Research Article

ACMC-based hybrid AC/LVDC micro-grid

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Abstract: This study proposes the detailed modelling of a novel automatic centralised 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. The micro-grid is designed to work majorly with renewable power sources. This hybrid micro-grid is capable of interconnecting very large AC and LVDC networks, using a bi-directional AC/DC/AC converter. The AC and the LVDC networks consist of different feeders with loads connected at various voltages. The ACMC design proposed is responsible for controlling the real(P) and reactive(Q) power from the sources based on load requirement and voltage control of the LVDC network. 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

The paradigm shift toward renewable sources of energy generation is led by uncertainty created due to rapid depletion of conventional fossil fuels [1]. Incidentally, a large percentage of these renewable sources generate an inherent DC power output. This output needs to be converted appropriately for servicing the conventional AC loads. Concurrently, rapid growth and development in power electronics in the recent decade have seen a surge of devices using DC power for their operation. This has generated a renewed interest in the development of DC power systems in conventional electric networks. Hence, need of various conversion stages between AC and DC has arisen. Extensive research have given rise to highly efficient converters with DC/DC converters being more efficient than AC-DC converters [2]. In addition, the development of consumer durable electronic industry has led to the increase in many household items working on the DC power. These devices contain adapter units which convert the supplied AC power to their required DC power. There has been development of appliances using drives utilising DC power, due to ease of speed control. This employs additional AC/DC conversion stages, which reduce the efficiency due to conversion losses [3]. The affordable cost of renewable installations led to small-scale installation in households. This has led to the concept of AC micro-grids where distributed generation units are connected to the AC micro-grid to supply power locally [4]. The AC micro-grids supply the AC loads in the system after converting the input from DC to AC [4, 5]. In case of DC loads, an extra conversion stage of the already converted power is added leading to redundant power conversions. To address this issue, DC micro-grids have been discussed [6, 7]. However, the presence of AC loads still poses the problem of redundant conversions. Thus, the concept has been further extended to a hybrid AC/DC micro-grid which aims at solving the multi-conversion problem [8, 9]. Separate AC and DC buses that are interconnected by a bi-directional converter was proposed as a solution. The design of a bi-directional converter with two different types of control schemes has also been discussed [10]. The possible solutions of various power quality issues arising in hybrid microgrids have been briefly discussed in [11]. Further issues such as voltage stability of AC and DC buses were discussed with certain

control schemes proposed to maintain required voltage [12-15]. A predictive control strategy has been proposed to mainly manage the renewable resources in a micro-grid [16]. In [17], a microcontroller-based approach has been proposed for power management of a standalone micro-grid with hybrid sources. Hybrid AC/DC micro-grid topology consisting of a photovoltaic (PV) farm with battery storage has been discussed in [18] where the grid-connected and islanding modes of operation were discussed. A new analytical technique to manage the reliability assessment of renewable energy resources in a PV-wind storage system using probabilistic storage model has been developed in [19]. A supervisory control scheme for a hybrid AC/DC micro-grid containing diesel generator, wind farms and PV farms along with Li-ion battery banks in isolated mode of operation was discussed in [20]. Extending further, a robust optimal power management system for a hybrid AC/DC micro-grid based on an optimisation problem was discussed in [21].

Extending the survey further, the concept of low-voltage DC (LVDC) and increased LVDC penetration in typical households, office spaces as well as data centres has been addressed in the form of separate LVDC micro-grids. The LVDC distribution system eliminates the need for the use of multiple conversion stages since the DC power generated can be directly utilised, thus bringing down the number of adapters used. Extensive studies have shown that the usage of DC power for household appliances is more efficient than AC power. A detailed case study was presented in [22]. It has been observed that a voltage not exceeding 50 V is deemed ideal for use in typical households [23]. The household appliances work mainly on the voltage levels of 12, 24 or 48 V [24]. The concept of LVDC can also be extended to office spaces and the feasibility of the same was studied in [25]. The analysis on the efficiency of various appliances was done for different cable sizes and voltage levels of both AC and DC systems. Different voltage levels such as 326, 230, 120 and 48 V have been investigated for voltage drop analysis. The detailed study has shown that a voltage of 326 V is more suitable to the office environment than a 48 V voltage. This was because reliability was the main requirement for an office environment. The losses at 48 V were found out to be higher than other voltage levels for the office environment. On the contrary for a home environment, since safety



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Fig. 1 Typical hybrid AC/DC micro-grid

is a major concern, 120 V can be a better option of voltage level. In addition, depending on the cable size requirement of the house, 48 V can be an ideal option as most telecommunication as well as consumer appliances are rated at that level. The detailed case study and the efficiency at different operating conditions can be found in [26].

