matlab-simulink. Following are the major impacts on the existing power system:

- A greater autonomy in the operation leads to a development of various localised micro-grid clusters, thereby increasing the reliability, as local micro-grids may have minimal or no effect on the main grid depending on the degree of dependency.
- The effective implementation of such a design may even give rise to a situation which eliminates the need of upgrading the existing lines for bi-directional power transfer as each local energy source maybe utilised locally.
- If implemented in remote places with least or no accessibility to the conventional grid, this design may eliminate the need of connecting places through long transmission system by creating a self-sufficient local micro-grid.
- The presence of separate LVDC grid along with the AC will give a better power market which relaxes the condition where there is no compulsion of utilising all the energy produced as the excess energy can always be converted and stored in batteries connected to the LVDC grid and utilised accordingly when required.

This paper explains in detail the modeling of the main bidirectional converter. It also explains the modeling of various sources along with their control. The off-grid mode of operation of ACMC was simulated and the simulation results prove the reliable operation of such a system.

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