Chapter 21

Inverter Grid Connection for Embedded Generation

Distributed Generation (DG, or embedded generation) is a back-up electric power generating unit at or near the consumer premises that primarily is used by the energy user to provide emergency power when grid-connected power is unavailable. Installation of the back-up unit close to the demand centre avoids the cost of transmitting the power and the associated transmission losses. Back-up generating units are currently defined as distributed generation to differentiate from the traditional centralized power generation model. Although the centralized power generation model is economical and a reliable source of energy production, the lack of significant increase in new build generating capacity or even in expanding existing ones to meet the needs of current demand, presents a challenge to the electrical power industry, needing a solution.
The smart grid concept encompasses reliable and efficient electrical energy delivery when harnessing generation from renewable energy sources; for which power electronics is the enabling technology.

21.1 Distributed generation

A typical DG energy conversion system comprises two main energy converting stages. The first stage is the prime fuel converting block in which the prime fuel internal energy is converted into mechanical energy, as in the case of internal combustion engines. The second stage converts the mechanical energy into electrical power using an electromechanical energy conversion device such as synchronous alternator or induction generator, which produces AC power.
Another way of converting a prime fuel source into electrical energy is through a chemical or photosynthesis conversion process. Fuel cells and photovoltaic solar energy converters are examples that produce DC power. The interfacing unit is essential to convert the produced DC source into a harmonized constant voltage and frequency AC power source. A DC to AC power electronic inverter system is used as the interfacing unit. The inverter must produce high quality AC power with a voltage waveform of limited supply frequency fluctuation and low THD at the point of common coupling (PCC), in accordance with the appropriate standard. The inverter must be capable of preventing the DG from islanding (anti-islanding capability) on the hosting grid. Islanding is a condition occurring when a generator or an inverter and a portion of the grid system separates from the remainder of the large distribution system and continues to operate in an energized state. Islanding may pose a safety threat or cause equipment problems; therefore cannot be permitted without system coordination.
The inverter output produced must comply with hosting grid electricity voltage and frequency standards. A coupling transformer is needed to interface the DG generator with the grid to match the distribution voltage level at the point of connection. Only when it is safe and synchronised conditions exist is the DG interconnected with the permission and coordination of the grid operator.

Another configuration normally adopted for supplying power to sensitive electrical load demand is to use DG in conjunction with an uninterruptable power supply, UPS unit. A UPS system normally incorporates an energy storage medium such as batteries to enable power supply continuity as well as improve power quality and reduce the influence of voltage surges, spikes and swells which could cause loss of production.

Once the interconnection is established, the hosting utility assumes responsibility of DG operation and contribution, and treats it as part of its generation system.

Current DG/distribution network interconnected system practice is to revert the distribution network to its original configuration (radial or meshed distribution system) with all interconnected DG units de-energized whenever an unexpected disturbance occurs in the system. Since most distribution systems comprise radial feeders, this leads to supply discontinuation for all the down-line customers. In this way the DG contribution is restricted to the hosting utility demand and conditions.

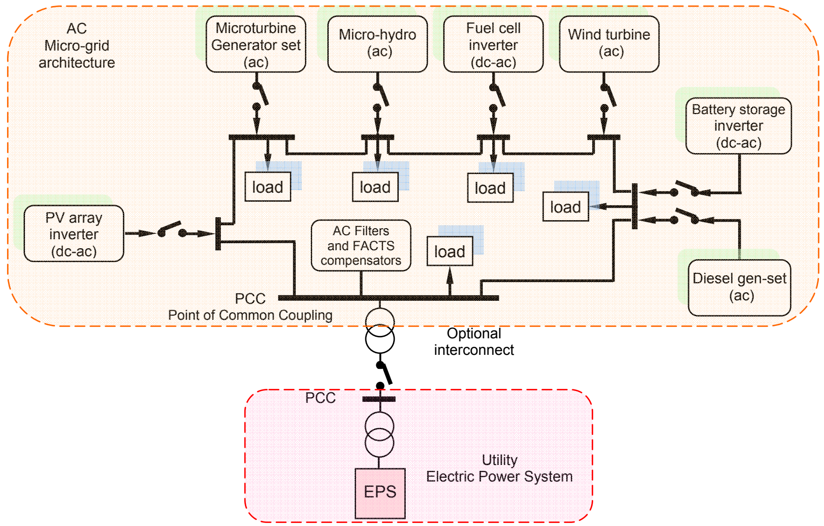

Figure 21.1. *AC microgrid architectural structure.*

21.1.1 DG Possibilities

DG is attractive for the following opportunities:

