A Cuk-Sepic based Modular Design Methodology for Smart Grid Inverters

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***Abstract*--Power supply systems all over the world are facing challenging situations where they have to be extremely flexible, reliable and expandable. Existing grids have to be modified due to the growing proportion of distributed and renewable energy sources. Power electronic inverters are the key components to couple different energy conversion systems and to manage their operation. To fulfill the changing demands of the growing smart grids, new concepts for inverter design are needed. In this paper an innovative concept for future oriented power systems – the modular inverter design - is detailed. A Modular inverter design is presented for a modern power system which inputs power from both AC and DC Renewable resources. The Converter is the combination of Cuk-Sepic converters, the input from the source can be either buck or boosted or stabilized at the particular value, the inductor in circuit further provides the function of filter reducing Harmonics. The Inverter is the combination of two kinds of Inverters and it supports both symmetric and asymmetric loads. System works on the presence of both or any one of the Renewable resources, Furthermore; existing systems can be changed, rescaled and expanded easily. The system senses the load (symmetric or asymmetric) and switches between the Inverters (Three leg inverter or three leg inverter with Neutral point) according to the loads**.

***Index Terms*—Smart grid, Energy Management, Hybrid Power, Interconnected Power Systems, Power Inverters, Power Conversion, Power Generation Reliability, Power System Planning, Pulse Width Modulated Inverter, Design Methodology, System Analysis and Design, DC-AC Power Conversion.**

I. INTRODUCTION

Power generation and power distribution systems worldwide are facing new significant challenges. On the one hand power demand is increasing enormously, caused by the worldwide economical growth. On the other hand the conventional fossil energy sources are limited and running out in close future. Over the last 30 years, global primary energy consumption has almost doubled. These challenges led to vast investigation efforts in the field of renewable energy sources (RES) and therewith towards sustainable and environmentally friendly technologies. These technologies are also able to reduce green house gas emission and therefore became a wide accepted trend in power generation nowadays. Rising fossil fuel prices and convenient national economic conditions support this evolution. The trend in power systems is developing towards distributed generation (DG). This means that the conventional few large power plants are step by step replaced by many small energy conversion systems (ECS), which are located close to the energy consumers. The main DG power sources applied today are e.g. hydropower turbines, wind turbines, biomass power plants, photovoltaic solar systems, and combined heat power (CHP) micro turbines. Also fuel cells, gas micro-turbines, solar-thermo power, as well as hybrid power systems consisting of a combination of different sources are available . Future power systems therefore need to be reliable and easy to maintain. Investigations in the field of renewable energies and distributed generation show that deep technologic changes are still needed [1]-[2].The change towards DG and RES is further pushed forward by the actual ailing status of the existing conventional power plants and distribution systems, which have to be reworked. When a source is unavailable or insufficient in meeting the load demands, the other energy source can compensate for the difference. Several hybrid wind/PV power systems with MPPT control have been proposed and discussed in works [3]-[6]. Most of the systems in literature use a separate DC/DC boost converter connected in parallel in the rectifier stage as shown in Figure 1 to perform the MPPT control for each of the renewable energy power sources [3]-[4]. A simpler multi-input structure has been suggested by [7] that combine the sources from the DC-end while still achieving MPPT for each renewable source. The structure proposed by [7] is a fusion of the buck and buck-boost converter. The systems in literature require passive input filters to remove the high frequency current harmonics injected into wind turbine generators [8]. The harmonic content in the generator current decreases its lifespan and increases the power loss due to heating [8]. Since the power system is continuously changing regarding the structure, the sources and the loads, the development of very flexible ECS integration concepts is necessarily needed. These concepts need to be adaptable to every supply situation with minimal effort in design and implementation. The inverter is considered as the essential component in optimization of RES and distributed energy resources (DER), since it is the active control element at the connection point between the sources and the grid or loads. Developments in the field of power electronic devices in combination with modern control strategies for inverters offer a variety of operation strategies for efficient system management.