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 centralised micro-grid controller (ACMC) is responsible for the control and monitoring of the entire microgrid. 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 utilises solar PV arrays with maximum power point tracking (MPPT) mechanism. The off-grid 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 modelling 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 modelling aspects have been discussed subsequently.

2.1 System configuration

The schematic representation of a typical hybrid AC/DC microgrid 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. 2 shows the proposed layout of hybrid AC/LVDC microgrid. 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 modelled 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 [27]. The design of an ACMC is proposed in this paper, whose modelling 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 modelled 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.

2.2 Modelling of the sources in the system

The modelling of DFIG-based wind generator as well as the solar PV array is carried out by the existing conventional approach. The modelling of the PV array has been done using one diode model of PV cell [28–31]. The DFIG has been modelled 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 modelling of the electrical subsystem of the machine has been done in d-q-axis in an arbitrary frame of reference [32].

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



Fig. 2 Schematic representation of the proposed hybrid grid



Fig. 3 Block diagram of the bi-directional converter

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 modelling of these converters.

3.1 Modelling of boost converter

An averaged state-space model has been used to model the converter [33–35]. This boost converter designed is used in implementing the P&O-based MPPT algorithm [36, 37].

3.2 Modelling of DFIG controllers

Different control strategies for modelling of DFIG have been discussed in detail in [38]. A pitch control mechanism as well as a rotor side converter is designed for the DFIG [39–41]. 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 modelled in d-q reference frame, the modelling of controllers becomes easy. This allows a decoupled design of the controllers which allows the control of real and reactive powers independently.

3.3 Modelling 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:

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- 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 modelled in the d-q reference frame for the ease of developing a decoupled control loop for both active and reactive powers as discussed in [42, 43]. The block diagram of the converter can be seen in Fig. 3. The two major control loops present in the controller are discussed briefly.

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 q-axis 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 [39].

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 [42].

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 microgrid. The major functions of the ACMC are as follows:



Fig. 4 Automatic power generation control flowchart

- 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 [44]. 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.

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.



Fig. 5 Test system used for case study

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.

Table 1 AC network parameters

SI. 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 2DC network parameters

	Be notifelit parametere	
SI. 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

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 modelling 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. 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 Simulation results and discussion

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.

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. 6*a* shows the variations in the irradiation level versus the output power of the module at a constant temperature. The irradiation was 0.2 kW/m^2 at *t*=0. It was increased to 0.4 kW/m^2 at

t=4 s and to a final value of 1 kW/m^2 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. 7a is the control signal given to the 1 MW DFIG in the system. Figs. 7b 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 highfrequency 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. 8a 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. 8c, 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. 8b. 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. 8d 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.

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



Fig. 7 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. 8 Four quadrant and voltage control operation of ACMC (a) Real power transferred to the DC side, (b) Reactive power transfer at DC-link bus, (c) Real power transferred from the DC side, (d) Voltage profile at the DC-link bus

7 Conclusion

Thus, in this paper a smart hybrid AC/LVDC micro-grid was proposed and the design was simulated on a test system. The results achieved, validate the concept of such a proposed design to achieve the desirable operation and control. The implementation and operation of such a smart hybrid micro-grid assumes importance in the background of development of renewable energy generating units fast replacing the conventional sources. Also, far more flexible autonomous operation can have the following 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 modelling of the main bidirectional converter. It also explains the modelling of various sources along with their control. The concept of ACMC has been introduced and its off-grid mode of operation was simulated which introduces a great degree of autonomy in the system and the simulation results prove the reliable operation of such a system.

8 References

- Gellings, C.W., EPRI: 'DC power production, delivery and utilization'. [1] Available at http://www.powerpulse.net/techPaper.php?paperID=130, accessed November 2015
- Pajanen, P., Kaipia, T., Partanen, J.: 'DC supply of low voltage electricity appliances in residential buildings'. Proc. CIRED 2009 Conf., June 8–11 [2] 2009, pp. 1-4
- Lasseter, R.H.: 'MicroGrids'. Proc. IEEE Power Engineering Society Winter [3] Meeting, 2002, vol. 1, pp. 305-308
- Baran, M.E., Mahajan, N.R.: 'DC distribution for industrial systems: [4] opportunities and challenges', IEEE Trans. Ind. Appl., 2003, 39, (6), pp. 1596 - 1601