- DG can be fuelled by locally available renewable and an alternative mix of fuel sources to meet current energy demand. Renewable sources are wind and solar, while alternative fuels are those produced from waste products or biomass and can be in gas, liquid or solid form. Greater independency from importing petroleum fuel can be achieved by incorporating DG that is powered by various fuel sources;
- DG can support the projected increase in demand, without investment in the expansion of existing distribution network, by installing the DG close to a new load centre;
- Installing DG within the industrial/commercial premises avoids negotiating land use and the need for rights-of-way for electric transmission and distribution, thereby minimizing further capital investment;
- DG can be used in reducing intermittent and peak supply burdens on utility grids by injecting power as required by the controller;
- DG has the ability to support the existing energy supply when needed and in a short time (black start) without incurring capital cost;
- DG penetration in the energy market will create overall competitive pricing of energy. The current DG generation rate ($/kWh) is competitive with the centralized generation system as more efficient fuel energy conversion units such as fuel cells and micro turbines are continuously improved and diversified;
- DG can decrease electric distribution system vulnerability to external threats and hidden undetected faults that may cause blackout by feeding power to the sensitive infrastructure;

- DG is flexible, being capability of being configured to operate in a stand-by mode, isolated mode, or sharing the load through integration with the electric grid.

Using DG that is fuelled by various prime alternative fuel sources will reduced fossil fuel consumption hence reduce CO_2 emissions.

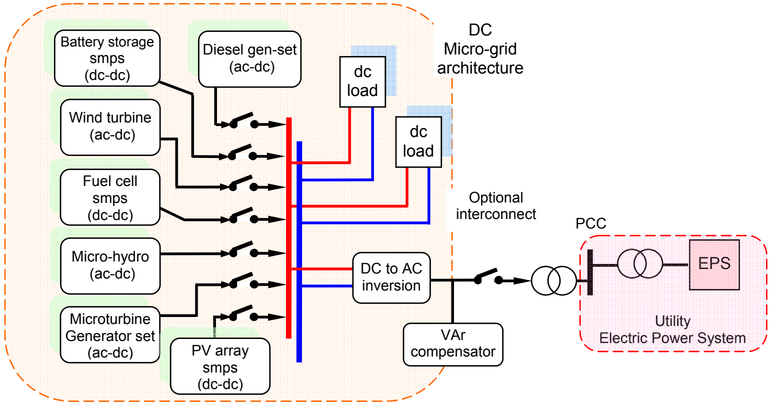

Figure 21.2. *DC microgrid architectural structure.*

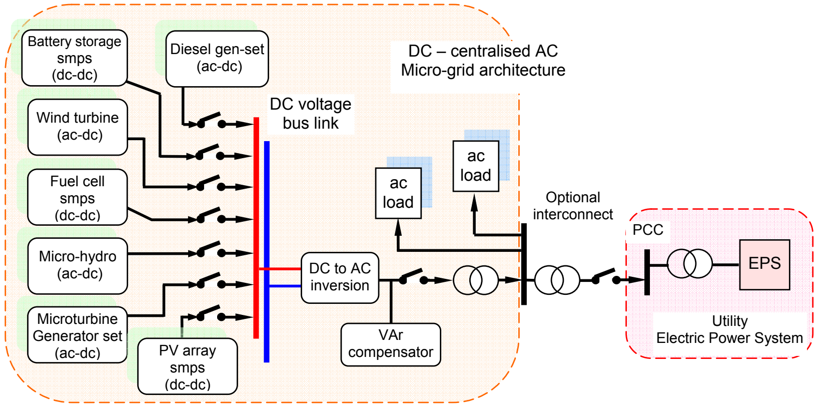

Figure 21.3. *DC – centralised ac microgrid architectural structure.*

21.1.2 Integration and Interconnection Requirements

Key elements for the reliability of distributed generation power systems are the performance of the electrical switchgear, interconnection, controls, and communication features. The main components of interconnection according to the protection functions they perform are categorized as follows:

Synchronization. Automatic sensing of the voltage and frequency can achieve fast interconnection to the hosting grid.