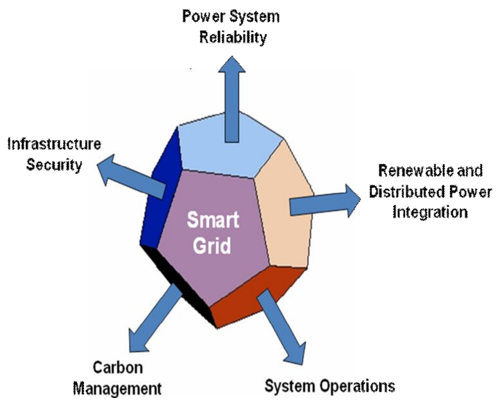

Figure 1. Functions of Smart Grid

In this paper, an alternative multi-input rectifier structure is proposed for hybrid wind/solar energy systems. The proposed design is a fusion of the Cuk and SEPIC converters and inverters are switched automatically according to the load *The Inverter systems supports both symmetric and asymmetric loads.* The features of the proposed topology are: 1) the inherent nature of these two converters eliminates the need for separate input filters for PFC 2) it can support step up/down operations for each renewable source (can support wide ranges of PV and wind input); 3) *System works on the presence of both or any one of the Renewable resources*; 4) individual and simultaneous operation is supported. The circuit operating principles will be discussed in this paper. Simulation results are provided to verify with the feasibility of the proposed system.

II. CUK – S EPIC MULTI INPUT RECTIFIER

A system diagram of the proposed rectifier stage of hybrid energy system is shown in Fig. 2, where one of the inputs is connected to the output of the PV array and the other input connected to the output of a generator. The fusion of the two converters is achieved by reconfiguring the two existing diodes from each converter and the shared utilization of the Cuk output inductor by the SEPIC converter. This configuration allows each converter to operate normally individually in the event that one source is unavailable. Fig. 3 illustrates the case when only the wind source is available. In this case, $D1$ turns off and $D2$ turns on; the proposed circuit becomes a SEPIC converter and the input to output voltage relationship is given by (1). On the other hand, if only the PV source is available, then $D2$ turns off and $D1$ will always be on and the circuit becomes a Cuk converter as shown in Fig. 4. The input to output voltage relationship is given by (2). In both cases, both converters have step-up/down capability, which provide more design flexibility in the system if duty ratio control is utilized to perform MPPT control.

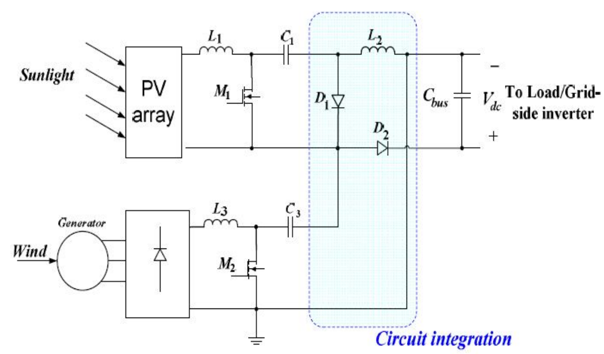

Figure 2 Cuk – Sepic Based Converter on Source side

Figure 6 illustrates the various switching states of the proposed converter. If the turn on duration of $M1$ is longer than $M2$, then the switching states will be state I, III. Similarly, the switching states will be state I, II, III if the switch conduction periods are vice versa. To provide a better explanation, the inductor current waveforms of each switching state are given as follows assuming that $d2 > d1$; hence only states I, II, III are discussed in this example. In the following, $I_{i,PV}$ is the average input current from the PV source; Ii, W is the RMS input current after the rectifier (wind case); and Idc is the average system output current. The key waveforms that illustrate the switching states in this example are shown in Fig.5, the mathematical expression that relates the total output voltage and the two input sources are shown below (11).

