The Impact of Hybrid AC/LVDC Micro-Grid with a Bi-Directional Converter

A.Ravi Kumar
Assistant Professor, Dept. of Electrical & Electronics Engineering, UCEN -JNTUK, Narasaraopeta, A.P., India.

Abstract - Micro grids intrinsically increase the efficiency of the electrical system by integrating the RES at the consumption level, which avoid most of the transmission losses. 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.

I. INTRODUCTION

A hybrid ac/dc micro grid is proposed in this paper to reduce processes of multiple reverse conversions in an individual acor dc grid and to facilitate the connection of various renewable ac and dc sources and loads to power system. Since energy management, control, and operation of a hybrid grid are more complicated than those of an individual ac or dc grid, different operating modes of a hybrid ac/dc grid have been investigated. The coordination control schemes among various converters have been proposed to harness maximum power from renewable power sources, to minimize power transfer between ac and dc networks, and to maintain the stable operation of both ac and dc grids under variable supply and demand conditions when the hybrid grid operates in both grid-tied and islanding modes. The advanced power electronics and control technologies used in this paper will make a future power grid much smarter. In an ac grid, embedded ac/dc and dc/dc converters are required for various home and office facilities to supply different dc voltages. AC/DC/AC converters are commonly used as drives in order to control the speed of ac motors in industrial plants.

Recently, dc grids are resurging due to the development and employment of renewable dc power sources and their inherent advantage for dc loads in commercial, industrial and residential applications. The dc micro grid has been proposed to integrate various distributed generators. However, ac sources have to be converted into dc before connected to a dc grid and dc/ac inverters are required for conventional ac loads. Multiple reverse conversions required in individual ac or dc grids may add additional loss to the system operation and will make the current home and office appliances more complicated.

II. AC-DC CONVERTER

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), current that flows in only one direction, a process known as rectification. Rectifiers have many uses including as components of power supplies and as detectors of radio signals. Rectifiers may be made of solid state diodes, vacuum tube diodes, mercury arc valves, and other components.

A device which performs the opposite function (converting DC to AC) is known as an inverter.

When only one diode is used to rectify AC (by blocking the negative or positive portion of the waveform), the difference between the term diode and the term rectifier is merely one of usage, i.e., the term rectifier describes a diode that is being used to convert AC to DC. Almost all rectifiers comprise a number of diodes in a specific arrangement for more efficiently converting AC to DC than is possible with only one diode. Before the development of silicon semiconductor rectifiers, vacuum tube diodes and copper (I) oxide or selenium rectifier stacks were used.

A. **Half-Wave Rectifier** - In half wave rectification, either the positive or negative half of the AC wave is passed, while the other half is blocked. Because only one half of the input waveform reaches the output, it is very inefficient if used for power transfer. Half-wave rectification can be achieved with a single diode in a one-phase supply, or with three diodes in a three-phase supply.

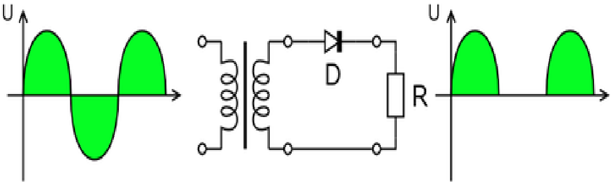

Figure 1: Half Wave Rectifier

The output DC voltage of a half wave rectifier can be calculated with the following two ideal equations:

$$V_{rms} = \frac{V_{peak}}{2}$$

$$V_{dc} = \frac{V_{peak}}{\pi}$$

B. Full-Wave Rectifier - A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to DC (direct current), and is more efficient. However, in a circuit with a non-center tapped transformer, four diodes are required instead of the one needed for half-wave rectification. Four diodes arranged this way are called a diode bridge or bridge rectifier:

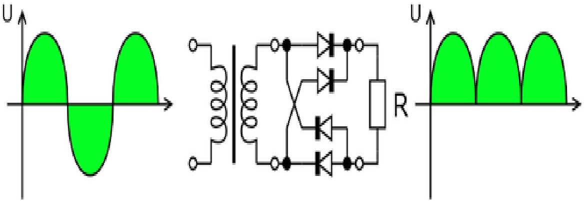

Figure 2: Full Wave Bridge Rectifier

For single-phase AC, if the transformer is center-tapped, then two diodes back-to-back (i.e. anodes-to-anode or cathode-to-cathode) can form a full-wave rectifier. Twice as many windings are required on the transformer secondary to obtain the same output voltage compared to the bridge rectifier above.