Islanding. Islanding protection is a mandatory feature that the hosting grid requires from the DG operator. Islanding on part of the hosting network could jeopardize maintenance crew safety and cause malfunction of nearby coordinated protection units. Relays are normally used to provide protection at both the grid and the DG end of the connection. DG inverters should incorporated built-in features to disconnect from the hosting grid once anti-islanding conditions are violated.

Voltage and frequency tolerance. For high quality power injection, both the voltage and frequency margins should not exceed the grid tolerance specification. Both voltage and frequency detection is part of the anti-islanding protection control.

DC injection level. Under abnormal operating conditions, grid tie inverters could inject low level DC current into the hosting grid. Similarly, transformer-less grid-tie inverters may inject DC current into the grid. It is part of the inverter feedback loop to detect the presence of the DC component and adjust the triggering sequence to the switching devices to remedy the situation. A coupling transformer could be used to isolate the DC current from flowing to the AC side. A low cost solution is to incorporate a DC detection device to disconnect the inverter in the case of severe DC level injection.

Grounding. Protective grounding is mainly designed to protect the operator. Grounding could also contribute to reducing the magnitude of transient over-voltages and lightning protection. Grounding components must be capable of carrying the maximum available fault current and withstanding a second strike within a few cycles after the first. Grounding cables must be connected directly to the equipment. No impedance, circuit breaker or measuring devices, *etc.*, are permitted between the grounding cable and the equipment.

Metering and monitoring. Monitored parameters can include current, voltage, real and reactive power, harmonics, oil temperature, vibration, *etc*. Metered parameters also include power output, which may be used for billing that requires utility-grade metering accuracy.

Dispatch, communication, and control. These integration and communication components interface the DG units with the utility. Their functions include:

- regional load management, work order management, and billing services;
- distribution automation;
- feeder switching;
- short circuit analysis; and
- voltage profile calculations and trouble calls management.

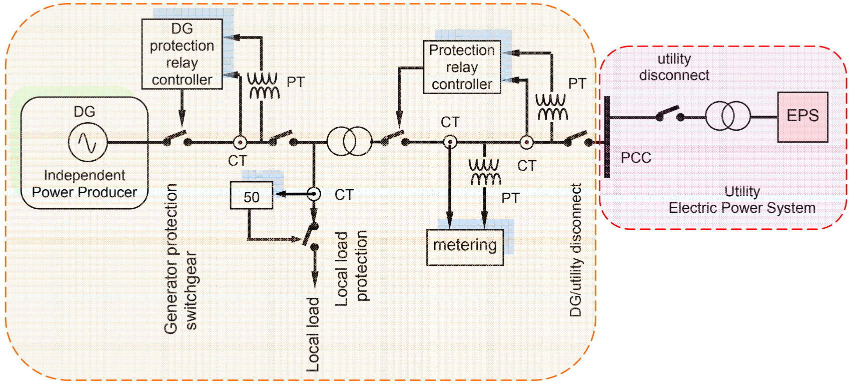

Figure 21.4. *DG-utility interconnection protection requirements.*

A typical interconnection line schematic with the protection elements between the DG and the hosting grid is shown in Figure 21.4. Typical minimum DG/utilities interconnection protection relay requirements are:

- The DG protective switchgear should include an over/under voltage trip function, an over/under frequency trip function, and a means for disconnecting the DG from the utility when a protective function initiates a trip;
- The DG and associated protective switchgear must not contribute to the formation of an unintended island;
- DG switchgear must be equipped with automatic means to prevent DG reconnection with the utility distribution system unless the distribution system service voltage and frequency is of specified settings and is stable for a specified time, typically 60s;
- Circuit breakers or other interrupting devices at the PCC must be capable of interrupting the maximum available fault current.

21.2 Interfacing conversion methods for dc energy sources

A common feature of embedded generation interfacing is voltage translation and stabilisation using the boost converter concept. The boost converter is used since its input current can be continuous thus drawing continuous energy, with minimal ripple current from the energy source, tracking the maximum power point, for maximum source energy extraction efficiency. Alternatively an LC filter can be used to achieve continuous source current.

Most single stage, electrical energy sources are voltage generating sources, for example the battery ($\Delta E^o = -G^o/n{\times}F$, equation 23.9), the fuel cell ($\Delta E = -G/n{\times}F$, equation 22.14), electrical machines ($V = N{\times}d\Phi/dt$ and $E = B\ell{\times}v$), Seebeck thermal electric effect ($\Delta V = s{\times}\Delta T$, equation 25.27), etc., while a notable exception is the photoelectric effect PV cell (or any semiconductor minority carrier device) which is a current generator ($I = G{\times}A$, equation 22.23).

