Subject

Electronics for Information and Communication Systems

MASTER ON INFORMATION AND COMMUNICATION ELECTRONIC SYSTEMS

Power Supply Design Techniques for Conventional and Energy Harvesting Power Systems

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Abstract

Development of electronic systems was always intrinsically related to the power that makes them work. Each electronic system may it be a conventional domestic device, hand-held gadget, or embedded system, has to be provided with a required power supply. The present work discusses important issues related to the power supplies and suitable for the majority of electronic devices.

The document follows two research lines related to conventional and energy harvesting power systems. While conventional power sources are based on fossil fuels burning or even renewable sources as wind, energy harvesting uses small amounts of exclusively clean and inexhaustible energy. Energy sources used in both fields are discussed presenting a concise overview for each source.

Electronic systems require an appropriate input power. To achieve these level of power the input power has to be transformed. Main techniques for power transformation used with AC- or DC-powered systems are presented and explained in detail.

Two significant issues which have to be considered in almost all designs, namely power supply protection and combination of multiple power sources are discussed and crucial points plainly exposed for the reader.

This document can serve as a reference during custom power supply design process.

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1 Introduction

The world today is witnessing such an unprecedented explosion of the number of electronic devices as never before. Portable electronic devices as mobile phones, tablets, or more complex ones like laptops or TVs; microcontroller-based embedded systems used in industrial automation processes, automotive industry, health-monitoring or IoT devices to name few are the evidence of this phenomenon. Undoubtedly, the world is dominated by electronic devices in a degree that nobody imagines the life without their presence.

In order to function properly any electronic device needs to be provided with corresponding and sufficient power. Moving throughout a Printed Circuit Board (PCB) or Multichip Module (MCM) traces electrons, under magnetic field, force power conversions according to engineered schemes providing necessary power supply for desired functionality. Although power conversions are the foundation and essence of electronics and found everywhere, the interest of the present work is situated in power supply energy conversions.

The schemes and techniques along with standard rules for power supply design will be considered in detail.

On the other hand, a good power supply design should provide a protection for the power supply itself and the end electronic devices. There are many combinations of AC power supply techniques and DC/DC converters created to provide desired characteristics with input/output safety isolation, low noise, and transients protection.

Moreover, project needs may include a support for combination of various power supply sources (AC/DC, DC/DC, or Non-Isolated Point of Load), power systems, and necessary isolation from supplied systems which can be control systems, communication modules, sensors, or other power management integrated circuits, i.e. battery chargers or fuel gauges.

Due to movements in global market trends and technology advances various niches were formed outlining applications segments. It was possible to standardize power supply systems and integrated circuits within each application segment. Thus, a wide offer of solutions, such as standard AC/DC power supply, efficient DC/DC voltage regulators accepting broad input voltage ranges and adjusted to custom or fixed standard (3.3 V, 5 V) output voltages. It widened the market with increased volume of specialized products and reduced costs.

A hardware designer may face a challenge to consider a custom power design solution where reduced costs due to specific characteristics and project needs may prevail over starting design and approval costs and related risks. More often, continuously growing standard solutions available on the market negate such strategies.

AC power supplies and step-up/step-down voltage regulators come in various formats and packages adapting to a wide variety of power ranges and end applications. Those chips can be integrated into end designs as through hole (THT) or Surface Mount Device (SMD) PCB mount, chassis mount, and other formats.

Linear voltage regulators, switching power supplies continue to advance in performance. Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) are the areas of development which provide greater conversion efficiencies reducing heat dissipation.

Another area which is being highly developed nowadays is Energy Harvesting (EH). The notable growth of IoT devices and sensor networks as well as the social and political trend of climate change threat urged the development of various families of EH power management devices. Photovoltaic, thermoelectric, vibration, radio frequency, piezoelectric to name few sources become possible energy sources for low-power and ultra-low-power electronic devices.

The present work considers in detail each stage of power conversion from energy sources to regulated power delivery. Moreover, the reader will be able to notice two lines of research development: general energy source power supplies and EH power solutions design techniques.

The work starts with the introduction, following by general and EH power sources descriptions. Then, common power transformation topologies are considered. Two final sections discuss power supply protection techniques and possible ways of combining multiple power supplies as well as multiple power sources.

2 Power Sources

All electronic equipment has to be powered. Before the end device receives the regulated voltage and sufficient current it has to be connected to or "plugged in" one or another power source.

There are many types of power sources. Generally, all of them can be divided into two huge groups: Alternative Current (AC) and Direct Current (DC) power sources. Both use completely different principles for generating and managing the power.

This section will give an insight into the major power sources and explain principles which stay behind them.

2.1 Sources of Energy

Nowadays, the major sources of energy, called primary sources, are fossil fuels, particularly, coal and natural gas; falling water from where come hydroelectric power, and heat from nuclear fusion. The humanity rapidly gets concerned about environmental impact of the primary sources what impulses the proportionally growing development of electric power generated from renewable sources like wind and solar sources. Some electric grids are even based on geothermal energy of volcanic heat (Kirtley, 2020).

There are two basic ways of electric power production: by generators which can be moved by different forces, and by direct conversion from a primary source which can be sun or vibration sources. The force which moves a generator can be heat, gas, internal diesel combustion, gasoline, wind, or falling water.

This section will concisely describe the major power sources used nowadays.

2.1.1 Heat Engines

Heat engines are the most widely used source of energy today. They burn a primary fossil fuels, coal or natural gas, and use the released energy to generate mechanical power. The mechanical power is then used to drive an AC generator to produce electrical power. AC generators are discussed in Section 2.2.1.

Not all produced heat is converted to the mechanical power, but only its portion. From here stands the importance of efficiency optimizations. The efficiency of a heat engine is determined by the mechanical output power matched to the heat input power. The mechanical power is characterized by difference between the input heat and rejected heat. The rejected heat is the wasted portion of input energy. Carnot efficiency inequality presented in Equation 2.1 outlines a heat engine efficiency.

$$W_m < Q_h \frac{T_h - T_l}{T_h} \tag{2.1}$$

Where W_m is mechanical output, Q_m input heat, T_h and T_l are input and rejection temperatures. Engines designed for higher input heat and temperatures operate with higher efficiencies as it can be seen from the Equation 2.1.

2.1.2 Power Plants

The power plants are facilities which generate electrical power by different means and distribute it. Each power plant is unique in a certain degree however a common structure can be derived. A common power plant basic scheme is presented in Figure 2.1.

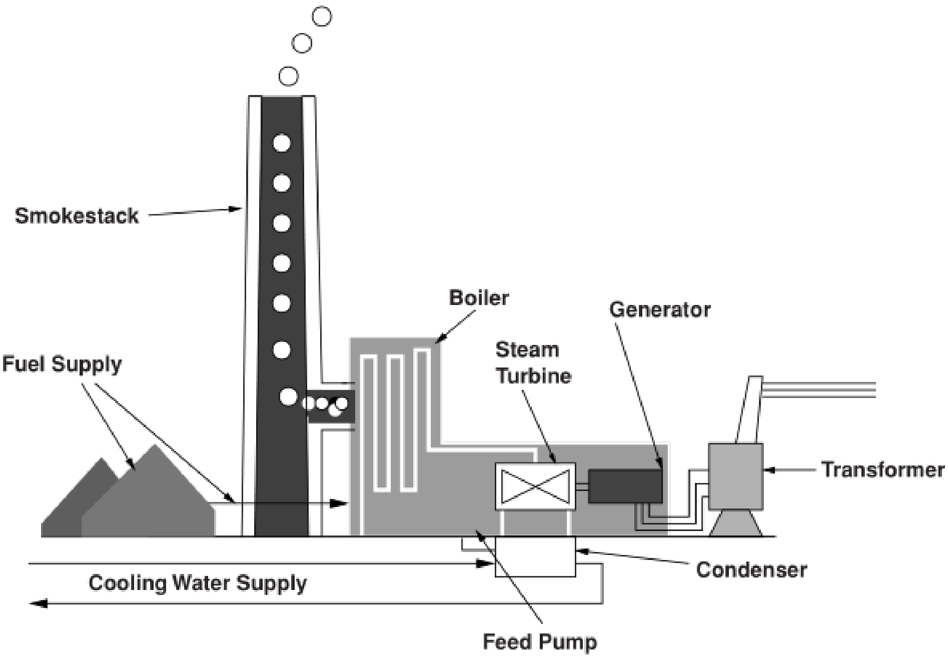


Figure 2.1: A basic power plant facility sketch

Electrical power generating tool is a steam turbine in this example. The first step is water compression and pumping it into a boiler. The boiler heats the water with the fuel supply and the resulting hot air pressure moves a steam turbine which turns a generator. As can be observed, the heat rejected by the generator is absorbed by a condenser, where it is cooled. Power plants generate voltages limited up to 30 kV (Kirtley, 2020).

2.1.3 Nuclear Power Plants

The same thermodynamic cycle as in fossil-fuel plants is employed at nuclear power plants. However, the thermal efficiency is slightly lower than in fossil-fuel plants. It is due to a complex facility structure, where carrying high-pressure water requires more sophisticated solutions. A basic nuclear power plant structure is shown in Figure 2.2.

The reactor generates heat through fission of atoms with massive nucleus into multiple atoms with smaller nuclei. The process is done usually utilizing the isotopes of uranium (U^{235} and U^{238}). The typical generated voltages placed in the same range as power plants.