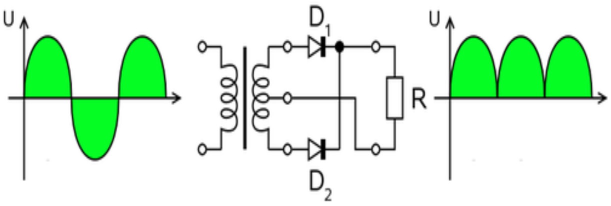

Figure 3: Full Wave Center-tapped Rectifier

A very common vacuum tube rectifier configuration contained one cathode and twin anodes inside a single envelope; in this way, the two diodes required only one vacuum tube. The 5U4 and 5Y3 were popular examples of this configuration.

III. RECTIFIER OUTPUT SMOOTHING

While half-wave and full-wave rectification suffice to deliver a form of DC output, neither produces constant-voltage DC. In order to produce steady DC from a rectified AC supply, a smoothing circuit or filter is required.[1] In its simplest form this can be just a reservoir capacitor or smoothing capacitor, placed at the DC output of the rectifier. There will still remain an amount of AC ripple voltage where the voltage is not completely smoothed.

The circuit shown in figure 4 was designed and simulated using Multisim 8 software:

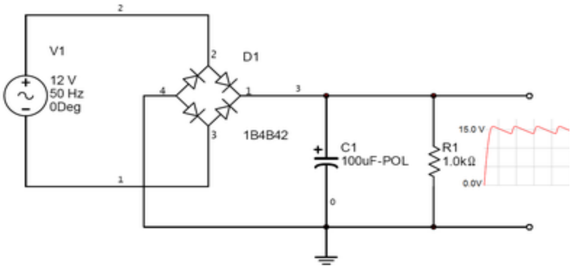

Figure 4: RC-Filter Rectifier

Sizing of the capacitor represents a tradeoff. For a given load, a larger capacitor will reduce ripple but will cost more and will create higher peak currents in the transformer secondary and in the supply feeding it. In extreme cases where many rectifiers are loaded onto a power distribution circuit, it may prove difficult for the power distribution authority to maintain a correctly shaped sinusoidal voltage curve.

For a given tolerable ripple the required capacitor size is proportional to the load current and inversely proportional to the supply frequency and the number of output peaks of the rectifier per input cycle. The load current and the supply frequency are generally outside the control of the designer of the rectifier system but the number of peaks per input cycle can be affected by the choice of rectifier design.

A **half-wave rectifier** will only give one peak per cycle and for this and other reasons is only used in very small power supplies. A full wave rectifier achieves two peaks per cycle and this is the best that can be done with single-phase input. For three-phase inputs a three-phase bridge will give six peaks per cycle and even higher numbers of peaks can be achieved by using transformer networks placed before the rectifier to convert to a higher phase order.

IV. APPLICATIONS

The primary application of rectifiers is to derive DC power from an AC supply. Virtually all electronic devices require DC, so rectifiers find uses inside the power supplies of virtually all electronic equipment.

Converting DC power from one voltage to another is much more complicated. One method of DC-to-DC conversion first converts power to AC (using a device called an inverter), then use a transformer to change the voltage, and finally rectifies power back to DC.

Rectifiers also find a use in detection of amplitude modulated radio signals. The signal may be amplified before detection, but if un-amplified, a very low voltage drop diode must be used. When using a rectifier for demodulation the capacitor and load resistance must be carefully matched. Too low a capacitance will result in the high frequency carrier passing to the output and too high will result in the capacitor just charging and staying charged.

Rectifiers are also used to supply polarized voltage for welding. In such circuits control of the output current is required and this is sometimes achieved by replacing some of the diodes in bridge rectifier with thyristors, whose voltage output can be regulated by means of phase fired controllers.