Topologies based on the voltage boost circuit in figure 21.5a are applicable to any voltage generating source, while the current boost circuit in figure 21.5b is applicable to any current generating source, like the PV cell. The boosted output voltage and boosted output current transfer function in each case, respectively, are

$$\frac{V_o}{E_i} = \frac{1}{1-\delta} \qquad \text{for a switch duty cycle} \quad 0 \le \delta \le 1 \quad V_o \ge E_i \qquad (23.1)$$

and

$$\frac{I_o}{I_i} = \frac{1}{\delta} \qquad \text{for a switch duty cycle} \quad 0 \le \delta \le 1 \quad I_o \ge I_i \qquad (23.2)$$

Features and design aspects of these boost converters can be found in Chapter 17, sections 17.3 and 17.11 respectively. Other constant and controllable input energy dc-to-dc converters are shown in figure 21.5. The key converter feature is series input inductance and shunt input capacitance for voltage and current converters respective.

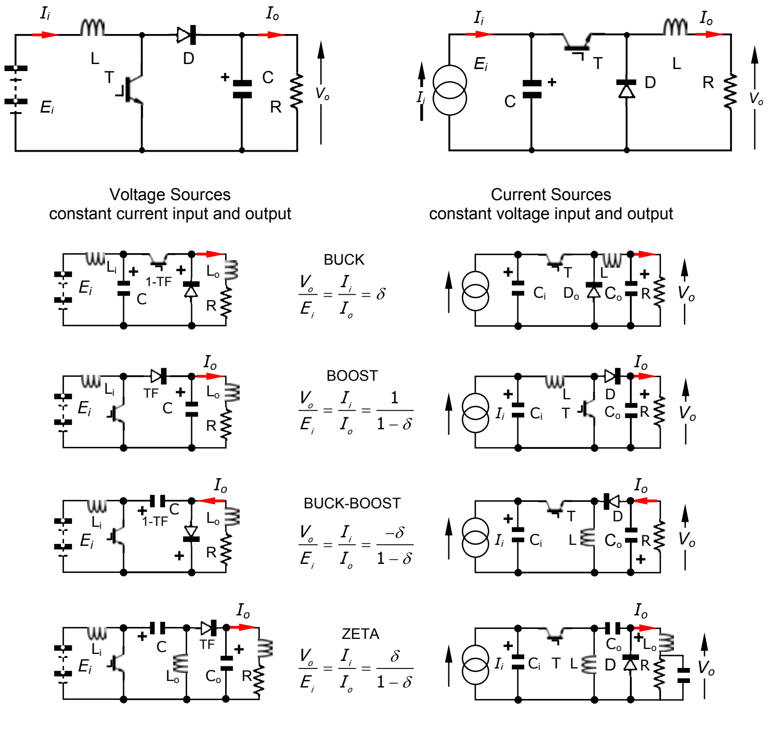

Figure 21.5. *DC to dc boost converters: (a) voltage sourced and (a) current sourced.*

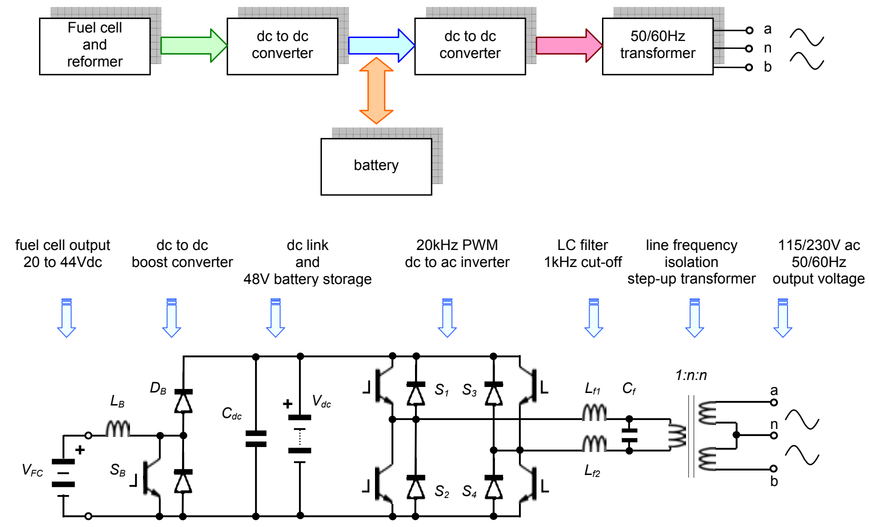

Figure 21.6. *Dc to line frequency power conditioner: (a) block diagram and (b) circuit topology.*