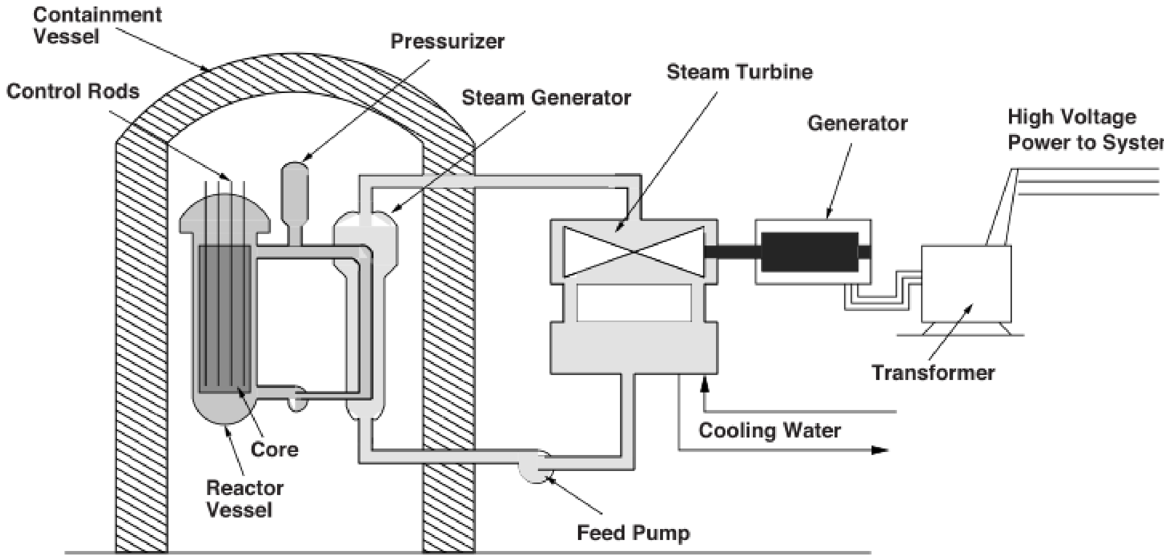


Figure 2.2: A basic nuclear power unit sketch

2.1.4 Hydroelectric Power

Hydroelectric power plants take advantage of the law of gravity. A generator has to be moved to produce electrical power and its rotation, in this case, is caused by falling through a pipe water on a turbine wheel. A basic hydroelectric unit is shown in Figure 2.3. In this kind of power plants many of such units installed.

Hydro plants produce a small portion of total primary energy, however they often serve as energy storage due to reservoirs availability. Exploiting those reservoirs produce proportional amounts of power. Moreover, the generated power can be modulated and further adapted for casual variations in load.

There are two reservoirs: the upper and the lower. They are located on different elevations. The generators are built in such a way that they can serve additionally as pumps. When electric power is in surplus, water is pumped to the upper reservoir. When the electric power is in short supply, water is allowed to fall out to the lower reservoir providing extra-generated power. Often, a river serves as a lower reservoir and a mountain or hill as a place for the upper reservoir.

2.1.5 Wind Turbines

Wind turbines are one of the most widely developed renewable and sustainable sources of energy along with solar power generators discussed in the next section. Both are currently under rapid development in China (Zhang, Zhao, Andrews-Speed, and He, 2013), India (Khare, Nema, and Baredar, 2013), and many other countries. Combined together they can form a unified hybrid energy system (Nema, Nema, and Rangnekar, 2009).

The facility usually comprises many wind units. Each unit has blade disk with a

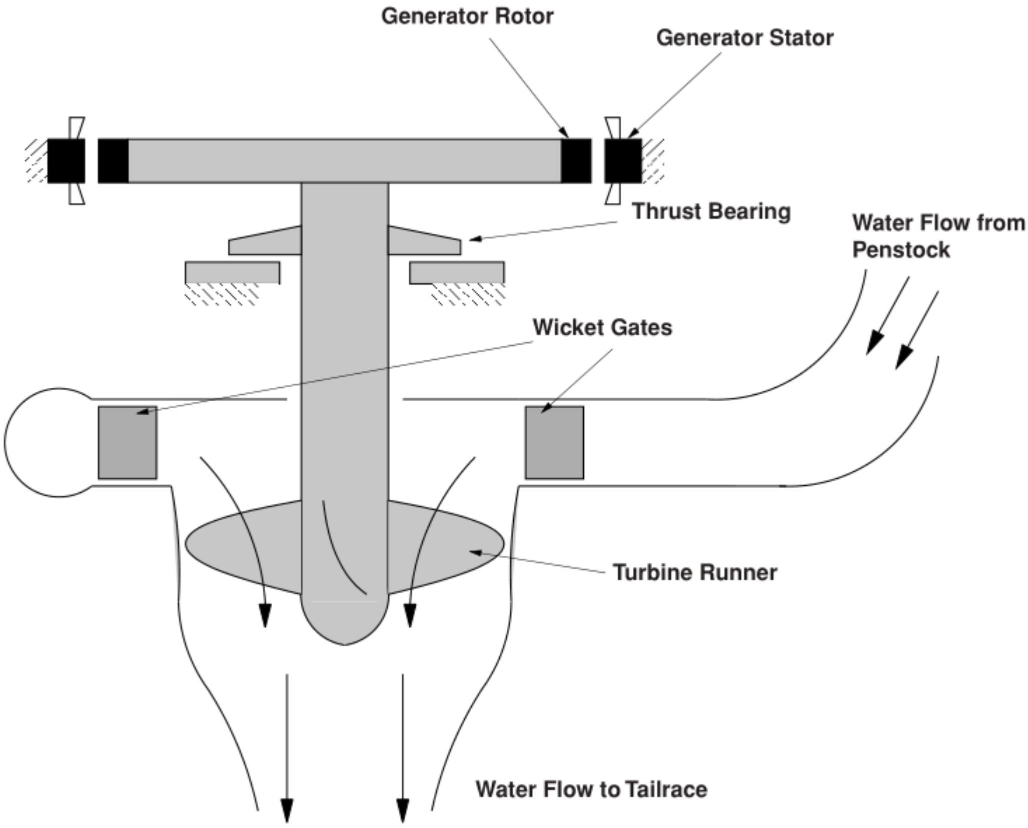


Figure 2.3: A basic hydroelectric unit sketch

diameter about 77 m and hub height ranging from 65 m to 100 m (Kirtley, 2020). A basic construction of a typical wind unit is presented in Figure 2.4.

As can be observed, the turbine blades are mounted on a nose cone with pitch adjustments for speed control. The turbine speed generated by the wind is increased by a factor of about 80 within a gear box. A generator is usually a doubly fed induction generator with cascade electronics which couples the rotor windings with the stator windings. Depending on a case, there is a transformer integrated to the wind unit what constitutes a local power system. Altogether, the unit is capable to supply a constant frequency at variable speed conditions.

2.1.6 Solar Power Generation

Another rapidly growing source of sustainable and renewable energy is the solar irradiation. Theoretically, the all-spectrum sun radiation is capable to generate $1\,kW/m^2$ of electric power. However, there are a number of factors which impede practical acquisition of this amount of power. Among the reasons are the atmosphere layer which lets only a part of solar radiation to pass through, the Earth turnaround what implies a day-light limited energy cycle, clouds interference and others.

There are two main forms of converting solar radiation to the electrical power: heat

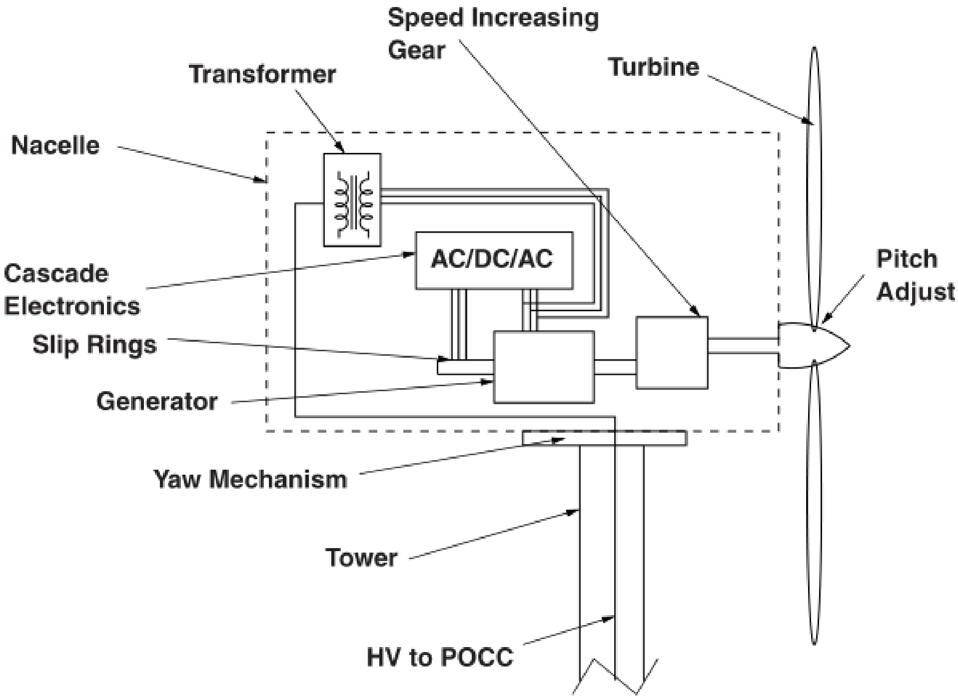


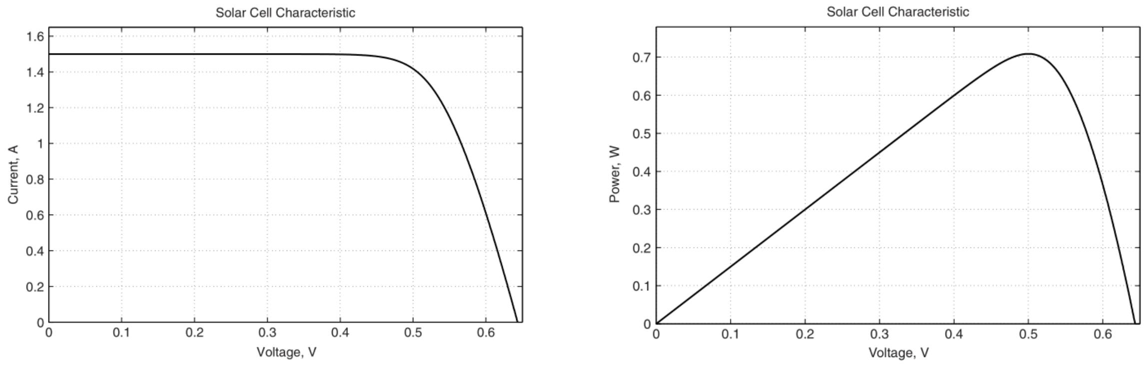
Figure 2.4: A basic construction of wind unit

engines and photovoltaic cells. The heat engines employed in this method are similar to the used in power plants discussed above. The only difference is that they use the sunlight to heat the top part of the heat engine. Usually, a lot of mirrors which focus on the engine heat area are installed around a tower. A good example of the power plant based on this kind of engines is the PS10 located in Seville, Andalusia.

The other method is using the photovoltaic cells. The cell is basically a large junction diode, which, on sunlight, splits electron/hole pairs producing a current. The photovoltaic cells, though not that highly efficient in contrast to other power sources, are major Energy Harvesting source and under rapid development, a topic of continuous research and improvement.