Thyristors are used in various classes of railway rolling stock systems so that fine control of the traction motors can be achieved. Gate turn-off thyristors are used to produce alternating current from a DC supply, for example on the Euro star Trains to power the three-phase traction motors.

V. DC-DC CONVERTER

A DC-to-DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at a different voltage level than the input. In addition, DC-to-DC converters are used to provide noise isolation, power bus regulation, etc. This is a summary of some of the popular DC-to-DC converter topologies.

A. Buck Converter Step-Down Converter - In this circuit the transistor turning ON will put voltage Vin on one end of the inductor. This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor but now flowing through the diode.

We initially assume that the current through the inductor does not reach zero, thus the voltage at Vx will now be only the voltage across the conducting diode during the full OFF time. The average voltage at Vx will depend on the average ON time of the transistor provided the inductor current is continuous.

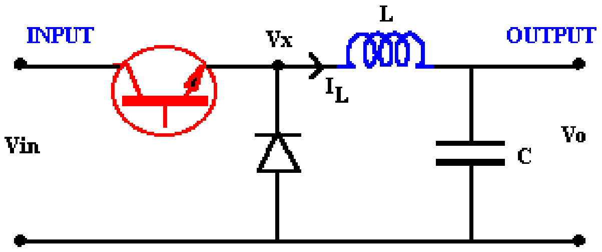

Figure 5: Buck Converter

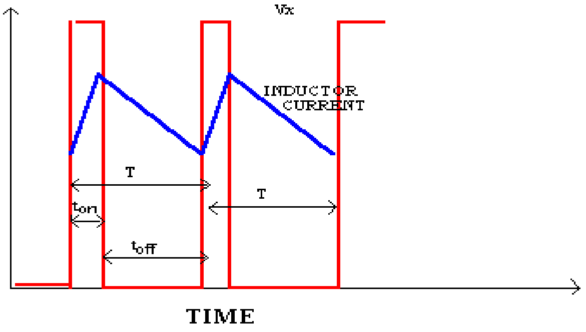

Figure 6: Voltage and current changes

To analyse the voltages of this circuit let us consider the changes in the inductor current over one cycle. From the relation

$$V_x - V_o = L\frac{di}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The change of current satisfies

$$di = \int_{ON}(V_x - V_o)dt + \int_{OFF}(V_x - V_o)dt \quad \ldots\ldots\ldots (2)$$

For steady state operation the current at the start and end of a period T will not change. To get a simple relation between voltages we assume no voltage drop across transistor or diode while ON and a perfect switch change. Thus during the ON time Vx=Vin and in the OFF Vx=0. Thus

$$0 = di = \int_0^{t_{on}}(Vin - Vo)dt + \int_{t_{on}}^{t_{on}+t_{off}}(-Vo)dt \quad \ldots\ldots (3)$$

Which simplifies to

$$(Vin - Vo)t_{on} - Vo\, t_{off} = 0 \quad \ldots\ldots\ldots\ldots\ldots (4)$$

or

$$\frac{Vo}{Vin} = \frac{t_{on}}{T} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

And defining "duty ratio" as

$$D = \frac{t_{on}}{T} \quad \ldots\ldots\ldots (6)$$

The voltage relationship becomes Vo=D Vin Since the circuit is lossless and the input and output powers must match on the average Vo* Io = Vin* Iin. Thus the average input and output current must satisfy Iin =D Io These relations are based on the assumption that the inductor current does not reach zero.

Transition between continuous and discontinuous: When the current in the inductor L remains always positive then either the transistor T1 or the diode D1 must be conducting. For continuous conduction the voltage Vx is either Vin or 0. If the inductor current ever goes to zero then the output voltage will not be forced to either of these conditions. At this transition point the current just reaches zero as seen in Figure (buck booster boundary). During the ON time Vin-Vout is across the inductor thus

$$I_L(peak) = (Vin - Vout)\cdot\frac{t_{ON}}{L} \quad \ldots\ldots\ldots\ldots (7)$$

The average current which must match the output current satisfies

$$I_L(average\ at\ transition) = \frac{I_L(peak)}{2} = (Vin - Vout)\frac{dT}{2L} = Iout(transition) \quad \ldots\ldots\ldots\ldots\ldots (8)$$