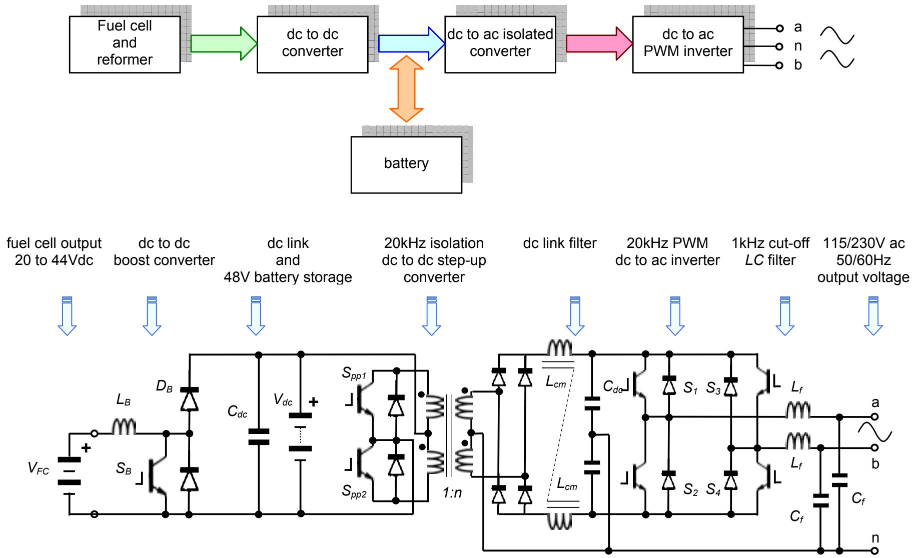

Figure 21.7. *Dc to line frequency power conditioner with high frequency isolation: (a) block diagram and (b) circuit topology.*

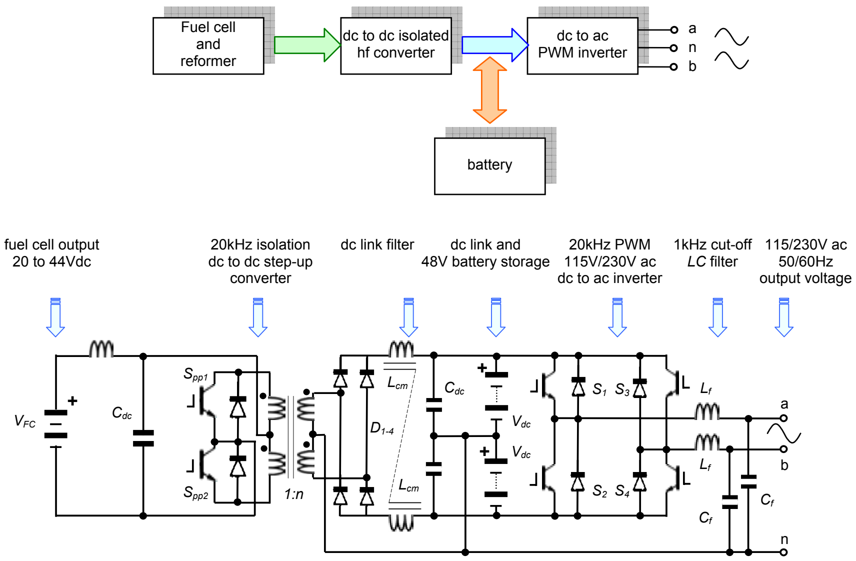

Figure 21.8. *Dc to line frequency power conditioner with high frequency isolation and two power conversion stages: (a) block diagram and (b) circuit topology.*

Single phase grid connection has a number of drawbacks, which will hamper its efficient and cost effective exploitation in a domestic environment, which is a low power, low cost application area. The first problem is dc current injection and isolation. A solution is associated with cost and size of single phase 50/60Hz transformers. The second single phase ac problem often overlooked is the high second order harmonic (even harmonics) associated with the effectively rectified ac grid, reflected back to the energy source. A three-phase grid connected inverter can deliver constant power to the grid, hence can draw continuous power from the energy source, which is highly desirable for maximum source energy extraction. On the other hand, the single phase ac grid can only receive power with a large component at twice the grid frequency. This energy pulsation is feed back to the energy source unless decoupled by large inductance or capacitance on the intermediate dc current or voltage link. An alternative is a front end continuous input current converter that can track the source maximum power point. Another temporary storage method is a parallel LC filter tuned to the second harmonic, in series with the dc link.