$$\frac{V_{dc}}{V_W} = \frac{d_2}{1-d_2} \qquad (1)$$

$$\frac{V_{dc}}{V_{PV}} = \frac{d_1}{1-d_1} \qquad (2)$$

State I (M_1 on, M_2 on)

$$i_{L1} = I_{i,PV} + \frac{V_{PV}}{L_1}t \qquad 0<t<d_1T_s \qquad (3)$$

$$i_{L2} = I_{dc} + \left(\frac{v_{c1}+v_{c2}}{L_2}\right)t \qquad 0<t<d_1T_s \qquad (4)$$

$$i_{L3} = I_{i,w} + \frac{V_w}{L_3}t \qquad 0<t<d_1T_s \qquad (5)$$

State II (M_1 off , M_2 on)

$$i_{L1} = I_{i,PV} + \left(\frac{V_{PV}-v_{c1}}{L_1}\right)t \qquad d_1T_s <t< d_2T_s \qquad (6)$$

$$i_{L2} = I_{dc} + \frac{v_{c2}}{L_2}t \qquad d_1T_s <t< d_2T_s \qquad (7)$$

$$i_{L3} = I_{i,w} + \frac{V_w}{L_3}t \qquad d_1T_s <t< d_2T_s \qquad (8)$$

State III (M_1 off , M_2 off)

$$i_{L1} = I_{i,PV} + \left(\frac{V_{PV}-v_{c1}}{L_1}\right)t \qquad d_2T_s <t< T_s \qquad (9)$$

$$i_{L2} = I_{dc} - \frac{V_{dc}}{L_2}t \qquad d_2T_s <t< T_s \qquad (10)$$

$$i_{L3} = I_{i,w} + \left(\frac{V_w - v_{c2} - V_{dc}}{L_3}\right)t \qquad d_2T_s <t< T_s \qquad (11)$$

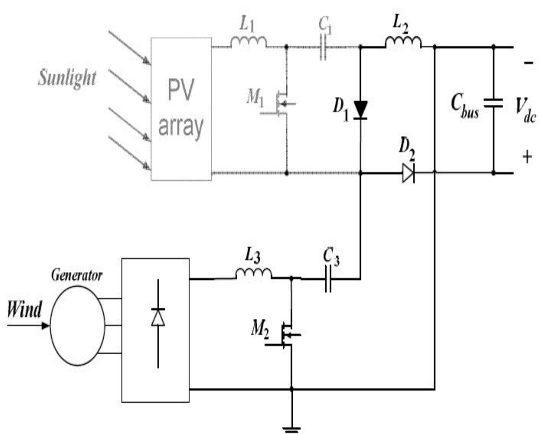

Figure 3 Sepic Converter (Wind source available)

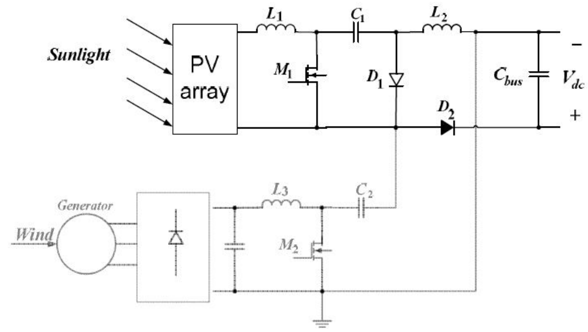

Figure 4 Cuk Converter (PV source available)

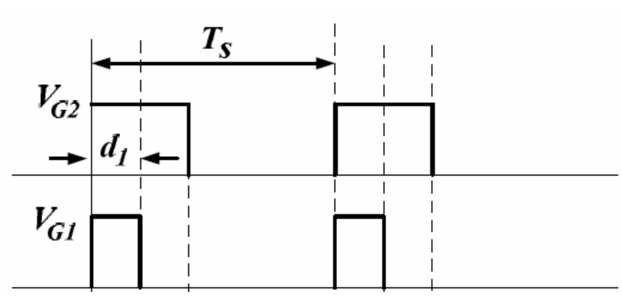

Figure 5 Switching Pulses V_{G2} & V_{G1}

$$V_{dc} = \left(\frac{d_1}{1-d_1}\right)v_{PV} + \left(\frac{d_2}{1-d_2}\right)v_W \qquad (12)$$