One feature regarding photovoltaic cells has to be discussed. When observed, a characteristic current vs voltage curve of a typical photovoltaic cell in Figure 2.5a, several conclusions might be deduced. The maximum voltage and current areas have to be examined. When the cell is open it produces a voltage, when shorted it does a current. On both extremes no power is produced and there is a maximum efficiency point in between. This point can be seen in Figure 2.5b and it is called the maximum power point. From here originates a problem of designing a system which will be capable to optimize the power input resolving the Maximum Power Point Tracking (MPPT) problem.

This kind of energy becomes very attractive for electronic systems requiring autonomous power self-maintenance. There are a number of solutions integrating solar power chargers which can work with Lithium batteries or supercapasitors. These solutions find many applications in Industrial Monitoring, Wireless Sensor Networks, IoT, Environmental Monitoring and, generally, in Energy Harvesting area.



(a) Current vs voltage

(b) Power vs voltage (MPPT tracking)

Figure 2.5: Characteristic curves of photovoltaic cells

More profound overview of solar energy source and other energy harvesting sources can be found in Section 3, Energy Harvesting Power Sources.

2.2 AC Power Sources

The first electricity applications were very basic. Generally, they consisted in dissipation of energy in the form of heat. The most prominent application was a light bulb which brought to the electricity a new name, the light. The other applications like heaters or weldering were less prominent. In these devices it does not matter the polarity or direction of current while there is enough energy to make the load work. It turns out that with the AC power it is possible to build electric management devices and systems such as generators or distribution systems much more efficiently than with the DC power.

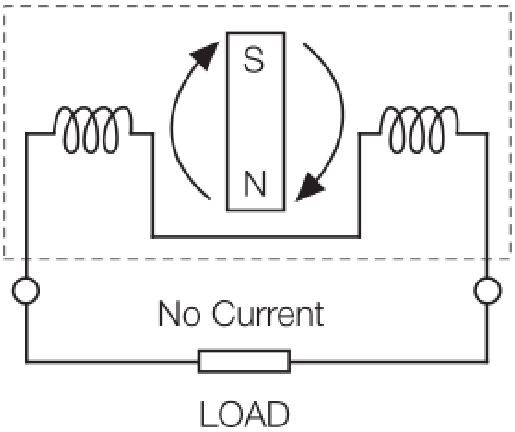
2.2.1 AC Generator

One of the most important and predominant AC power sources used in the processes of transformation of different types of energy , described in the previous sections, to the electric power is an AC generator.

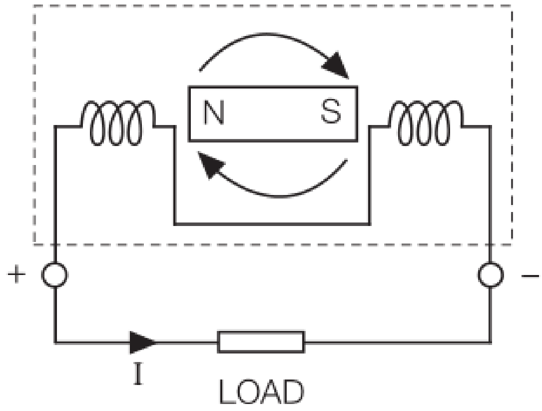
The Faraday's Law of electromagnetic induction is the foundation principle of the AC generator. Basically the AC electric potential is created by a rotation of a magnetic field around a set of stationary coils. The basic operation steps of the AC generator, sometimes called alternator, are shown in Figure 2.6.

The polarity of the generated voltage grows reversed while the magnet opposite poles pass by creating reversing current. The resulting frequency depends on the speed of rotation.

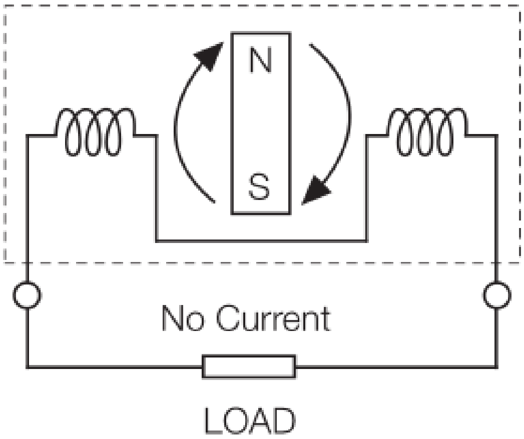
Further, produced current comes into transformer when it is stepped up or down. An advantage given by the AC power distribution on long distances is due the ease of transformation of voltage. It is more efficient to transmit higher voltages and low currents due to physical cables impedance characteristics. The wire thickness can be lowered and



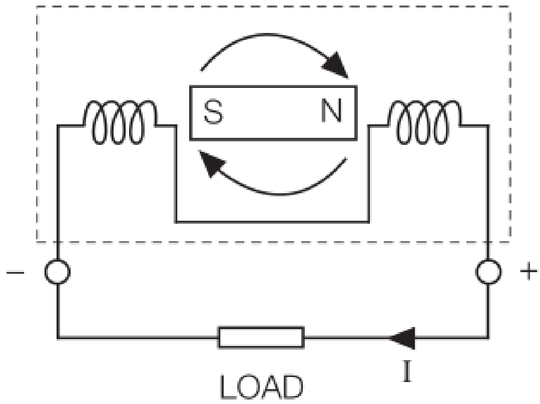
(a) Step 1



(b) Step 2



(c) Step 3



(d) Step 4

Figure 2.6: Basic AC generator operation steps

resistive power losses are less relevant, among other benefits. The transformers are used for stepping up first the voltage, transmit it, and then step it down back to the required power levels for general purpose uses.

Improved versions of the AC generators were created introducing the third phase and, thus, preventing the wires to reach zero-level power. The coils are located 120° equally distanced and the resulting voltage produced by each coil is shifted 120° out of phase respect each other.

2.3 DC Power Sources

The major disadvantage of the AC power is its non-portability. It is available as far as the distribution system can reach. In contrast, the DC power sources are always portable and refer to different types of batteries. The end electronic equipment is powered by the DC voltage and can be supplied without or combined with an AC/DC converter. This section will provide an overview of the existing types of batteries used in electronic systems.

2.3.1 Lithium Batteries

Lithium batteries are very typical power source used in portable applications. It has higher energy density rates than Nickel Cadmium or Lead Acid batteries considered in further sections. Lithium batteries derive into different variations based on chemistry used to generate voltage potential. Lithium iron phosphate, lithium manganese, lithium titanate, all with similar properties.

A strict proper charging algorithm must be employed in lithium battery chargers. Otherwise, several drawbacks are possible: the battery can be irreversibly damaged (same when overdischarged) or, even more dangerous, an explosion can occur with inextinguishable fire as the battery has in the package fuel and oxidants.

A battery cell must never discharge less than 3V, otherwise it will be overdischarged and, thus, irreversibly damaged. The charging process consists of 3 stages. If the cell is below 2.9 V the pre-charging stage start with 0.1 times capacity (C) constant charging current. This stage tries to recover the battery if it is possible. Once 3.0 V level is reached the constant current stage begins. During the this stage the constant current, around 1 C, is supplied to the cell. When the voltage reaches about 4.2 V, it is maintained constant while the current continually reduces down to 0.05 C. When it reaches down the 0.05 C of current draw, the charge is complete. The process is depicted in Figure 2.7.

Over-voltage, over-temperature characteristics are monitored during the charging to avoid the possible drawbacks.

2.3.2 Nickel Cadmium and Nickel Metal Hydride Batteries

Nickel Cadmium (NiCad) is almost obsolete technology generally substituted by the lithium batteries. It has the same power density as lithium batteries. A big disadvantage of

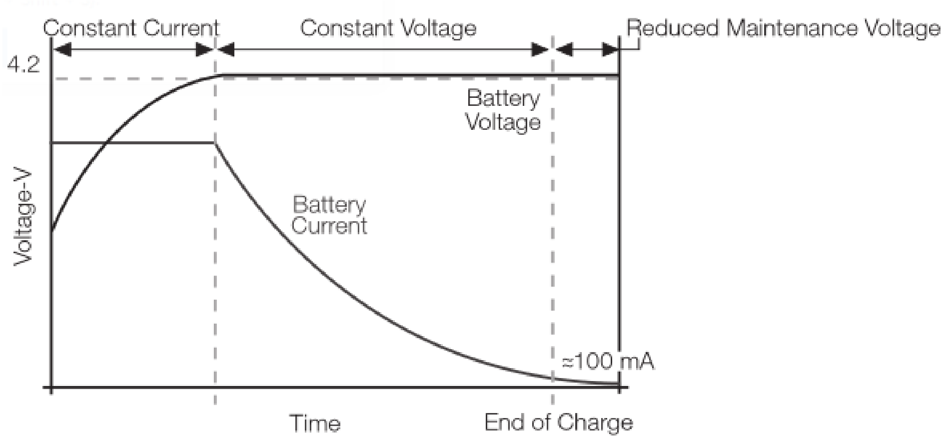


Figure 2.7: Lithium batteries charging process

this kind of batteries is the memory effect. It consists in the losing battery capacity when it is not fully charge/discharge cycled.

Nickel Metal Hybrid (NiMH) battery is an upgrade of NiCad one removing the memory effect.

The charge cycle is the same for both types. It uses a delta peak charging regime. The charging starts with a constant current about 5 C monitoring the battery voltage. When the charging reaches 95%, the battery voltage slightly drops. This is called the knee point. The charger circuit must recognize it and change to the constant voltage until the charging cycle is finished. This process is illustrated in Figure 2.8.

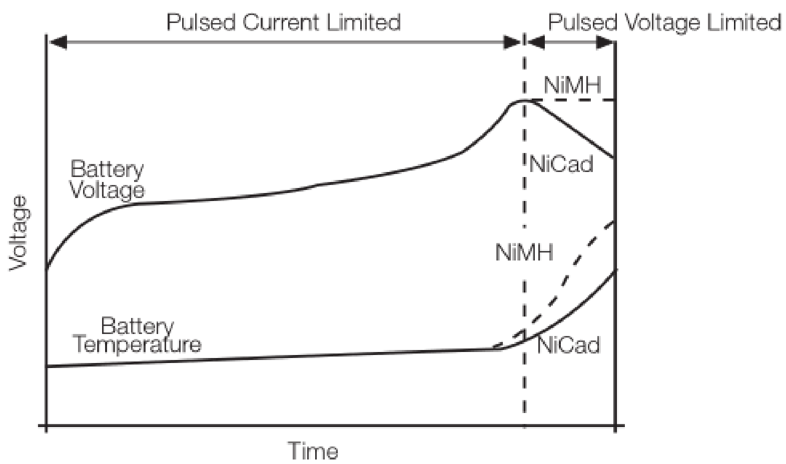


Figure 2.8: NiCad/NiMH batteries charging process

2.3.3 Lead Acid Batteries

Lead Acid batteries are extensively used in automotive industry, industrial control, Uninterruptible Power Supplies for data centers, and security systems.

