in turn comprised individual PV cells. Each PV cell is actually a very thin semiconductor wafer of photosensitive silicon or selenium that has been “doped” with boron (positively-charged, p-type material) and phosphorous (negatively-charged, n-type material) to increase its electrical conductivity to a level that is sufficiently for the cell to distribute charge and induce an electric field.

By themselves, PV modules or arrays do not represent an entire PV system. Systems also include structures that point them toward the sun and components that take the direct-current electricity produced by modules and "condition" that electricity, usually by converting it to alternate-current electricity. PV systems may also include batteries and/or back-up generators. These items are referred to as the balance of system (BOS) components. Combining PV modules with BOS components creates an entire PV system. A system is usually everything needed to meet a particular energy demand, such as an industrial appliance, the lights in a home, or – if the system is large enough – the electrical demand of an entire community. A BOS may also include any or all of the following: a renewable energy credit revenue-grade meter, a maximum power point tracker (MPPT), a battery system and charger, a GPS solar tracker, energy management software, solar irradiance sensors, and an anemometer.

Flat panel systems account for the majority of renewable energy installations in the United States. At any given location on a clear day, the amount of sunlight striking the earth’s surface is equivalent to approximately 1,000 watts of power per square meter [1]. A single, flat panel is composed of at least 600 PV cells and can produce between 5 to 300 volts of electrical power depending on sunlight exposure. One panel alone is rarely sufficient for home or industrial applications, so multiple panels are wired together in series, parallel, or series-parallel topologies to create the large PV arrays that most people associate with “solar power.” Most commercially available PV systems can deliver voltage magnitudes in multiples of 12 volts and current magnitudes in multiples of 3 amps. Roof installations of PV arrays – facilitated by simple and versatile mechanical brackets – are most common among home and business consumers, although an increasing number of business/industrial consumers are installing solar panels on large tracts of open land – such as land that has been contaminated and is un-developable.

The feeding of electricity from a PV system back into the grid requires the transformation of DC power into AC by a synchronizing grid-tied inverter. Modern inverters used in this capacity are quite effective; they allow the PV array to operate at the maximum power point (MPP) under all conditions, they generate AC output current in phase with the AC utility grid voltage, and they achieve a power conversion efficiency of nearly 100%. In some cases, the inverter even provides energy storage to balance the power difference between the PV array (DC power) and the AC (time-domain) power of the grid.

3. Wind Turbine Systems

A wind power system relies on the fluid flow of air to apply a force on its rotor blades, causing the turbine to rotate; the system will then convert the rotational kinetic energy of the turbine into DC electricity via an electric generator. The two critical factors for power generation are wind speed and the quality of wind. Environmental (buildings) and atmospheric factors (turbulence) can interfere with the available wind; thus wind turbines are most efficient when constructed in elevated, open areas.

The primary difference between wind and solar systems is that wind systems convert pure mechanical (kinetic) energy into electrical power, whereas solar systems rely on chemical reactions and thermal properties to generate electrical power. Consequentially, the physical design of a wind turbine is far simpler than something like a PV array. A wind turbine’s most visible components are its blades, which are aerodynamically designed to capture the maximum amount of the wind’s kinetic energy. The blades turn a rotor, which in turn rotates a shaft.

Ultimately, the most important part of any wind turbine is its generator, which is driven by the shaft and functions similarly to an electric motor. The generator consists of a rotor and a stator; the wind turbine’s shaft is connected to the rotor such that it causes the rotor to spin, creating (inducing) a rotating magnetic field within the stator (stationary portion of the motor). This induced magnetic field (B) effectively rotates the North-South poles of the stator, which “pulls along” the loops on the armature (rotor) windings, ultimately causing the armature to “follow” the rotation of the field and create an electromotive force (E) that is harnessed as electrical power.