III. SIGNIFICANCE OF MODULAR INVERTERS

Conventional three phase inverter system structures are fixed in size and function and offer only limited flexibility demands and to be more versatile in production and development, a new standardized system concept with modular structure is needed. Modularity basically means a segmentation of the complex structures into functional groups. In this way the main components of an inverter structure can be subdivided and the resulting modules can be treated as stand alone systems. By use of standardized interfaces these separated modules can be scaled independently. The result is an inverter system that is completely adaptive regarding size, components, configuration and the operating control. The system is flexible to be quickly adapted and optimized for any application demands. Modularity or modular design is the subdivision of a complex system into smaller units (modules) with basic functionalities. These modules can then be used in different systems with multiple functionalities. Fig. 6 shows the basic principle of modular design. A module pool keeps different discrete modules that can perform defined discrete tasks or functions. To connect any modules in a free selectable order and topology, standardized interfaces have to be defined to react on linked neighbor modules and hand over information to them. Production costs are reduced by completely independent manufacturing of the various modules. Furthermore, modular design offers additional benefits such as augmentation and exclusion. An existing system can be enlarged, updated, modified or pared down in functionality by adding or excluding new sub functional modules.

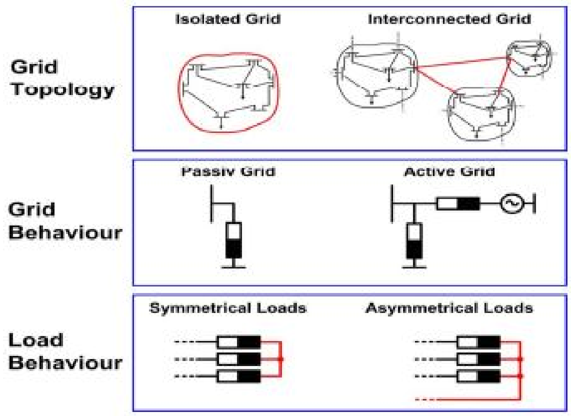

Figure 6 Various Grid Behavior

IV. PRINCIPLE TO DESIGN MODULAR INVERTERS

The basic principle of modularity can be applied to the two main fields of inverter design, the hardware and the software design. Although these design fields are functional closely related to each other, they can be more or less decoupled in design by standardized interfaces or e.g. by the use of per unit (pu) or standardized values for communicated data. In the underlying project, the modular approach has been applied to the design of an exemplary inverter system the applied modularity will now be detailed. At this point it has to be mentioned that the level and depth of modular design applied to inverters, but also to any other system, always depends on the product range of the manufacturer and the applications to be covered by the designed systems. The more complex a system is and the more functions it has to perform, the higher the level of modularity should be.

The characteristic of the inverter load regarding the symmetry is one of the main influencing factors of the desired power electronic inverter topology. The inverter topology for Symmetrical loads are shown in Fig 7. This basic inverter is built of three IGBT legs. Each of the legs is generating the voltage for one grid phase by pulsing the intermediate circuit voltage. For asymmetrical loads two strategies are commonly applied. The three leg inverter with a neutral point Fig 8 is a combination of three single phase inverters sharing a common neutral line. The neutral line is connected to the mid-point of a common intermediate circuit built by two capacitors These characteristics lead to different hardware topologies and also different control modes that have to be implemented regarding to the environment conditions of the inverter on its primary and secondary side. As stated in the introduction, most inverters are fixed in their power rating and functionality. Future inverters, however, need to be able to adapt changing source and load situations.