The charging cycle starts with an initial pre-charge stage supplying the constant current about 0.1 C. It follows by the constant voltage period with 2.25 V per cell completing the charge cycle with the slow charge, reducing the current and voltage. The charge cycle is presented in Figure 2.9.

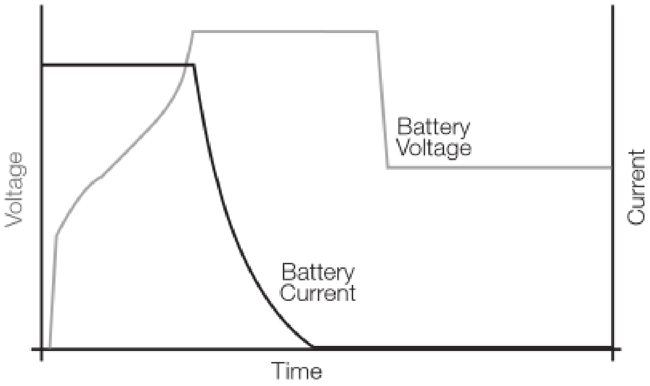


Figure 2.9: Lead Acid batteries charging process

These batteries are very sensitive to temperature variations. They normally work in range of 20 to 25°C. When the temperature drops to 0°C, the capacity lowers to 80%. When it grows to 40-50°C, the capacity can drop to 40-10%.

Typical discharging curves for all three types of batteries are presented in Figure 2.10

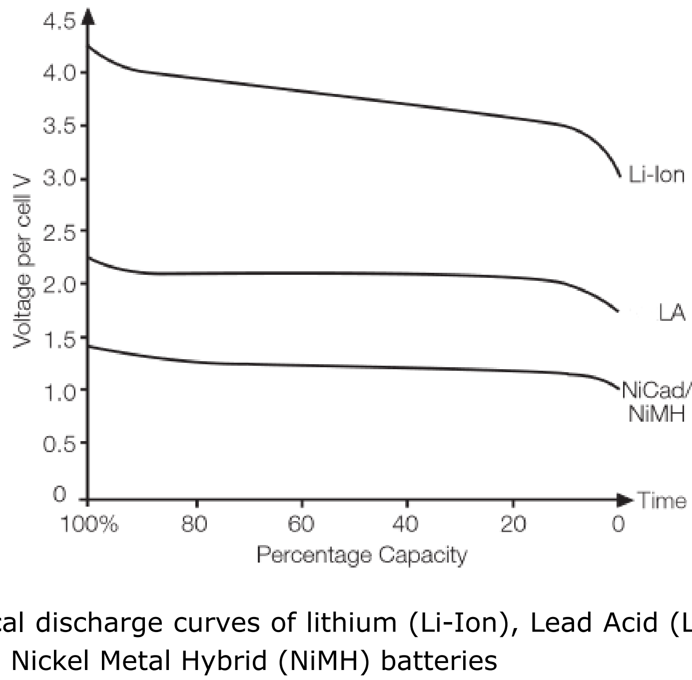


Figure 2.10: Typical discharge curves of lithium (Li-Ion), Lead Acid (LA), and Nickel Cadmium (NiCad) and Nickel Metal Hybrid (NiMH) batteries

3 Energy Harvesting

Energy harvesting raises as one of the key emerging technologies of the twenty first century. The environment can supply a certain amount of energy. The recollection of this energy and its conversion to electrical energy is generally referred as energy harvesting. In terms of volume of produced power, energy harvesting often includes small or even tiny systems which produce power in the range from nanowatts to milliwatts (Kiziroglou and Yeatman, 2012).

For the sake of clarification the energy harvesting has to be distinguished from energy scavenging and renewable energy sources. Energy scavenging distinguishes in terms of the ambient or environment predictability. That is, when the ambient is unknown or irregular the energy scavenging applies, whereas in energy harvesting the energy sources and ambient are clearly defined. On the other hand, in terms of local availability, in contrast to renewable energy sources, energy harvesting is defined as a recollection of locally available energy for local needs.

The mentioned range of possible harvested energy narrows its suitability for many applications. Wireless devices, such as sensors or actuators, become the main applications category. Home and industrial automation, construction, health care are the main application fields. The amount of energy that can be recollected in a particular environment, size requirements, weight, lifetime, ecological demands are the key factors for determination if energy harvesting is appropriate for an application.

Next energy sources were considered feasible for energy harvesting: light, motion, temperature variation, electromagnetic radiation and chemical energy. Motion energy harvesting uses three types of transdusers: piezoelectric, electromagnetic and electrostatic. Light harvesters use photoelectric effect, electromagnetic harvesters use induction and thermal harvesters use thermoelectric effect, also called the Seebeck effect. There are also a number of chemical reactions which are capable to produce energy. This classification of energy harvesting sources is depicted in Figure 3.1.

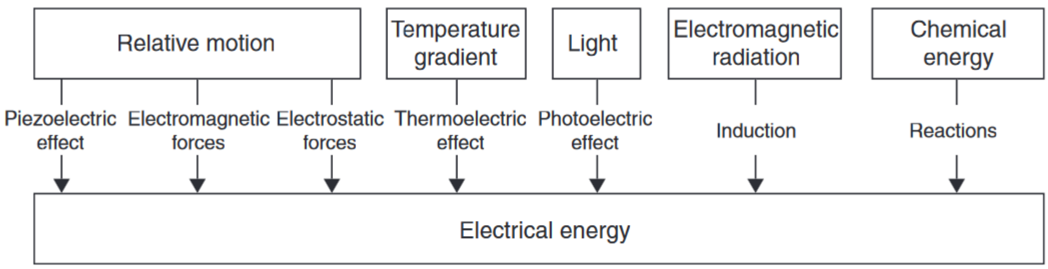


Figure 3.1: Classification of energy harvesting sources

This section will provide in-depth overview of each harvesting source available nowadays and make clear their working principles.

3.1 Photonic Energy Harvesting

Photonic energy harvesting methods can be resumed in recollection and conversion of light or solar energy into electrical power. This kind of energy has been renowned as ecologically clean and inexhaustible. The working principle is based on photovoltaic materials which absorb a large number of photons. The electrical power is obtained when a sufficient number of photons were recollected to activate the electric optical pool (Wan, Tan, and Yuen, 2011). This recollection is only possible when a device with appropriate structure and design is employed. The efficiency of harvesting process strongly depends on the environment. To obtain more power these devices have to be placed in conditions of good lightning, if possible where mostly exposed to the sun. Refer to the Table 3.1 to consult the potentially available average power from different lightning conditions. Solar cells can be connected in series to achieve the desired voltage levels. Trends in the market lead to the reduction of costs for solar cells what makes it a good option to be the energy harvesting source for wireless network nodes.

Condition	Power incident (mW/cm^2)
Midday, no clouds	100
Outdoors, overcast	5
3 m from an incandescent bulb	10
3 m from a CF bulb	1

Table 3.1: Power available from a variety of lighting sources (Priya and Inman, 2009, Chapter 9)

Different materials can be used for solar cell production. Typically amorphous silicon (a-Si) is used. This material is able to convert up to 11% of incident radiation into effective electric power. In applications for wireless sensor nodes the cost-per-area concerns are negligible since those devices used to be very small and have few centimeters of exposed area.

The a-Si is not the only material used for photovoltaic panels production. Currently, there exist several lines of research to achieve more power employing different materials. Multi-gap or Wide band gap solar systems have increased number of excitation states what permits them to fuller take advantage of the solar spectrum than traditional a-Si cells (Lu, Diaz, Kotulak, Opila, and Barnett, 2011). The results achieved in experiments state that cells area currently used in application can be decreased by 60% (Priya and Inman, 2009, Chapter 9). Table 3.2 demonstrates current pholovoltaic technologies and their maximum conversion efficiencies.

Technologies as Organic and CIGS demonstrated flexibility and durability characteristics. However, it is important to note that not many applications have more than one side well-exposed to the sun. This reduces significantly the application area for flexible solar cells. Nevertheless, the flexible cells allow greater degree of exposition to the sun during the day cycle. Figure 3.2 shows that even with a three-fold solar cell installed on a device only two sides will produce effective power.

The main disadvantage of this kind of power sources is its daytime dependency.

Technology	Maximum reported conversion efficiency (%)
a-Si	11
p-Si	18
SC-Si	25
Dye-sensitized	11
Organic	5
CdTe	15
CIGS	19
Multi-gap	35

Table 3.2: Currently available photovoltaic technologies and their maximum conversion efficiencies (Priya and Inman, 2009, Chapter 9)

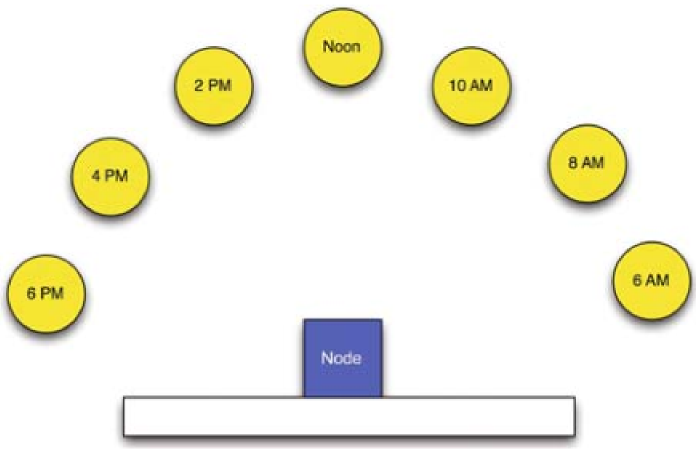


Figure 3.2: Exposition to the sun of a device with a three-fold solar cell respect to the sun position

The power is available during daytime for outdoor environment and during office hours for the indoor environment. In indoor environments sun radiance drops down in 10% of the outdoor condition what imposes a low-duty cycle of a converter or proportionally larger photovoltaic cell area. Practical solutions should foresee these inconveniences and in many cases integrate a battery or a supercapacitor to assure uninterrupted device functionality.