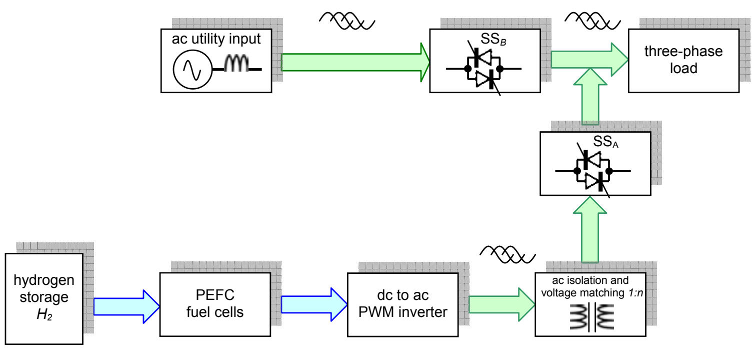

Figure 21.9. *Modular fuel cell power conversion system supplying a three phase load in parallel with the grid, via solid state circuit breaker for source isolation and islanding.*

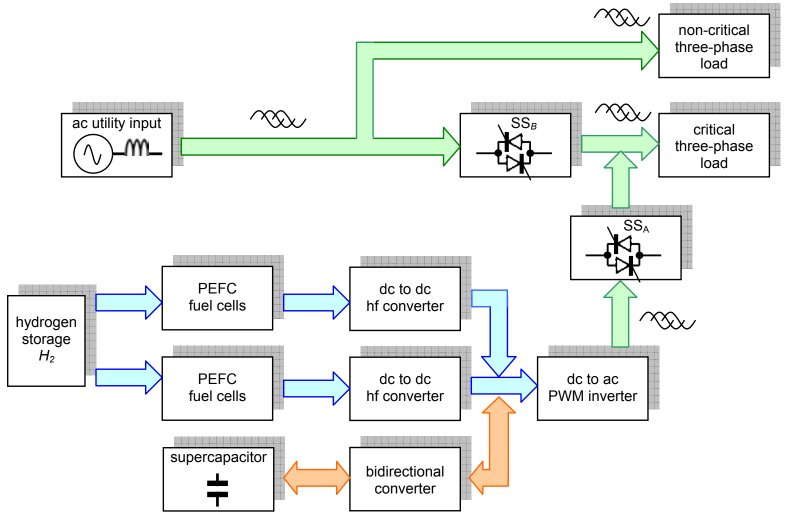

Figure 21.10. *Modular fuel cell power conversion system for grid connection with supply backup for critical loads.*

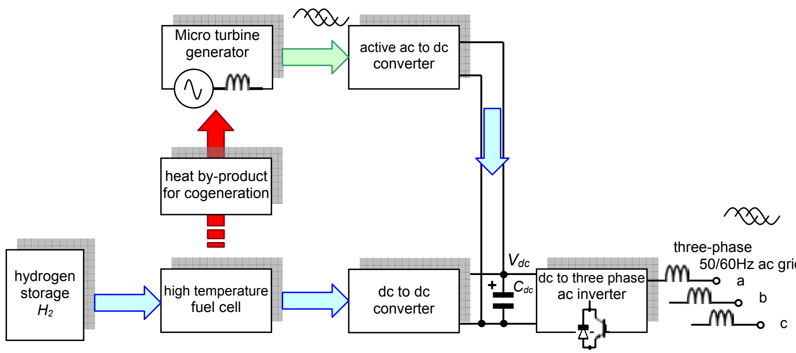

Figure 21.11. *Modular fuel cell power conversion system for three-phase grid connection, with cogeneration onto a common dc link.*

21.3 Interfacing conversion methods for ac energy sources

Single phase ac energy sources, such as low frequency sea wave-based generators, present a significant power electronics challenge. (Even multiphase versions develop pulsating power.) This is because the generated power is dominated by a second harmonic component (typically ½Hz). Since the grid code limits injected low frequency power fluctuations, large energy level intermediate energy storage is essential. It is inefficient, having converted mechanical energy into electrical energy to then converter that electrical energy into some other intermediate form for storage, only to then convert it back to an electrical form. Power electronics based intermediate storage methods are dc based, namely battery, electrolytic capacitor, or super capacitor, with increasing efficiency, although lifetime and reliability will be two issues.