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- Hammerstrom, D.J.: 'AC versus DC distribution systems did we get it [5] right?'. Proc. IEEE Power Engineering Society General Meeting, June 2007, p. pp. 15 Ito, Y., Yang, Z., Akagi, H.: 'DC micro-grid based distribution power
- [6] generation system'. Proc. IEEE Int. Power Electronics and Motion Control Conf., August 2004, vol. **3**, pp. 1740–1745
- Sannino, A., Postiglione, G., Bollen, M.H.J.: 'Feasibility of a DC network for [7] commercial facilities', IEEE Trans. Ind. Appl., 2003, 39, (5), pp. 1409-1507
- Liu, X., Wang, P., Loh, P.C.: 'A hybrid AC/DC microgrid and its coordination [8] control', IEEE Trans. Smart Grid, 2011, 2, pp. 278-286
- [9] Baharizadeh, M., Karshenas, H.R., Guerrero, J.: 'New control strategy of interlinking converters as the key segment of hybrid AC-DC microgrids', *IET. Gener. Transm. Distrib.*, 2016, **10**, pp. 1–20 Mohamed, A., Elshaer, M., Mohammed, O.: 'Bi-directional AC-DC/DC-AC
- [10] converter for power sharing of hybrid AC/DC systems'. Proc. IEEE Power Engineering Society General Meeting, July 2011, pp. 1-8
- [11] Guerrero, J.M., Loh, P.C., Lee, T.-L., et al.: 'Advanced control architectures for intelligent microgrids – part II: power quality, energy storage, and AC/DC microgrids', *IEEE Trans. Ind. Electron.*, 2013, **60**, (4), pp. 1263–1270
- Akbari, M., Golkar, M.A., Tafreshi, S.M.M.: 'A PSO solution for improved voltage stability of a hybrid AC–DC microgrid'. Proc. IEEE PES Innovative [12] Smart Grid Technologies - India (ISGT India), Kerala, December 2011, pp. 352-357
- Radwan, A.A.A., Mohamed, Y.: 'Assessment and mitigation of interaction dynamics in hybrid AC/DC distribution generation systems', *IEEE Trans.* [13] Smart Grid, 2012, 3, (3), pp. 1382-1393
- Eghtedarpour, N., Farjah, E.: 'Power control and management in a hybrid [14] AC/DC microgrid', *IEEE Trans. Smart Grid*, 2014, **5**, (3), pp. 1494–1505 Marinelli, M., Sossan, F., Costanzo, G.T., *et al.*: 'Testing of a predictive
- [15] control strategy for balancing renewable sources in a microgrid', IEEE Trans. Sustain. Energy, 2011, 5, (4), pp. 1426–1433
- Belvedere, B., Bianchi, M., Borgetti, A., et al.: 'A microcontroller based power management system for standalone micro-grids with hybrid power [16] supply', IEEE Trans. Sustain. Energy, 2012, 3, (3), pp. 422-431
- Nilsson, D.: 'DC distribution systems'. Licentiate of Engineering thesis, [17] Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology, 2005
- [18] Ma, T., Cintuglu, M.H., Mohammed, O.: 'Control of hybrid AC/DC microgrid involving energy storage, renewable energy and pulsed loads'. 2015 IEEE Industry Applications Society Annual Meeting, Addison, TX, 2015, pp. 1–8
- Paliwal, P., Patidar, N.P., Nema, R.K.: 'A novel method for reliability [19] assessment of autonomous PV-wind-storage system using probabilistic storage model', Int. J. Electr. Power Energy Syst., Elsevier, 2014, 55, pp. 692-703
- Hosseinzadeh, M., Salmasi, F.R.: 'Power management of an isolated hybrid [20] AC/DC micro-grid with fuzzy control of battery banks', *IET Renew. Power Gener.*, 2015, 9, (5), pp. 484-493
- Hosseinzadeh, M., Salmasi, F.R.: 'Robust optimal power management system [21] for a hybrid AC/DC micro-grid', IEEE Trans. Sustain. Energy, 2015, 6, (3), pp. 675–687
- Sannino, A., Postiglione, G., Bollen, M.H.J.: 'Feasibility of a DC network for [22]
- commercial facilities', *IEEE Trans. Ind. Appl.*, 2003, **39**, (5), pp. 1499–1507 Vaessen, P.: 'Direct-current voltage (DC) in households', September 2005. Available at http://www.leonardoenergy.org/webfm_send/366 Rodriguez, Otero, M.A., O'Neill, C.E.: 'Efficient home appliances for a future [23]
- [24] DC residence'. IEEE Conf. Energy 2030, 2008, no. 3, pp. 1-6, doi: 10.1109/ ENERGY.2008.4781006
- Postiglione, G.: 'DC distribution system for home and office'. MS thesis, Department of Electric Power Engineering, Chalmers University of [25] Technology, 2001