4. Hybrid PV/Wind Micro-grids

When a reliable grid can be accessed from the location at which renewable energy sources are being used, it is common for excess power generated by those renewable sources be fed into the main power grid. This allows consumers to save money on their electric bills because they are generating power for the electric company. Feeding some amount of renewable-sourced power back into the grid is also a common practice because batteries are one of the most expensive components in renewable systems’ designs. Batteries take up space, need to be properly stored, require extra circuitry for control purposes, and even after all of that, they will still eventually need to be replaced.

Although grid connection is a more common practice than battery storage, there are some challenges and considerations to take into account when connecting a renewable system to the main grid. The first challenge is making sure that the hybrid system will be able to reliably output the same voltage and frequency, so as to input that voltage and/or frequency into the grid on a

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continuous cycle. This is especially important for the grid side of the system, because if the voltage and frequency are not what they needs to be, then there will be a loss of power quality within the grid. In a PV-wind hybrid system, the power generated from both wind and solar components is stored in a battery bank for later use, thus increasing the reliability of the system. In some cases, the size of the battery storage may be slightly reduced compared to a pure-solar or pure-wind system, because the system is capable of generating power from more than one source. Wind speeds are often low in periods when the sun resources are at their best (summer). The wind is often stronger in seasons when there are fewer solar resources (winter). Even during the same day, in many regions worldwide or in some periods of the year, there are different and opposite patterns in terms of wind and solar resources. Additionally, these different patterns can render the hybrid systems the "best of both worlds" for power generation.

One potential drawback of the hybrid PV-wind systems is that they carry a significantly higher up-front cost than pure-solar or pure-wind systems. However, the PV-wind hybrid system offers the greatest return on investment (ROI) in terms of output and performance achieved per dollar invested.

Figure 1 presents a basic overview (block diagram) of the intended micro grid system. The proposed design of the energy conversion power electronic circuit consists of a combination of the Cuk converter and Single-Ended Primary Industry Converter (SEPIC).

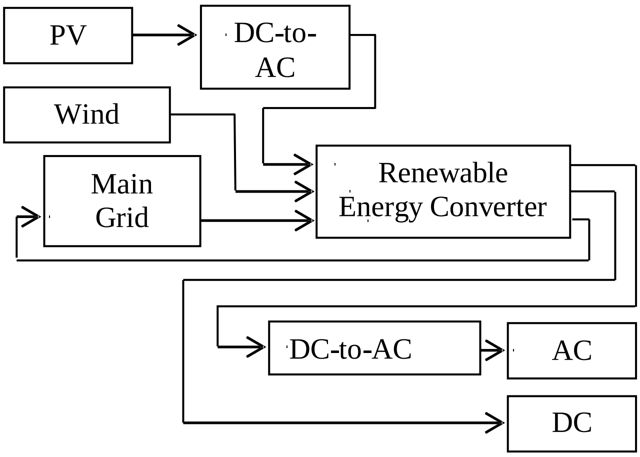

Figure 1: Block diagram of the ybrid PV/Wind system

5. Multi-input Converters

In hybrid solar/wind energy system, 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. [3] This configuration allows each converter to operate individually in the event that one source is unavailable.

Figure 2 illustrates the case when only the wind source is available. In this case, the proposed circuit becomes a SEPIC converter. If only the solar source is available, the circuit configuration becomes a Cuk converter as shown in Figure 3. In both cases, both converters have step-up/down capability, which provides more design flexibility in the system where duty ratio in turn is utilized to manage MPPT control.