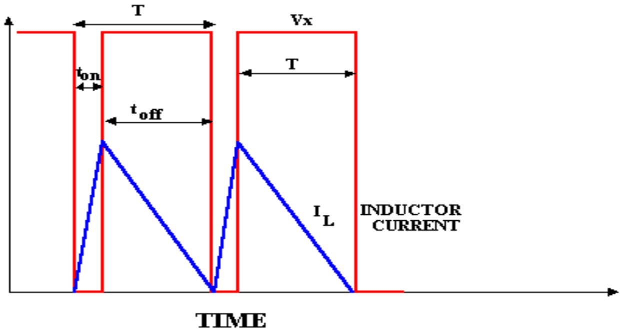

Figure 7: Buck Converter at Boundary

If the input voltage is constant the output current at the transition point satisfies

$$Iout(transition) = Vin \frac{(1-d)d}{2L} T \quad \text{………..(9)}$$

Voltage Ratio of Buck Converter (Discontinuous Mode) - As for the continuous conduction analysis we use the fact that the integral of voltage across the inductor is zero over a cycle of switching T. The transistor OFF time is now divided into segments of diode conduction ddT and zero conduction doT. The inductor average voltage thus gives

(Vin - Vo) DT + (-Vo) □dT = 0 …………(10)

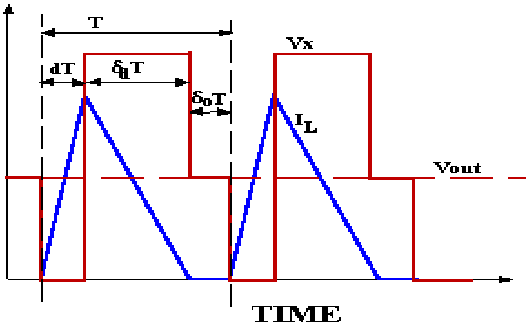

Figure 8: Buck Converter - Discontinuous Conduction

$$\therefore \frac{Vout}{Vin} = \frac{d}{d+\delta_d} \quad \text{…………. (11)}$$

for the case $d+\delta_d<1$. To resolve the value of δ_d consider the output current which is half the peak when averaged over the conduction times $d+\delta_d$

$$Iout = \frac{I_L(peak)}{2} d+\delta_d \quad \text{……….. (12)}$$

Considering the change of current during the diode conduction time

$$I_L(peak) = \frac{V_0(\delta_d T)}{L} \quad \text{………….. (13)}$$

Thus from (6) and (7) we can get

$$I_{out} = \frac{V_0 \delta_d T \cdot (d+\delta_d)}{2L} \quad \text{………… (14)}$$

Using the relationship in (5)

$$Iout = \frac{Vin\, d\, \delta_d T}{2L} \quad \text{……………..…. (15)}$$

And solving for the diode conduction

$$\delta_d = \frac{2L\, Iout}{Vin\, d\, T} \quad \text{………………..... (16)}$$

The output voltage is thus given as

$$\frac{Vout}{Vin} = \frac{d^2}{d^2 + (\frac{2L\, Iout}{Vin\, T})} \quad \text{………… (17)}$$

Defining k* = 2L/(Vin T), we can see the effect of discontinuous current on the voltage ratio of the converter.

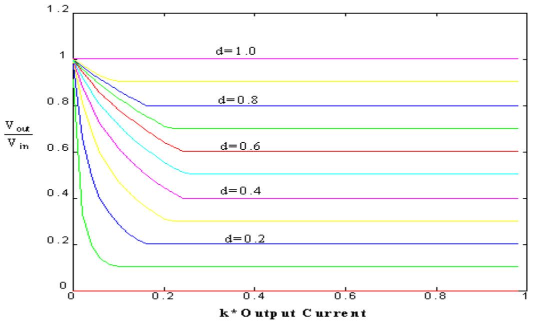

Figure 9: Output Voltage vs Current

As seen in the figure, once the output current is high enough, the voltage ratio depends only on the duty ratio "d". At low currents the discontinuous operation tends to increase the output voltage of the converter towards Vin.

B. Boost Converter Step-Up Converter - The schematic in Fig. 6 shows the basic boost converter. This circuit is used when a higher output voltage than input is required.