In any *n*-phase ($n \geq 3$) balanced symmetrical sinusoidal voltage system, in steady state, if the current in each phase is a duplicate of the associated voltage waveform, then the instantaneous power is constant throughout each cycle. If the current and voltage are in phase then, not only is the instantaneous power constant, but maximum power is extracted. Importantly, in a mechanical sense, the instantaneous electromagnetic power is constant, as is the instantaneous mechanical torque. That is, if the sinusoidal electrical voltage and current are in phase then maximum power is delivered, and with minimum resultant mechanical torque ripple induced from the electrical side.

Generators produce voltage sources where the source magnitude is related to the speed (for example, $E = B\ell v$ for a permanent magnet generator) and the shape is determined by the gap mmf space distribution. A sinusoidal mmf results in a sinusoidal generated voltage. For maximum power extraction from the generator, the current drawn should be in phase with the generated emf. A winding associated with a voltage source also suffers with leakage inductance associated with imperfect coupling between the stator and rotor. This inductance means that the terminal voltage is likely to be phase shifted (lagging) from the emf source voltage. Any interfacing converter requires rotor position information to synchronise the current drawn in phase with the generated emf. This implies the interfacing converter input operate with continuous sinusoidal current, and this continuous current aspect, in conjunction with unavoidable leakage inductance implies a boost function.

21.3.1 Unity Power Factor Current Control of a Sinusoidal Current Active Boost Rectifier

The generator interfacing converter in figure 21.12 consists of six boost converters configured as three parallel connected bidirectional converters, which allow control of the generator current magnitude and phase angle. Due to switching frequency limitations, the machine leakage inductance may be insufficient thence additional external inductance is added. The output is a dc voltage source where the minimum output voltage is that which results due to full-wave rectification through the six bridge diodes. Only the input inductance controls the initial start-up in-rush current through the diodes, on connection.

To control the DC output voltage of the PWM boost-rectifier, the input line currents must be regulated and controlled in terms of phase and magnitude. In typical rectifier controllers, the DC bus voltage error is used to synthesize a line current reference. Specifically, the line current reference is derived through the multiplication of a term proportional to the bus voltage error by a reference sinusoidal waveform.

With the aid of a rotor position transducer, the reference waveform is phase locked to the generator emf. Since the sinusoidal reference is directly proportional (phase and magnitude) to the machine generated emf voltage, a unity power factor results. The line current is then controlled by the converter to track this reference. Current regulation is achieved by the use of hysteresis controllers, although a constant switching frequency, pwm modulation method is better from a filtering and emc point of view.

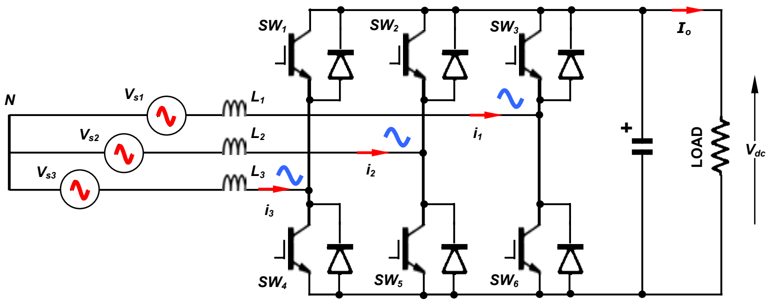

Figure 21.12. *Three-phase active rectifier for unity power factor generator operation.*

Switch matrix theory can be used to formulate the closed-loop operation of the PWM boost-rectifier. The output current I_o of the matrix converters is a function of the converter transfer function vector T and the input current vector i, and is given by

$$I_o = T \times i \tag{21.1}$$

The converter transfer function vector T is composed of three independent line-to-neutral switching functions: SW_1, SW_2, SW_3. The switches SW_4, SW_5, SW_6 are corresponding complementarily operated.