3.2 Motion Energy Harvesting

Motion energy harvesting principally uses mechanisms capable to take advantage from the piezoelectric effect. The motion energy is converted into the electrical power by means of the piezoelectric effect. The effect consists in a generation of electrical charge through mechanical strains on a piezoelectric material layer. This charge, when transmitted on wires, produces AC power output which is captured by the transducer and transformed to desired characteristics. Natural and synthetic materials, also crystals on compression can be considered piezoelectric.

The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids (Batra, Alomari, Chilvery, Bandyopadhyay, and Grover, 2016). The change of polarization when mechanical stress has been applied to a material is of great importance. Two factors can change the polarization. First, the external stress can reorient molecular dipole moments. Second, by reconfiguration of dipole-inducing surroundings. Piezoelectric energy is then produced through a variation of polarization. This process depends of three factors: orientation of crystal polarization, crystal geometrical structure, the applied stress.

The polarization change is realized through a variation of charge density upon the surface of crystal. As an example, if a weight of approximately 227 kg is appropriately applied to a 1-centimeter cube of quartz, a potential of about 12.5 kV will be generated.

Piezoelectric materials possess also the reverse effect. If an electrical field applied to a crystal, it will cause mechanical deformations of material. This effect is called converse piezoelectric effect. The direct and reverse conversions are schematically presented in Figure 3.3. One can observe that the electrical potential is generated by the direct effect through an applied mechanical force and the reverse effect generates mechanical fluctuations.

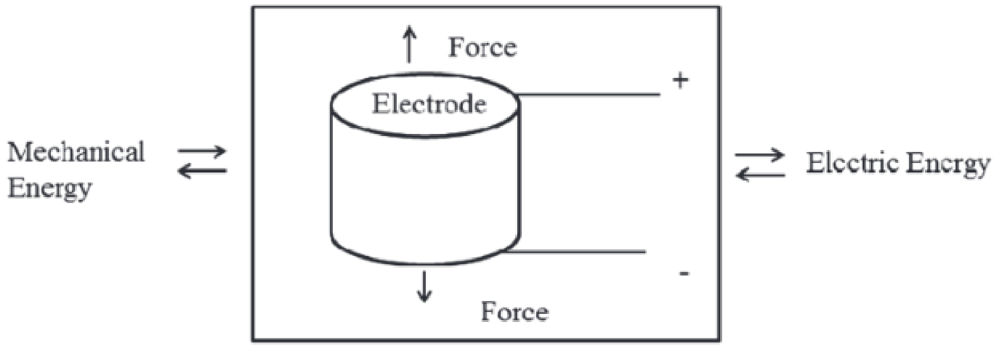


Figure 3.3: Electrical to mechanical energy conversion scheme

Generally, the electric potential is created via electric field generated during the distribution of electrical charge. Similarly, the mechanical stress triggers the distribution of electrons in a piezoelectric material. Some piezoelectric materials are polarized by nature, however, the mechanical force alter the polarization resulting in the piezoelectric effect. Materials not polarized by nature, get polarized when a force applied. It can be seen as non-polarized materials become polarized when stressed. Figure 3.4 demonstrates the piezoelectric effect on a quartz crystal.

Typical piezoelectric energy harvesting system is composed by six blocks, the system load being the last element:

1. Energy source, usually mechanical
2. Mechanical energy transformer
3. Piezoelectric transducer
4. Power electronics, usually AC/DC conversion circuit

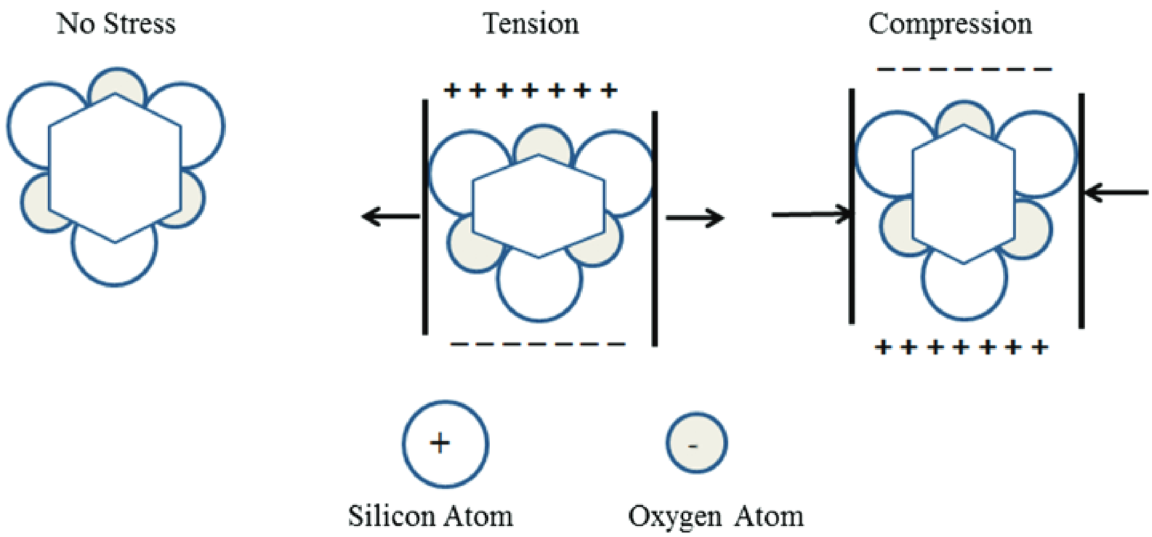


Figure 3.4: The piezoelectric effect produced in quartz

5. Storage management module
6. System load

The possible energy sources can be acoustic, movement, or rotational energy, i.e. pressure, acceleration, force. Matching the mechanical impedance and conversion of non-translational into translational energy are carried out in the mechanical energy transformer block. Piezoelectric power harvesting circuit has three main steps. First, the current has to be rectified. Second, the filtering and stabilization has to be applied. And, at last, the power has to be transferred. The power before being supplied to the load has to be stored. The load, typically a microcontroller-based system, has to take into account that the available power is not that much and has to be utilized with precaution. This process, shown as a diagram, is presented in Figure 3.5.

3.3 Thermal Energy Harvesting

The thermoelectric energy harvesting is founded on the Seebeck effect. It was discovered by T.J. Seebeck in 1821 researching metal thermocouples (Seebeck, 1895). It consists in conversion of a heat flow into electricity. Figure 3.6 illustrates the working principle of the Seebeck effect.

Two materials, A and B, are placed in a way that both have two common sides. One side should be maintained at high temperature T2 and the other at low temperature T1. The electrical connection of the materials are performed on high temperature side while the voltage is monitored across the cold side terminals. Free particles (electrons and holes) in a material spread according to a heat flow created by the temperature difference. Another elements moved by the heat flow are phonons or lattice vibrations. The motion of charged particles will concentrate space charges at both material terminals. These charges, in turn, create an opposing electric field. The opposing field exists while the complete equilibrium

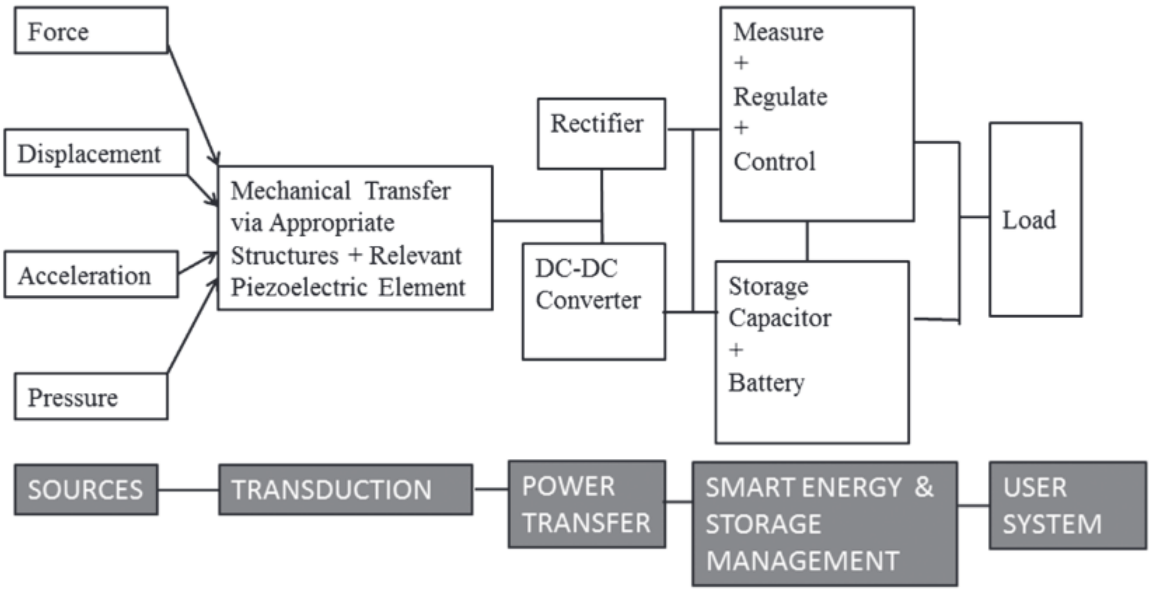


Figure 3.5: Diagram of a typical piezoelectric energy harvesting system

condition has not been reached.

If the materials A and B from the Figure 3.6 were identical, the resulting potential differences would cancel each other generating no voltage. However, if A and B are different, the output voltage will be a positive value. The load connected to the output terminals will receive the generated power. This way the electrical power is generated by the heat flow. The resulting structure was called a thermocouple.

The output voltage V and temperature difference ΔT are equalized by the equation $V = \alpha\Delta T$, where α is the Seebeck coefficient, different for each material. The deduced relationship is not linear and, thus, α depends on temperature. The output voltage of the thermocouple shown in Figure 3.6 will be equal to $V = V_A - V_B = (\alpha_A - \alpha_B)\Delta T$. Each thermocouple has its Seebeck coefficient equal to $\alpha = \alpha_A - \alpha_B$.

There are several factors which determine the output power of a thermocouple: series resistance and the conversion efficiency. The efficiency represents the ratio between the output power and the total heat flow. Critically thinking of these factors will lead to a conclusion that the Seebeck coefficient, high electrical and low thermal conductivity are the key properties for the used materials. Considering the low thermal and high electrical conductivities will create a trade off for the optimal material selection. Decreasing the thermal conductivity will result in decreasing the electrical conductivity.