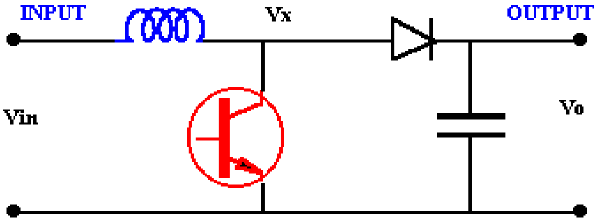

Figure 10: Boost Converter Circuit

While the transistor is ON Vx =Vin, and the OFF state the inductor current flows through the diode giving Vx =Vo. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in Fig. 7 and the average must be zero for the average current to remain in steady state

$$Vin\, t_{on} + (Vin - Vo) t_{off} = 0 \quad \text{………… (18)}$$

This can be rearranged as

$$\frac{Vo}{Vin} = \frac{T}{t_{off}} = \frac{1}{(1-D)} \quad \text{………..………. (19)}$$

And for a lossless circuit the power balance ensures

$$\frac{Io}{Iin} = (1-D) \quad \text{……….. (20)}$$

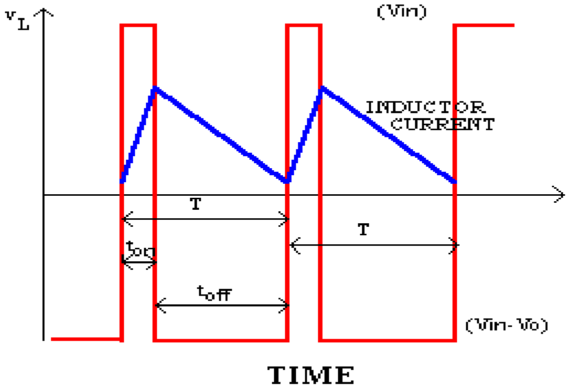

Figure 11: Voltage and current waveforms (Boost Converter)

Since the duty ratio "D" is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

C. Buck-Boost Converter -

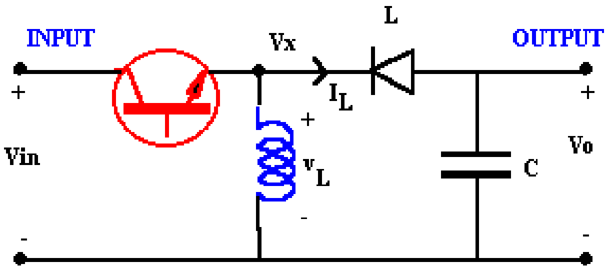

Figure 12: Schematic for buck-boost converter

With continuous conduction for the Buck-Boost converter Vx =Vin when the transistor is ON and Vx =Vo when the transistor is OFF. For zero net current change over a period the average voltage across the inductor is zero

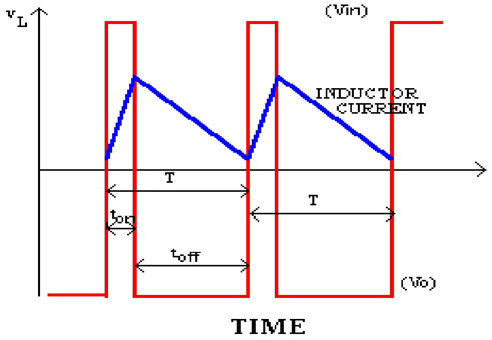

Figure 13: Waveforms for buck-boost converter

$$V_{in} t_{ON} + V_o t_{OFF} = 0 \quad \ldots\ldots\ldots\ldots\ (21)$$

Which gives the voltage ratio

$$\frac{V_o}{V_{in}} = -\frac{D}{(1-D)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (22)$$

And the corresponding current

$$\frac{I_o}{I_{in}} = -\frac{(1-D)}{D} \quad \ldots\ldots\ldots\ldots\ (23)$$

Since the duty ratio "D" is between 0 and 1 the output voltage can vary between lower or higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

D. Converter Comparison - The voltage ratios achievable by the DC-DC converters is summarized in Fig. 10. Notice that only the buck converter shows a linear relationship between the control (duty ratio) and output voltage. The buck-boost can reduce or increase the voltage ratio with unit gain for a duty ratio of 50%.