$$T = \begin{bmatrix} SW_1 & SW_2 & SW_3 \end{bmatrix} \tag{21.2}$$

The input current vector is given by

$$i = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \tag{21.3}$$

The line-to-neutral switching functions are balanced and are represented solely by their fundamental components, with modulated magnitude M.

$$\begin{aligned} SW_1(t) &= M\sin(\omega t - \phi) \\ SW_2(t) &= M\sin(\omega t - \tfrac{2}{3}\pi - \phi) \\ SW_3(t) &= M\sin(\omega t + \tfrac{2}{3}\pi - \phi) \end{aligned} \tag{21.4}$$

Therefore, the converter synthesized line-to-neutral voltages can be expressed as

$$\begin{aligned} V_{s1} &= \tfrac{1}{2} V_{dc} M\sin(\omega t - \phi) \\ V_{s2} &= \tfrac{1}{2} V_{dc} M\sin(\omega t - \tfrac{2}{3}\pi - \phi) \\ V_{s3} &= \tfrac{1}{2} V_{dc} M\sin(\omega t + \tfrac{2}{3}\pi - \phi) \end{aligned} \tag{21.5}$$

Equation (21.4) shows the rectifier synthesized voltages. V_{dc} represents the output dc voltage.

In the time domain, the fundamental components of the three-phase input currents are given by

$$\begin{aligned} i_1(t) &= I\sin(\omega t - \varphi) \\ i_2(t) &= I\sin(\omega t - \tfrac{2}{3}\pi - \varphi) \\ i_3(t) &= I\sin(\omega t + \tfrac{2}{3}\pi - \varphi) \end{aligned} \tag{21.6}$$

By combining equations (21.1), (21.4), and (21.6), the output current $I_o(t)$ is given by

$$\begin{aligned} I_o(t) = {} & I\sin(\omega t - \varphi)M\sin(\omega t - \phi) + I\sin(\omega t - \tfrac{2}{3}\pi - \varphi)M\sin(\omega t - \tfrac{2}{3}\pi - \phi) \\ & + I\sin(\omega t + \tfrac{2}{3}\pi - \varphi)M\sin(\omega t + \tfrac{2}{3}\pi - \phi) \end{aligned} \tag{21.7}$$

By using a trigonometric identity, $I_o(t)$ becomes

$$I_o(t) = \tfrac{3}{2} I \times M \times \cos(\phi - \varphi) \tag{21.8}$$

Because the angle $\phi - \varphi$ is constant for any set value of the input power factor, the output dc current, $I_o(t)$, is proportional to the magnitude of the input current, $I(t)$, and so is the output voltage, V_{dc}. For unity power factor control, angle φ is equal to zero.

The output voltage, V_{dc} is

$$V_{dc} = R \times I_o \tag{21.9}$$

$$\left(V_{dc\,ref} - V_{dc}\right) = k \times I \tag{21.10}$$

The dc bus error, ($V_{dc\,ref}$ - V_{dc}), is used to set the reference for the input current magnitude. The input sinusoidal voltage, V_a, is multiplied by the dc bus error and becomes a reference for the input current in phase 1. The reference value for the current in phase 2 is phase-shifted by ⅔π with respect to the current in phase 1. Since the sum of the three input currents is always zero, the reference for the current in phase 3 is obtained indirectly from:

$$i_{3\,ref}(t) = -i_{1\,ref}(t) - i_{2\,ref}(t) \tag{21.11}$$

The input currents, $i_1(t)$, $i_2(t)$, $i_3(t)$ are measured and compared with the reference currents, $i_{1\,ref}(t)$, $i_{2\,ref}(t)$, $i_{3\,ref}(t)$. The error is fed to a comparator with a prescribed hysteresis band $2\Delta I$. Switching of the leg of the rectifier (SW_1 off and SW_4 on) occurs when the current attempts to exceed a set value corresponding to the desired current $i_{ref} + \Delta I$. The reverse switching (SW_1 on and SW_4 off) occurs when the current attempts to become less than $i_{ref} - \Delta I$. The hysteresis controller produces a quality waveform and is readily implemented. Unfortunately, with this type of control (hysteresis controller) the switching frequency is not constant but varies at different points of the desired current.

Given the generated voltage is linearly speed dependant, hence always specified, the reference current is specified at that speed (voltage) to track a maximum power point characteristic.

Reading list