- Arafat, Y., Amin, M.: 'Feasibility study of low voltage DC house and compatible home appliance design'. *MS thesis, Division of Electric Power* [26] Engineering, Department of Energy and Environment, Chalmers University of Technology, 2011
- Subudhi, B., Pradhan, R.: 'A comparative study on maximum power point [27] tracking techniques for photovoltaic power systems', IEEE Trans. Sustain. Energy, 2013, 4, (1), pp. 89-98
- [28] Chowdhury, S., Chowdhury, S.P., Taylor, G.A., et al.: 'Mathematical modeling and performance evaluation of a stand-alone polycrystalline PV plant with MPPT facility'. Proc. IEEE Power Engineering Society General Meeting on Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburg, USA, July 2008
- Jung, J.-H., Ahmed, S.: 'Model construction of single crystalline photovoltaic [29] panels for real-time simulation'. IEEE Energy Conversion Congress & Exposition, Atlanta, USA, 12–16 September 2010 Nema, S., Nema, R.K., Agnihotri, G.: 'MATLAB/Simulink based study of
- [30] photovoltaic cells/modules/array and their experimental verification', *Int. J. Energy Environ.*, 2010, **1**, (3), pp. 487–500 Bizzarri, F., Bongiorno, M., Brambilla, A., *et al.*: 'Model of photovoltaic
- [31] power plants for performance analysis and production forecast', IEEE Trans. Sustain. Energy, 2013, 4, (2), pp. 422–431 Kelber, C.R., Schumacher, W.: 'Adjustable speed constant frequency energy
- [32] generation with doubly-fed induction machines'. Proc. European Conf. Variable Speed in Small Hydro, Grenoble, France, 2000
- [33] Liu, H., Tao, S.-G.: 'The methods of simulation of boost converter based on MATLAB', Commun. Power Supply Technol., 2004, 4, (21), pp. 22-24
- Davoudi, A., Jatskevich, J., Rybel, T.D.: 'Numerical state-space average value [34] modeling of PWM DC-DC converters operating in DCM and CCM', IEEE *Trans. Power Electron.*, 2006, **21**, (4), pp. 1003–1012 Cao, W.-S., Yang, Y.-X.: 'Simulation analyses of boost converter based on
- [35] state-space averaging principle', J. Syst. Simul., 2007, 19, (6), pp. 1329–1334

- [36] Chee, W.T., Green, T.C., Carlos, A.H.A.: 'Analysis of perturb and observe maximum power point tracking algorithm for photovoltaic applications'. Proc. IEEE Second Int. Power and Energy Conf. (PECon), Johor Bahru, Malaysia, 2008
- [37] Esram, T., Chapman, P.L.: 'Comparison of photovoltaic array maximum power point tracking techniques', IEEE Trans. Energy Convers., 2007, 22, (2), pp. 439–449
- [38] Tremblay, E., Atayde, S., Chandra, A.: 'Comparative study of control strategies for the doubly fed induction generator in wind energy conversion systems: a DSP-based implementation approach', IEEE Trans. Sustain. Energy, 2011, 2, (3), pp. 288–299
- Rodriguez-Amenedo, J.L.: 'Automatic generation control of a wind farm with [39] variable speed wind turbines', IEEE Trans. Energy Convers., 2002, 17, (2), pp. 279–282
- [40] Slootweg, J.G., de Haan, S.W.H., Polinder, H., et al.: 'Aggregated modelling of wind parks with variable speed wind turbines in power system dynamics simulations'. Proc. 14th Power Systems Computation Conf., Seville, 2002
- Hofmann, W., Okafor, F.: 'Doubly-fed full-controlled induction wind [41] generator for optimal power utilization'. Fourth IEEE Int. Conf. Power Electronics and Drive Systems, 2001
- [42] Shiva Prasad, J.S., Bhavsar, T., Ghosh, R., et al.: 'Vector control of three-
- phase AC/DC front-end converter', *Sadhana*, 2008, **33**, Part 5, pp. 591–613 Zhao, J.F., Jiang, J.G., Yang, X.W.: 'AC–DC–DC isolated converter with bidirectional power flow capability', *IET Power Electron.*, 2010, **3**, (4), pp. [43] 472-479
- [44] Liu, B., Liu, F., Mei, S., et al.: 'AC-constrained economic dispatch in radial power networks considering both continuous and discrete controllable devices'. 27th Control and Decision Conf. (CCDC), Qingdao, May 2015, pp. 6249-6254