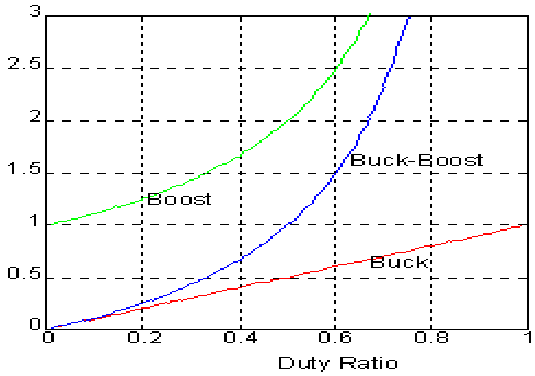

Figure 14: Comparison of Voltage ratio

E. Cuk Converter - The buck, boost and buck-boost converters all transferred energy between input and output using the inductor, analysis is based of voltage balance across the inductor. The CUK converter uses capacitive energy transfer and analysis is based on current balance of the capacitor. The circuit in Fig. below (CUK converter) is derived from DUALITY principle on the buck-boost converter.

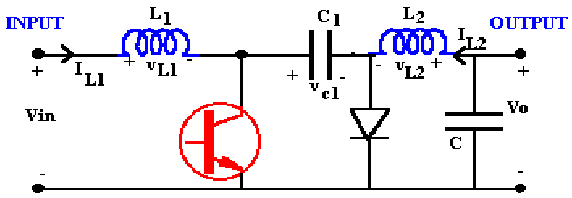

Figure 15: CUK Converter

If we assume that the current through the inductors is essentially ripple free we can examine the charge balance for the capacitor C1. For the transistor ON the circuit becomes

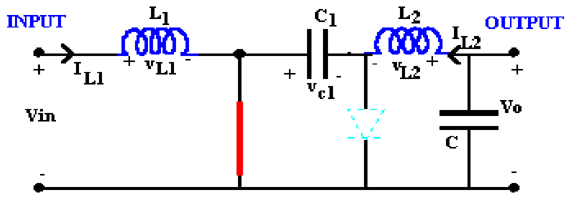

Figure 16: CUK "ON-STATE"

And the current in C1 is I_{L1}. When the transistor is OFF, the diode conducts and the current in C1 becomes I_{L2}.

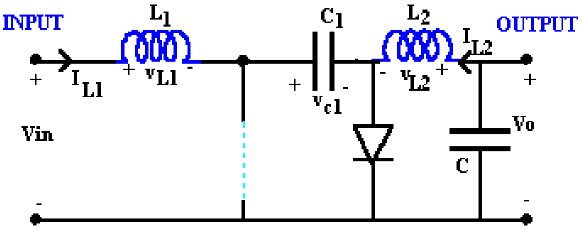

Figure 17: CUK "OFF-STATE"

Since the steady state assumes no net capacitor voltage rise, the net current is zero

$$I_{L1}t_{ON} + (-I_{L2})t_{OFF} = 0 \quad \text{…………… (24)}$$

Which implies

$$\frac{I_{L2}}{I_{L1}} = \frac{(1-D)}{D} \quad \text{…………………….…….. (25)}$$

The inductor currents match the input and output currents, thus using the power conservation rule

$$\frac{Vo}{Vin} = -\frac{D}{(1-D)} \quad \text{…………………....… (26)}$$

Thus the voltage ratio is the same as the buck-boost converter. The advantage of the CUK converter is that the input and output inductors create a smooth current at both sides of the converter while the buck, boost and buck-boost have at least one side with pulsed current.

VI. SYSTEM CONFIGURATION AND MODELING

A. Grid Configuration:

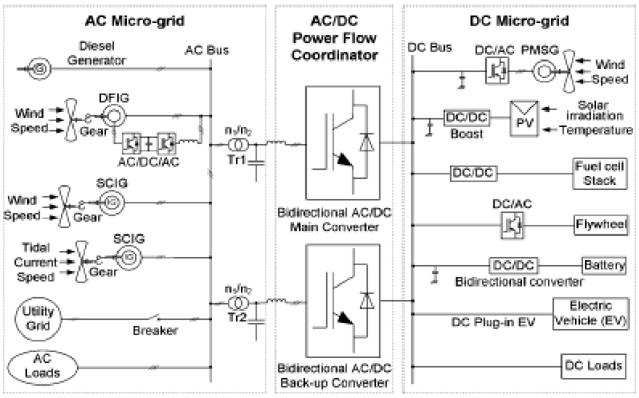

Figure 18: A hybrid ac/dc microgrid system.