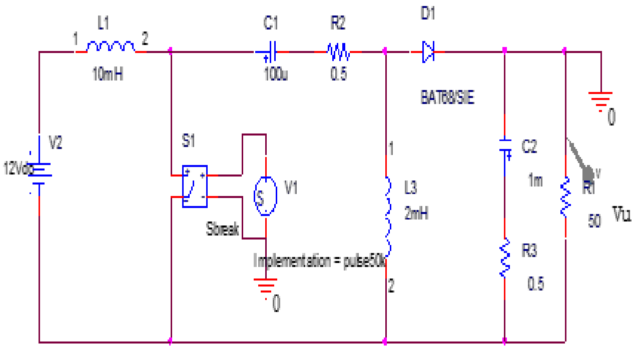

Figure 2: SEPIC converter operating under wind source

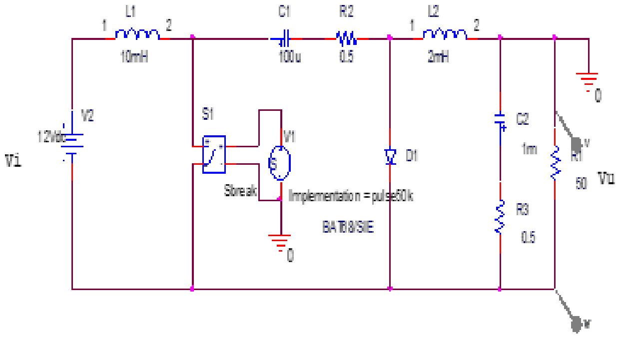

Figure 3: Cuk converter operating under solar source

A Boost-Inverter hybrid is conceptually simpler – amplify the input DC voltage with the Boost converter, and then invert it to an AC signal to drive the load – but mechanically more complex. The converter and inverter must be constructed in parallel to each other, which decreases the system's overall efficiency (measured in terms of power transfer, P_{out} / P_{in}).

With consideration given to the practical advantages and disadvantages of each converter topology, as well as to the commercial availability of components in the US, it is advisable to use the Cuk-SEPIC converter for this and any stand-alone Microgrid application.

Within the Cuk-SEPIC converter, it is necessary to include integrated circuits for both AC-to-DC rectifiers and DC-to-AC inverters. Depending on the characteristics of a system's input voltages (AC or DC, magnitude, and phase), rectifiers will be needed to step up or step down the voltage so that it is suitable to drive the load. Similarly, inverters will be needed to transform any DC signal into an output that is compatible with an AC load.

There are two widely-accepted rectifiers for renewable energy applications: (1) a switching power supply, and (2) integrated microcontrollers. The latter option increases the cost of the rectifier considerably and does not yield noticeably better results, so the use of a switching power supply is recommended for most renewable energy applications. For a Cuk-SEPIC topology, the pairing of the two converters is possible because the existing diodes are reconfigured such that the SEPIC converter shares the Cuk converter's output inductor as given in Figure 4 [4]. This topology is advantageous because it does not require any low-pass filters between the DC inputs and the hybrid converter, which were utilized in previous designs to eliminate high-frequency harmonics.

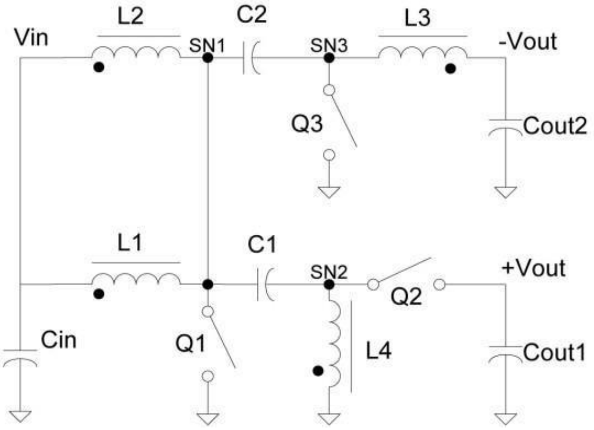

Figure 4: Cuk-SEPIC Converter Circuit Integration for Hybrid Solar/Wind Systems

6. Flat Panel PV Array Simulation

When simulating the flat panel photovoltaic system, it is important to first consider the theory. In particular, the PV modules' equivalent circuit design, open-circuit voltage, and power and I-V curves under specified standard test conditions (STC). STC for a typical PV module is generally taken as 1000 W/m^2 irradiance, 25°C temperature, and 1.5AM air mass [3].