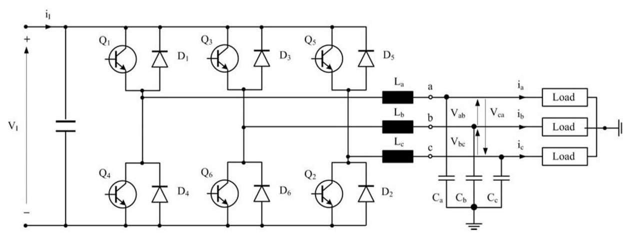

Figure 7 Three-leg Inverter

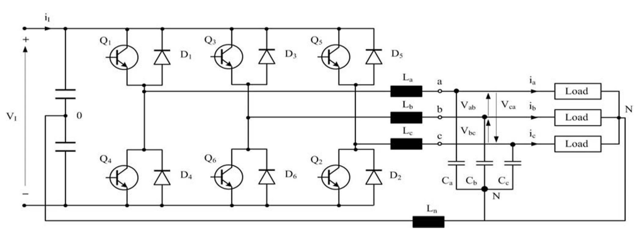

Figure 8 Three-leg Inverter with neutral point

V. MODULAR INVERTER SPECFICATIONS

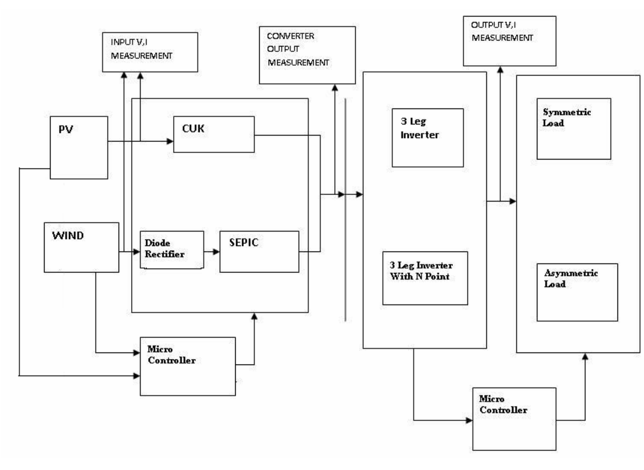

Figure 9 Modular Inverter Blocks

All basic inverter topologies are built of a couple of main functional elements. The selection and composition of these elements is mainly based on the type and behavior of the ECS as well as the grid which the inverter is connected to. The basic components needed to operate any ECS and grid type are shown in Fig. 9 Three main module pools can be built. These are the converter, the intermediate circuit and the switch topology module pool. By selection of modules from these three module pools any typical basic inverter topology can be set up in hardware. The converter module pool itself contains DC/DC converters to adjust the voltage level of DC ECS to the intermediate circuit voltage and to actively control the DC sources. Passive and active rectifiers of this pool are able to connect AC sources to the intermediate circuit. The intermediate circuit pool keeps two different module types The circuits are the standard two level intermediate circuits built by one capacitor and the three level intermediate circuits with divide the intermediate circuit voltage in halves by the use of two series capacitors. The third wire in this case is connected to midpoint between the two capacitors. A chopper circuit is available for all intermediate circuit modules. It is closely linked to the intermediate circuit and will not be treated as separated module because of security aspects.. The inverter topology for symmetrical loads is This basic inverter is built of three IGBT legs either three leg inverter or Three leg inverter with neutral point.

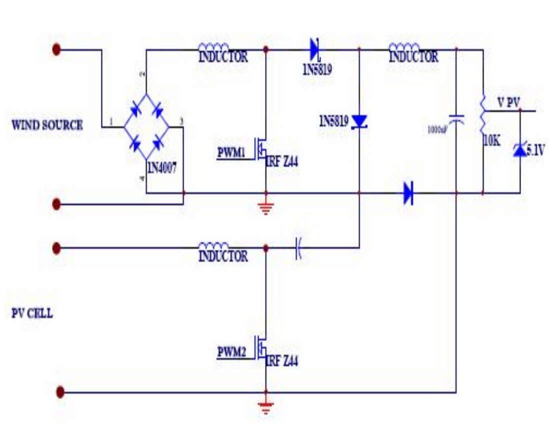

Figure 10 Schematic diagram of converters

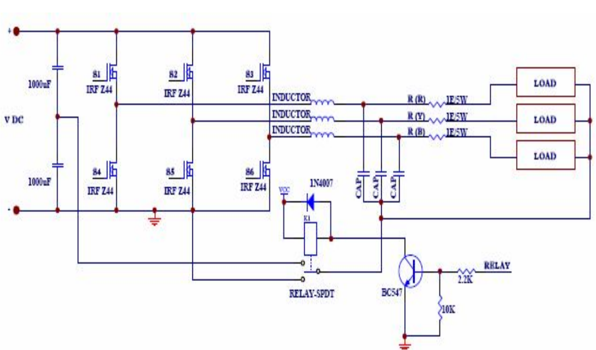

Figure 11 Schematic diagram of Inverter Load and Switching Circuits

VI. TEST SIMULATION AND RESULTS

Inverter system was simulated using MATLAB/SIMULINK .The system was finally tested under common ECS and grid conditions and with different loads. The designed inverter is able to handle AC and DC sources as inputs. Symmetrical and asymmetrical load situations were successfully handled by application of three-leg, three leg four-wire IGBT bridge configurations. The intermediate circuit was adjusted to these different switch topologies.