Figure 18 shows a conceptual hybrid system configuration where various ac and dc sources and loads are connected to the corresponding dc and ac networks. The ac and dc links are connected together through two transformers and two four-quadrant operating three phase converters. The ac bus of the hybrid grid is tied to the utility grid.

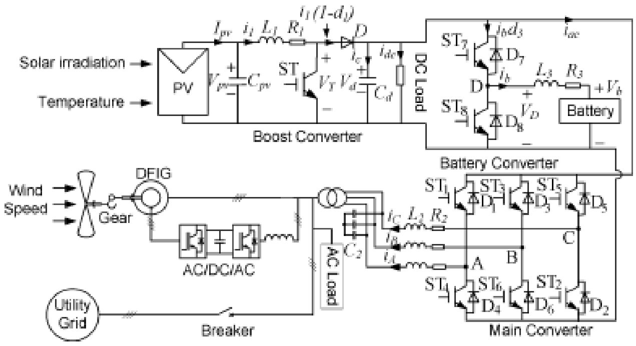

Figure 19: A compact representation of the proposed hybrid grid.

A compact hybrid grid as shown in Figure 19 is modeled using the Simulink in the MATLAB to simulate system operations and controls. Forty kW PV arrays are connected to dc bus through a dc/dc boost converter to simulate dc sources. A capacitor C_{pv} is to suppress high frequency ripples of the PV output voltage.

A 50 kW wind turbine generator (WTG) with doubly fed induction generator (DFIG) is connected to an ac bus to simulate ac sources. A 65 Ah battery as energy storage is connected to dc bus through a bidirectional dc/dc converter. Variable dc load (20 kW–40 kW) and ac load (20 kW–40 kW) are connected to dc and ac buses respectively. The rated voltages for dc and ac buses are 400 V and 400 V rms respectively. A three phase bidirectional dc/ac main converter with R-L-C filter connects the dc bus to the ac bus through an isolation transformer.

B. Grid Operation: The hybrid grid can operate in two modes. In grid-tied mode, the main converter is to provide stable dc bus voltage and required reactive power and to exchange power between the ac and dc buses. The boost converter and WTG are controlled to provide the maximum power. When the output power of the dc sources is greater than the dc loads, the converter acts as an inverter and injects power from dc to ac side. When the total power generation is less than the total load at the dc side, the converter injects power from the ac to dc side. When the total power generation is greater than the total load in the hybrid grid, it will inject power to the utility grid. Otherwise, the hybrid grid will receive power from the utility grid. In the grid tied mode, the battery converter is not very important in system operation because power is balanced by the utility grid.

In autonomous mode, the battery plays a very important role for both power balance and voltage stability. Control objectives for various converters are dispatched by energy management system. DC bus voltage is maintained stable by a battery converter or boost converter according to different operating conditions. The main converter is controlled to provide a stable and high quality ac bus voltage. Both PV and WTG can operate on maximum power point tracking (MPPT) or off-MPPT mode based on system operating requirements. Variable wind speed and solar irradiation are applied to the WTG and PV arrays respectively to simulate variation of power of ac and dc sources and test the MPPT control algorithm.