The equivalent circuit for a standard PV module is given in Figure 5, and it is derived from the physics of current generation, but for the purposes of this simulation it is most important to consider the electrical calculations relating to the actual application in real systems.

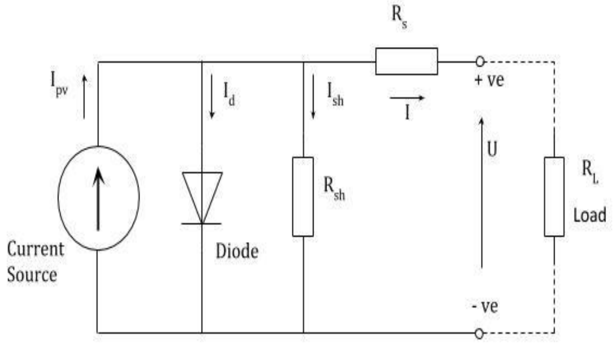

Figure 5: PV Module Equivalent Circuit

The Matlab simulation performed utilized a pre-published, detailed example file for a grid-connected, flat panel PV system. The example file was scripted for a 100-kW PV array connected to a 25-kV grid via a DC-DC boost converter and a three-phase (3φ), three-level (3L) VSC. When run in Simulink, the example file specified 66 parallel strings of 5 series-connected PV cells, with each cell capable of delivering a power output of 305.2-W at STC. Specifications also included: V_{OC} = 64.2-V; I_{SC} = 5.96-A; V_{MPP} = 54.7-V; and I_{MPP} = 5.58-A.

7. Battery Storage Considerations

The available power from the PV system is highly dependent on solar radiation. To overcome this deficiency, the PV module was integrated with the wind turbine system that requires a Cuk-SEPIC converter. Towards this. When operating a PV, wind, or hybrid system, there are times when more power will be generated than what is needed to drive the load. In such a case, the extra power can be stored in a battery bank. Even in the case of a grid-connected system, a battery back-up is often preferred.

Battery specifications to consider when designing a PV system include the charge/discharge cycle history, ambient temperature, and battery age. Lead-Acid batteries must not be overcharged, in order to avoid hydrogen particles to separate from the oxygen. Overcharging will cause the battery to start gassing, which results in water loss. Water loss will decrease the battery's charging efficiency and reduce the battery's operating life. Similarly, Lead-Acid batteries should not be undercharged because undercharging makes them susceptible to freezing, which also shortens their operating life.

Many PV, wind, or hybrid systems are "sized" or rated in terms of their battery capacity. Ideally, a battery bank should be sized to provide power to a load for up to five days during inclement weather conditions [5]. If the battery bank is smaller than a three day capacity, the battery will be deep-cycling on a regular basis, which will shorten its operating life.

Lead-acid batteries are used most frequently in PV systems, and various types include starting batteries, RV or marine "deep cycle" batteries, lead-calcium (Pb-Ca) batteries, and true deep-cycle batteries. A true deep-cycle battery is a battery that delivers on average a few amperes of current to the load for hundreds of hours between charges. In contrast, shallow-cycle batteries deliver hundreds of amperes to a load in a very quick amount of time and then the battery is recharged, making them ideal for automobile applications [5].

Many systems also incorporate a charge controller to assist in controlling the charging and discharging states of a battery. For example, a charge controller can be designed where the low voltage disconnect (LVD) will go into effect when the battery is going to fall below a 20% charge. When the LVD in engaged, the battery will be disconnected from the load until the battery has been charged to an appropriate level. A high voltage disconnect (HVD) also exists in charge controllers and is used to detect when the battery is fully charged. When a battery is fully charged, the HVD will go into effect and limit the amount of current that flows to the battery. True deep-cycle batteries are ideal for PV systems because they can go through hundreds or even thousands of cycles if the battery is properly cared for.