3.4 Radio Frequency Energy Harvesting

The Radio Frequency (RF) waves is another possible source of energy which has been under continuous development last decade. Briefly, it is a capability to receive and convert RF signals to electrical power. There are three wireless energy transfer techniques and RF energy transfer and harvesting is one of them. Another two techniques are mag-

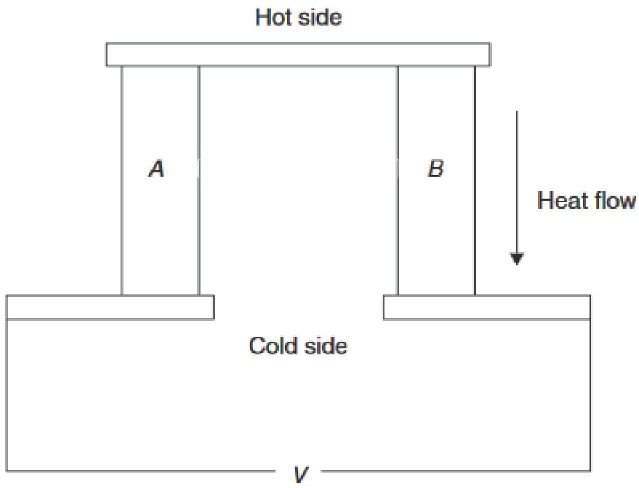


Figure 3.6: Thermoelectric generator working principle

netic resonance coupling and inductive coupling. Magnetic resonance coupling employs evanescent-wave coupling for generating and transferring electrical energy between two resonators (Wei, Wang, and Dai, 2014). The resonator is created by adding a capacitance to an induction coil (Lu, Wang, Niyato, Kim, and Han, 2015). The inductive coupling is based on magnetic coupling through which the electrical energy is delivered (Liu, 2011). Both coils, on transmitter and receiver have to be tuned to the same frequency. Generated magnetic field serves as the medium for energy transmission.

In contrast to RF energy harvesting the magnetic resonance and the inductive coupling are close-field wireless transmission techniques with high conversion efficiency and power density. According to the features associated to the magnetic resonance and the inductive coupling they do not suit for mobile and remote charging. However, RF electromagnetic waves cannot affect the antenna which created them if distance exceeds $\lambda/(2\pi)$ (Johnson, Ecker, and Hollis, 1973), therefore RF energy transfer is considered as far-field energy transfer technique (Lu et al., 2015). The far-field energy transfer makes possible to supply energy for powering numerous electronic devices dispersed through a wide area. General RF energy harvesting architecture is shown in Figure 3.7.

The RF waves are basically electromagnetic waves. Normally, they originate at a radio transmitter in a form of photons which oscillate within a determine transmission frequency. The transmission frequencies comply defined standards. UHF, SHF, VHF are common examples of standard RF transmission bands. Thus, the main source devices for RF energy harvesting are electronic devices which emit intentional electromagnetic radiation. It is important to note that the transmission frequency of the emitter is well-defined and frequencies of both emitter and receiver nodes must match.

A main disadvantage of this technique consists in the magnitude of energy harvested by these devices. It is considerably small. The limitation is given due to the low transmission frequencies, e.g. UHF ranges from 300 MHz to 3 GHz. Compared to the frequency of photons that hit a solar panel which typically ranges from 270 THz to 1600 THz, they differ in 5 to 6 orders-of-magnitude lower energy-per-photon for RF harvesting (Soyata, Copeland, and Heinzelman, 2016). This is why the application area of RF energy

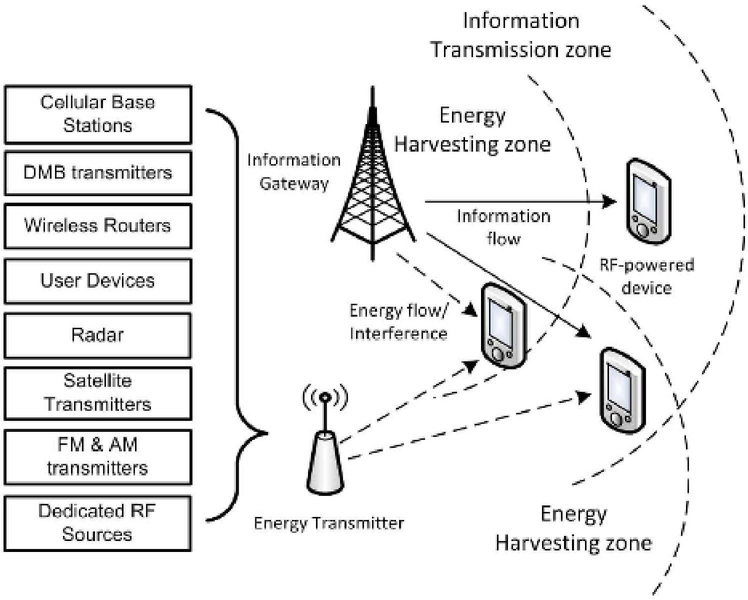


Figure 3.7: General architecture for RF energy harvesting

harvesting is substantially reduced and only tiny embedded systems can be powered by them.

3.5 Radioactive Sources

Radioactive energy is also can be considered as a source for energy harvesting. Since safety issues are of a great concern and complex processes assumed, these sources was not widely researched. However, there were studies carried on Al^{26} and how its radioactive decay can be exploited (Johansen and Okuzumi, 2017). A huge amount of energy released during these reactions and only using a small portion of it will supply power enough for functioning during centuries. There is no doubt that it is the most efficient source of energy, though, general access and use are still a challenge.

4 Common Power Transformation Topologies

As previosuly mentioned, electronic equipment industry has driven power supply systems design creating multiple niches. Depending on power requirements of a system there were elaborated many topologies, each one suited for a particual requirement.

This section reveals those common topologies and provides insights into principles that govern them.

4.1 Switching Topologies

Switching power supplies operate by changing states, with high frequency, of the pass units between two efficient operating states: on (saturation), where the highest current are allowed though the passing unit with a small voltage drop and off (cutoff) where no current passes through the passing unit and there is high voltage across its terminals. A semiconductor device such as a MOSFET or BJT usually serve as the passing unit. In essence, the semiconductor switch produces an AC voltage from DC input. The created AC voltage can be than stepped up or stepped down, employing different combinations of magnetizing electronic components (usually transformer, inductor or both), and, finally, filtered to DC output again. Switching power supplies are very efficient, ranging from 65 to 95 % of efficiency.

The most common switching power supplies topologies are described in the following sections.

4.1.1 Isolated Fly-Back Converter

Fly-Back Coonverter is a popular solution suited for low and moderate power levels (up to 150 W) when an electronic isolation is needed. The popularity of this topology is due to the following characteristics.

1. Isolation from high voltages
2. Low components count
3. Cost
4. Relative simplicity

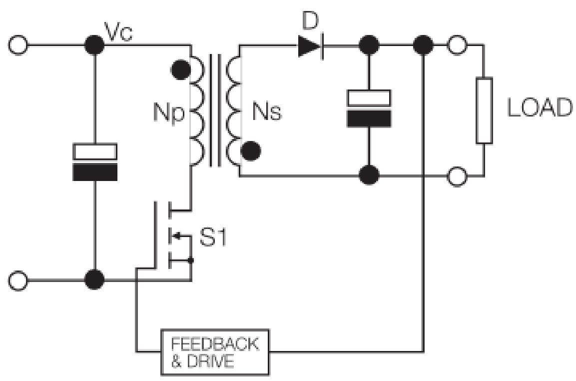


Figure 4.1: Isolated Fly-Back Converter Circuit

The topology is derived from the buck-boost converter discussed in 4.1.6 and 4.1.7, substituting the central inductor by the transformer, or inductor wound with two parallel wires, and the position of the MOSFET. The transformer is sometimes called as ”two-winding” inductor or *flyback transformer* (Erickson, 2004, Chapter 6). The difference between the ideal transformer and the flyback consists in the current flow. It does not flow simultaneously in both windings of the flyback transformer. The Fly-Back Converter circuit can be observed in the Figure 4.1.

Based on the MOSFET state, basic operation of the fly-back converter can be devided into two phases: on- and off-phase. When the MOSFET S1 is on, the current increasingly flows into the primary winding (Np side). A diode D in this phase is used to stop any current flowing to the load. Once the primary side inductor is charged, the S1 goes off causing the discharging of the primary side into the secondary one. The diode D becomes forward biased and the power is delivered to the load through the load capacitor. As the S1 goes off again, the voltage across it ”flies back” to the source voltage.

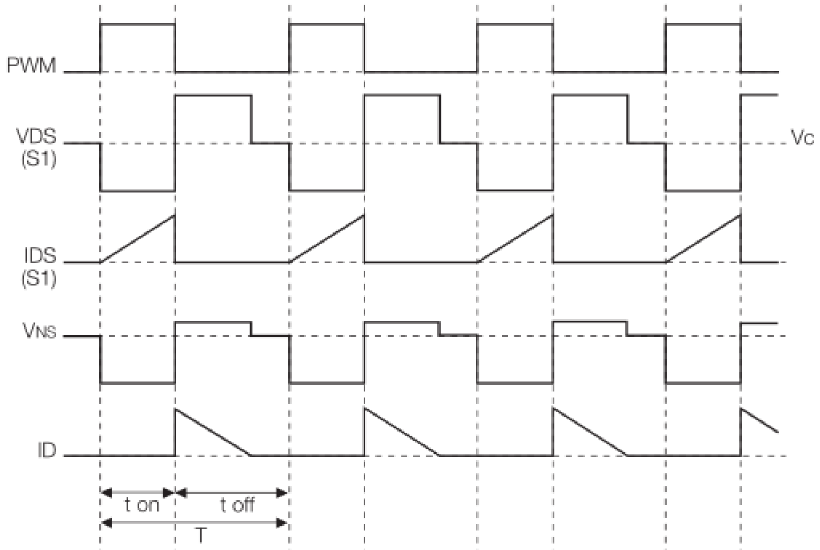


Figure 4.2: Isolated Fly-Back Converter Waveforms

The fly-back transformer serves as an isolated inductor which stores the energy every cycle, while normal transformer transfers energy immediately to the load. The converter can work in the continuous and discontinuous modes. In continuous mode the flyback transformer inductor current never reaches zero. The waveforms of on- and off-phases in discontinuous mode can be observed in Figure 4.2. Discontinuous mode waveforms are used for illustration since continuous mode will be easily derived.