VII. SIMULATION RESULTS

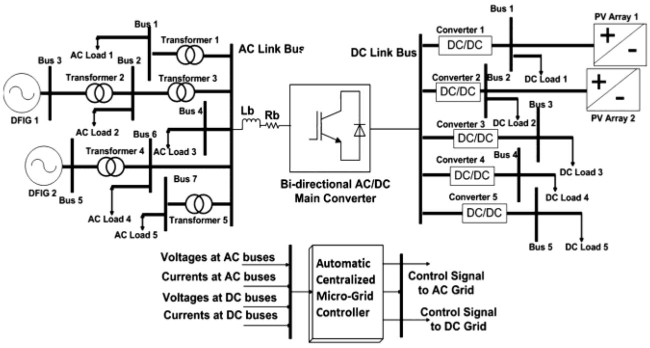

Figure 20: Test system used for case study

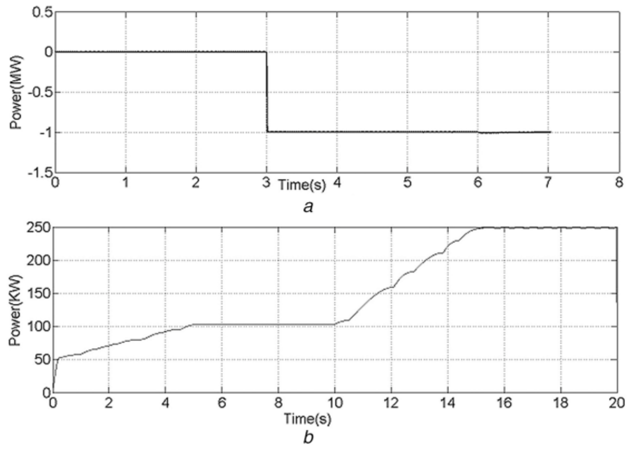

Figure 21: Power generation of renewable sources in the test system

(a) PV output power versus irradiation, (b) DFIG output power versus time

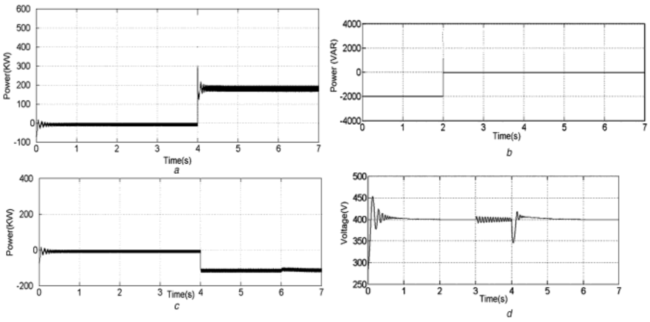

Figure 22: Four quadrant and voltage control operation of ACMC

(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

VIII. CONCLUSION

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. 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.

IX. REFERENCES

[1]. Gellings, C.W., EPRI: ‘DC power production, delivery and utilization’. Available at http://www.powerpulse.net/techPaper.php?paperID=130, accessed November 2015

[2]. Paajanen, P., Kaipia, T., Partanen, J.: ‘DC supply of low voltage electricity appliances in residential buildings’. Proc. CIRED 2009 Conf., June 8–11 2009, pp. 1–4

[3]. Lasseter, R.H.: ‘MicroGrids’. Proc. IEEE Power Engineering Society Winter Meeting, 2002, vol. 1, pp. 305–308

[4]. Baran, M.E., Mahajan, N.R.: ‘DC distribution for industrial systems: opportunities and challenges’, IEEE Trans. Ind. Appl., 2003, 39, (6), pp. 1596–1601

[5]. Hammerstrom, D.J.: ‘AC versus DC distribution systems – did we get it right?’. Proc. IEEE Power Engineering Society General Meeting, June 2007, p. pp. 15

[6]. Ito, Y., Yang, Z., Akagi, H.: ‘DC micro-grid based distribution power generation system’. Proc. IEEE Int. Power Electronics and Motion Control Conf., August 2004, vol. 3, pp. 1740–1745

[7]. Sannino, A., Postiglione, G., Bollen, M.H.J.: ‘Feasibility of a DC network for commercial facilities’, IEEE Trans. Ind. Appl., 2003, 39, (5), pp. 1409–1507

[8]. Liu, X., Wang, P., Loh, P.C.: ‘A hybrid AC/DC microgrid and its coordination 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

[10]. Mohamed, A., Elshaer, M., Mohammed, O.: ‘Bi-directional AC–DC/DC–AC converter for power sharing of hybrid AC/DC systems’. Proc. IEEE Power Engineering Society General Meeting, July 2011, pp. 1–8

[11]. Nilsson, D.: ‘DC distribution systems’. Licentiate of Engineering thesis, Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology, 2005.