Batteries are the key element for the storage of extra power generated from renewable energy systems, and they are most critically useful in remote and rural locations where a grid connection is not available. The inclusion of a battery bank in any system's design will ultimately save the consumer money as a long-term investment.

8. Grid-Tied Hybrid System Simulation

The hybrid system operates on dual three-phase, 60Hz input signals. The wind turbine inputs an AC signal, while the PV array inputs a DC signal that must be inverted prior to the load bus. The two AC signals are joined at the load bus, which feeds into the main grid and/or an alternate AC load given in Figure 6. The hybrid model outputs a significant amount of data to the Matlab workspace, which is vital for system analysis and proof of concept before construction. To prove the hybrid model's precision, separate simulations were run for the PV array and the wind turbine, with each being simulated under stand-alone and grid-connected conditions. In all four of these cases, the Simulink model compiled and the simulation ran smoothly and without errors.

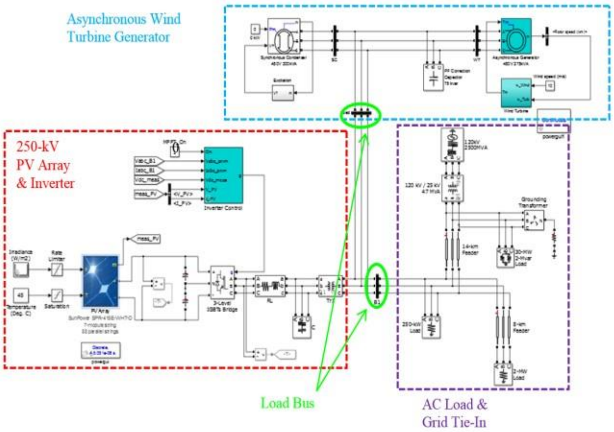

Figure 6: Complete Simulink Model of the Hybrid System

The use of a full• bridge inverter is overwhelmingly favored for renewable energy applications, although a half-bridge inverter may also be used , depending on the specifications of the system and the availability of components. Any renewable energy system that includes a PV array must also include an inverter, due to the array's DC output and the strong likelihood of an AC load or main grid connection. Figure 7 shows a full• bridge inverter simulation output. For commercial applications, an AC oscillation frequency of 60 Hz is preferred. The quality of an inverter is deter• mined by the smoothness of its 60 Hz signal, with better quality inverters yielding smoother signals. The more noise that is present in an inverter's output signal, the less power transfer that inverter can achieve.

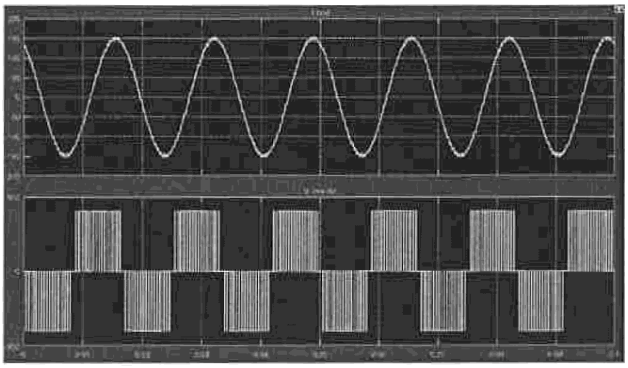

Figure 7. Simulink Scope for Full-Bridge Inverter Output

In general, as supported by figure 7, a full-bridge inverter will output a higher quality signal than a half-bridge inverter, which is why full-bridge inverters are preferred for renewable energy and power electronics applications. All the rest of the simulation results were in line with the theoretical calculations for both the photovoltaic and wind energy systems.

9. Conclusion

The available power from the PV system is highly dependent on solar radiation. To overcome this deficiency, the PV module was integrated with the wind turbine system that requires a Cuk-SEPIC converter. Towards this end, a new multi-input Cuk-SEPIC converter stage for hybrid wind/solar energy systems has been presented. By implementing this converter, we can increase the power transfer efficiency, and we can extract maximum power from the hybrid system without any interruption.

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