One can note that the transformer polarity is reversed. It is done to obtain a positive output voltage. However, if the transformer is not designed properly, it will generate losses (“Designing a Low Power Flyback Power Supply. Application Note”). Another limitation arises when this topology is used with loads requiring more than 100 W. At these rates the transformer generates significant losses and other, more efficient, topologies might be employed. The fundamental restrictions are based on the high levels of ripple current in the output capacitor and the need to store high levels of energy in the flyback transformer.

Another issue should be considered during the design process. Due to the transformer architecture, there is a gap in its core which supposes an increase in magnetic leakage flux generating a leakage inductance. The switching current also flows to the leakage inductance what generates an energy buildup. This energy does not transfer anywhere, thus, creating a surge voltage to the drain of the MOSFET. This voltage, if not considered, can exceed the voltage tolerance and destroy the MOSFET. In order to prevent this scenario a snubber circuit might be introduced ("Isolated Flyback Converter Basics: Flyback Converter Operation and Snubber", 2016). It will suppress the surge voltage. A typical snubber circuit is composed of a resistor, capacitor, and diode, thus called, RCD circuit. It can be observed in Figure 4.3 and values calculated according to a defined scheme ("Designing a Low Power Flyback Power Supply. Application Note").

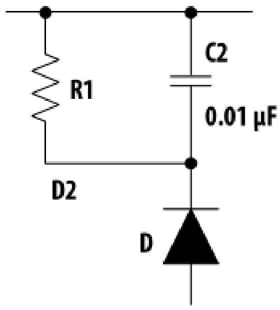


Figure 4.3: Typical snubber circuit

4.1.2 Forward Converter

The Forward Converter is based on the buck converter. Since its configuration requires a MOSFET, its power rates are lower than ones found in full-bridge and half-bridge topologies discussed further in Section 4.1.4. However, forward converters are used with higher power ranges than Isolated Flyback Converter, namely 100-300 W. The forward converter circuit is presented in Figure 4.4.

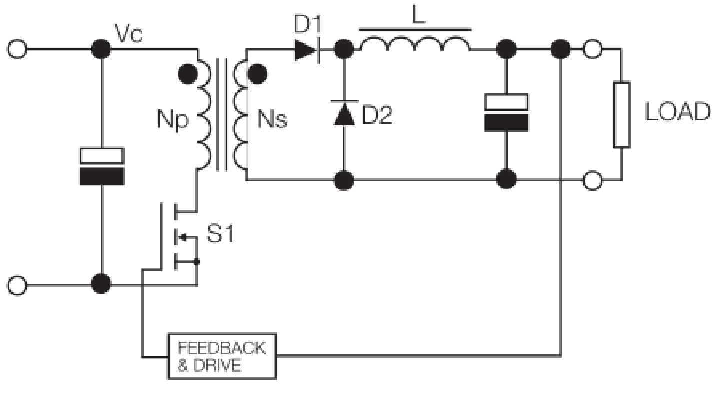


Figure 4.4: Forward Converter Circuit

The workflow of the converter is split into switching periods, and each period into 3 subintervals. During subinterval one the MOSFET S1 is on and diode D1 becomes forward biased, while D2, on contrary, reversed biased. The source voltage is applied to the primary side of the transformer increasing the magnetizing current of the transformer. Once the MOSFET S1 goes off, the next subinterval begins. Similarly to the flyback transformer, the charged side of the transformer discharges transferring current to the secondary side. Diode D1 prevents current flow into the secondary side of transformer entering to the reversed biased state, while D2 becomes forward-biased conducting output current to the inductor L. Finally, when the magnetizing current stored in the transformer reaches zero, the third subintervals begins. This subinterval exists for the sake of switching period balancing. Otherwise, the duty cycle will be distorted and the transformer saturated. The waveforms for described process are presented in Figure 4.5.

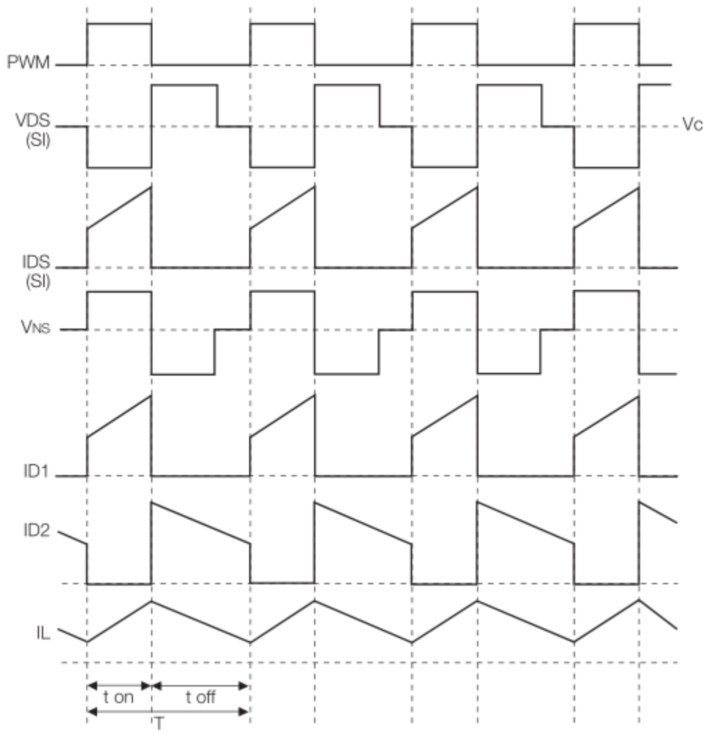


Figure 4.5: Forward Converter Waveforms

The output current is filtered from ripples and other pulsations by the inductor L, as in other buck-derived converters, what makes this type of converters well-suited for applications requiring high and stable output currents.

4.1.3 Two-Transistor Forward Converter

The two transistor forward converter can be used when higher power rates are required. Its operation principles are similar to the standard forward converter.

The converter circuit is shown on Figure 4.6. The MOSFETs S1 and S2 are driven by the same control signal. S1 and S2 conduct during subinterval 1 and are off during subintervals 2 and 3. The secondary side of the transformer is the same as in the standard forward converter. The main difference consists in the subinterval 2 behavior. The current stored in the primary side of the transformer changes the added diodes to the forward biased state, thus, connecting it to the source voltage with the opposite polarity to the first subinterval, decreasing the magnetizing current with the increased slope. Once the current reaches zero point, starts the third balancing subinterval.

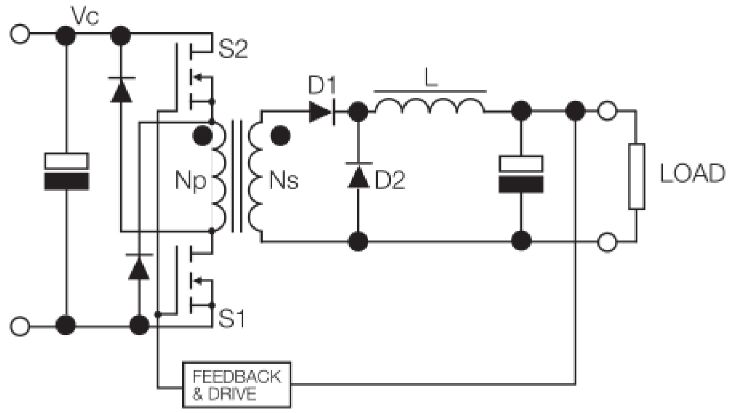


Figure 4.6: Two-Transistor Forward Converter Circuit

The limitations of duty cycle of the two-transistor forward converter remain the same as of the single-transistor one. Typically, the power levels of this topology are similar to the half-bridge configuration. The waveforms are presented in Figure 4.7.

4.1.4 Half Bridge and Full Bridge Converters

Half bridge converters are employed in relatively high power range, that is, from 150 W and up to 1000 W. It is a kind of buck converter which reduces voltage depending on the transformer winding proportions.

There are two basic major components used in this topology: a transformer and an inductor. Comparing to the forward converter the transformer's core here is better utilized, since it is spit into two windings. This has a benefit of doubling the switching frequency which reduces the volume of output inductor and capacitor. Another benefit is the halved MOSFET voltage managed by each element. Moreover, two power MOSFETs and two large-volume capacitors are needed, though one of them may be omitted. The Half bridge converter circuit can be observed in Figure 4.8.

The working principle splits into 4 subintervals. During the first subinterval the MOSFET S1 is on and S2 is off, charging the primary side with the transfer magnetizing current. The diode D1 is in forward biased state allowing the current flow to the load and D2 is reversed biased. During the second subinterval, both MOSFETs S1 and S2 are off while both diodes D1 and D2 are forward biased. The magnetizing current stored in the primary discharges into the upper secondary, Ns1, maintaining the current flow to the load. During the third subinterval S1 is off and S2 is on, charging the primary however with current and voltage of opposite polarity. The diode D2 is forward biased and D1 is reversed biased.

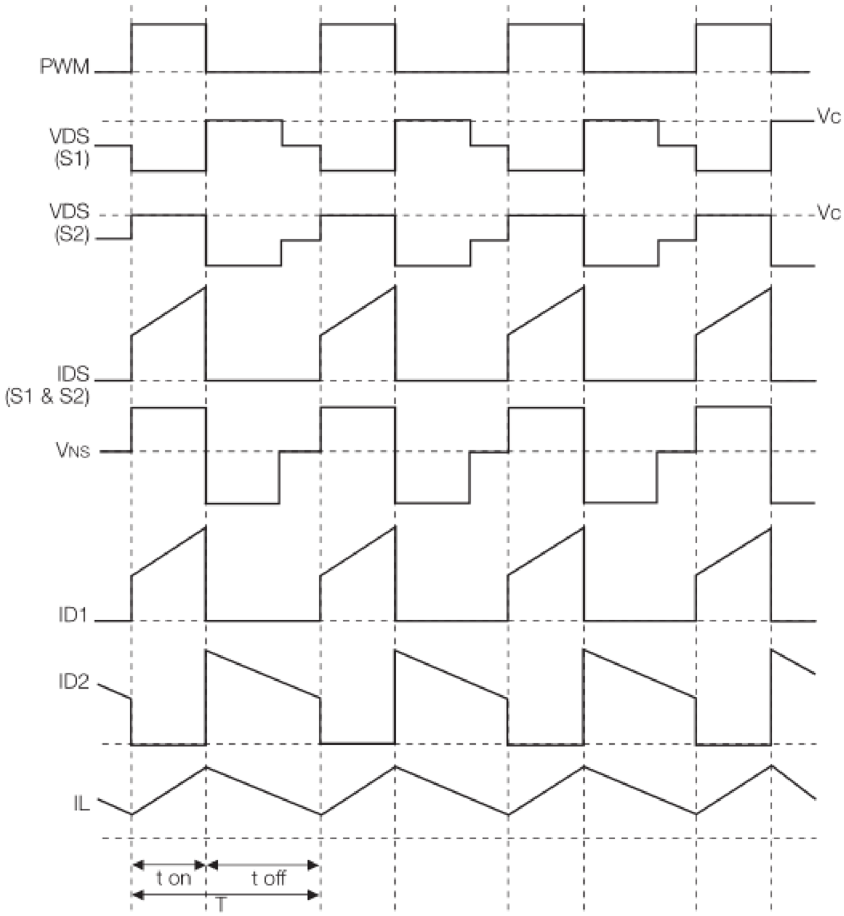


Figure 4.7: Two-Transistor Forward Converter Waveforms

The last, fourth subinterval is identical to the second one except the primary discharges into Ns2, the down side of the transformer. The basic waveforms can be observed in the Figure 4.9.