The test installation is set for a 3 phase system with a frequency of 50Hz. the applied switching frequency was 10 kHz, the PWM output mode was symmetrical PWM. Balanced load with a resistance of 50 Ω at all phases. The inverter output voltages are a nearly undisturbed three phase signal in amplitude and phase while the current is increased in phase “a”, due to the load step. In this case an unbalanced resistive-inductive load was placed. All phases were set to 50 Ω initially, while phase “a” includes a 3 mH inductance in series as well. An unsymmetrical load step from 50 Ω to 25 Ω in phase “a” was performed. The quick reaction of the modular inverter control to the load step can be seen.

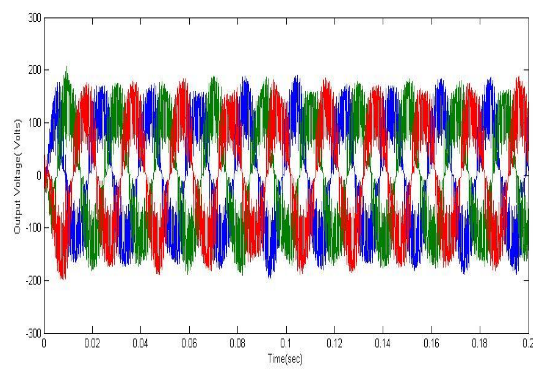

Figure 12 Symmetrical Load: Output voltage

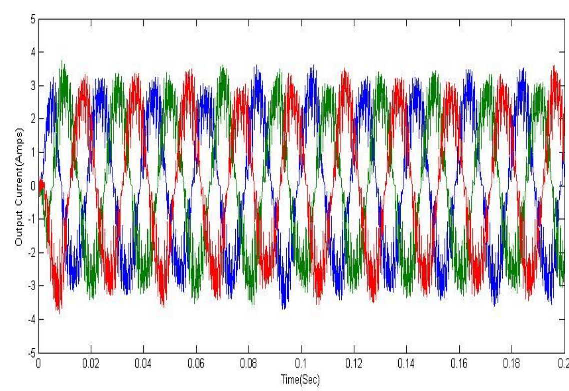

Figure 13 Symmetrical Load: Output Current

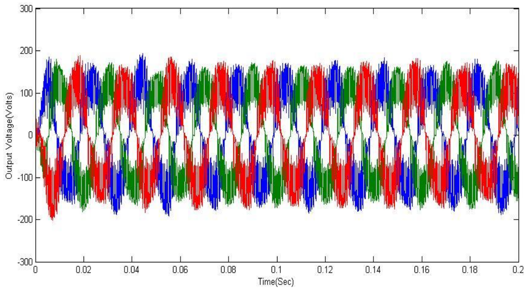

Figure 14 Asymmetrical Load: Output Voltage

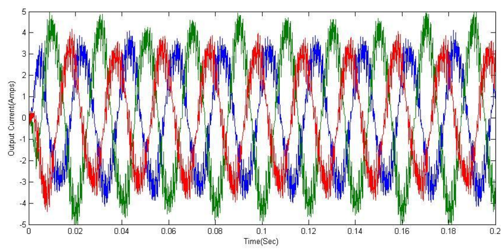

Figure 15 Asymmetrical Load: Output Current

VII. CONCLUSION

This modular design strategy has successfully been tested under various source and load conditions. The result of the presented approach is a powerful inverter system that is completely adaptive regarding size, components, configuration and the operating control. The system is flexible to be quickly adapted and optimized for various applications. in case of any faults single defective modules can easily be replaced without long downtime. Modular inverter design therewith safes efforts and time in maintenance and repair. new multi-input Cuk-SEPIC rectifier stage additional input filters are not necessary to filter out high frequency harmonics; both renewable sources can be stepped up/down (supports wide ranges of PV and wind input); MPPT can be realized for each source; individual and simultaneous operation is supported. Simulation results have been presented to verify the features of the proposed topology. With the proposed design methodology, inverter systems can further be changed, rescaled, integrated and expanded easily by adding new functional groups.

VIII. REFERENCES

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