Full bridge converters are used in solutions with even higher power requirements, 750 W and greater (Erickson, 2004, Chapter 6). This topology provides doubled primary current and voltage, but higher components count. It requires four power MOSFETs and more complex switching drive circuit compared to the Half bridge. The typical Full bridge circuit can be seen in Figure 4.10.

The working principle of the Full bridge is similar to the Half bridge. However, there are several differences which should be highlighted. There are also 4 subintervals from which only the first and the third are different. During the first subinterval MOSFETs S1 and S4 are on and S2 and S3 are off, allowing the source voltage to be applied to the transformer. Complementary to the first subinterval, during the third one the S2 and S3 are on and S1 and S4 off. This time the negative source voltage is applied to the transformer. There are several schemes of transistors control during the subintervals 3 and 4, where the most common one is all four transistors are off. The waveforms representing the workflow can be seen in Figure 4.11.

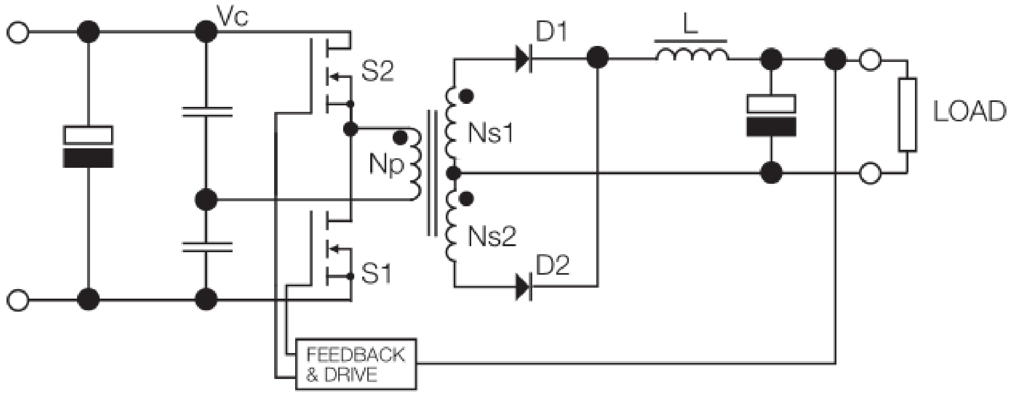


Figure 4.8: Half bridge converter circuit

The Full bridge and Half bridge converters utilize very efficiently the transformer since its magnetizing current can be positive or negative. It has a great utilization of the primary winding, however the secondary split winding do not. It is due to the fact that each half of it transmits only during alternative periods, having some power losses on the opposite winding side during 1 and 2 subintervals.

Despite the higher components count, the Full bridge topology has several advantages over the Half bridge. The MOSFETs used in design have to handle halved values of current than in the Half bridge. This led the Half bridge topology to find applications at lower power levels where the power MOSFETs requiring lower currents are widely available.

Though the Half bridge and the Full bridge converters are used in AC power supplies, however, there is a tendency to use them in DC/DC converters. This topology is slightly different and is called Push-Pull converter which will be described in the following section.

4.1.5 Push-Pull Converter

The Push-Pull converter is considered as buck type converter and is used typically with low voltage levels. This topology is very similar to the Full/Half bridge converters with identical secondary sides. The difference consists in the transformer configuration. Its primary side has center tapped winding. The converter circuit can be seen in Figure 4.12.

The converter is used with low input voltages due to a connection of only one MOSFET in series with a voltage source. Limited voltages guarantee the primary side conduction losses to be small. It can operate on the entire range of duty cycles, $0 \leq D < 1$, what allows the transformer turn ratio optimization, reducing the MOSFET current.

The working principle is simple and similarly to the Half/Full bridge is separated into four subintervals. During the first subinterval S1 is on and D2 conduct being forward biased. The subinterval two and four are identical, having both MOSFETs off and both diodes forward biased. The only difference is the voltage and current polarity applied to the primary winding being opposite in each subinterval. During the third subinterval S2 is on and D1 is forward biased transmitting the current to the load. The Push-Pull converter has identical waveforms as the Full bridge converter which can be seen in Figure 4.10.

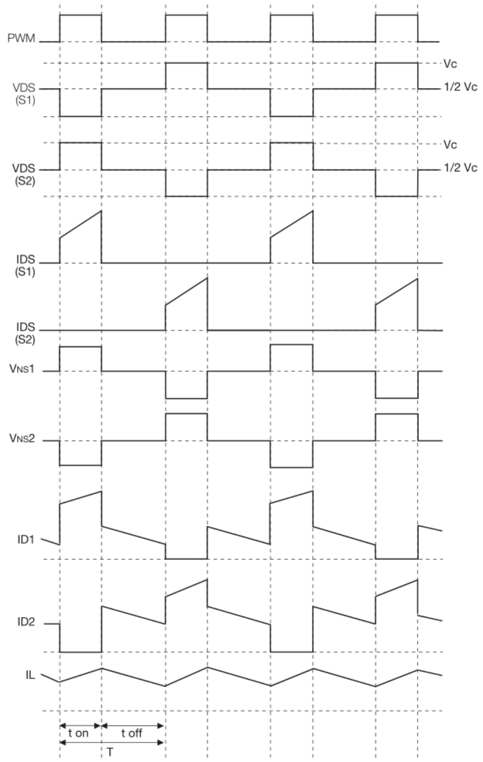


Figure 4.9: Half bridge converter waveforms

The Push-Pull converter has often problems with transformer saturation. The perfectly synchronized behavior of the MOSFETs S1 and S2 cannot be guaranteed, thus, even small differences in voltage drops or conduction times can lead to the application of small voltages across the transformer primary when it must be zero. Consequently, the magnetizing current will increase after each switching period leading to the net current accumulations which will provoke the transformer saturation. This problem can be mitigated using current control schemes.

4.1.6 Buck Converter

Buck converter is a very typical and popular power supply topology used in DC/DC step down voltage regulators nowadays. It is widely used when no load isolation is needed. As an example, it is often used in embedded systems design to regulate power supplied to the microcontroller (MCU), peripherals, and sensors. Moreover, due to its efficiency (often higher that 90%) it is employed in computer main supply voltage down to voltages needed by CPU, DRAM, USB, network cards and so on.

The circuit has low components count, usually 4 components: MOSFET switch, diode, inductor, and capacitor. The basic circuit is presented in Figure 4.13.

The basic operation of the buck converter consists of two subintervals controlled by the MOSFET S1. Starting with the S1 being off there is no current flow in the circuit and, hence, no output power. When S1 goes on, the current starts increasing triggering the inductor L to produce an opposing voltage across its terminals. The L charge current

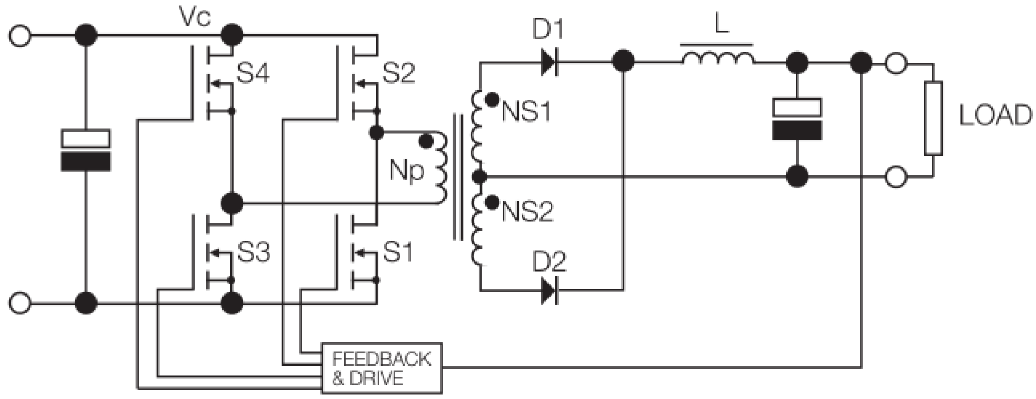


Figure 4.10: Full bridge converter

gradually increases until its saturation when the rate of current change decreases. The voltage across the L decreases increasing the load voltage. At this moment the energy is stored in L in form of a magnetic field. The step down effect is achieved disconnecting the source voltage while the L is still being charged. This way, the load voltage will never reach the source voltage. Next time, when the S1 is off, the source voltage is removed and the L becomes a current source. The diode D becomes forward biased and the magnetic field energy stored in L supplies the current to the load.

The current flowing during both the first and the second subintervals adds up a value greater than the original source current and ideally is proportional to the regulated voltage drop.

Typical waveforms for the Buck converter can be observed in Figure 4.14.

The converter can work in continuous and discontinuous modes, being the main difference between each mode the current level of the inductor. In the continuous mode it never falls to zero, while in the discontinuous it reaches zero. The most widely used mode is the continuous since the general load requirement is used to be at least low voltage supply. The discontinuous mode is used when the supply power is very small, allowing the current through the inductor to reach zero during a portion of the duty cycle.

4.1.7 Boost Converter

Another widely used power supply topology employed in DC/DC step up voltage regulators is the Boost converter. It transforms power by stepping up voltage and stepping down current. It requires the same components as the Buck converter however placed differently.

The Boost converter accepts a variety of power sources: batteries, rectifiers, energy harvesting sources, DC generators, and others. Its basic circuit is presented in Figure 4.15.

The working principle takes the same advantages of the components as the Buck converter, but achieving different goals, and the period is split into two subintervals. The subintervals are driven by the MOSFET switch S1. When the S1 is on, the current flows

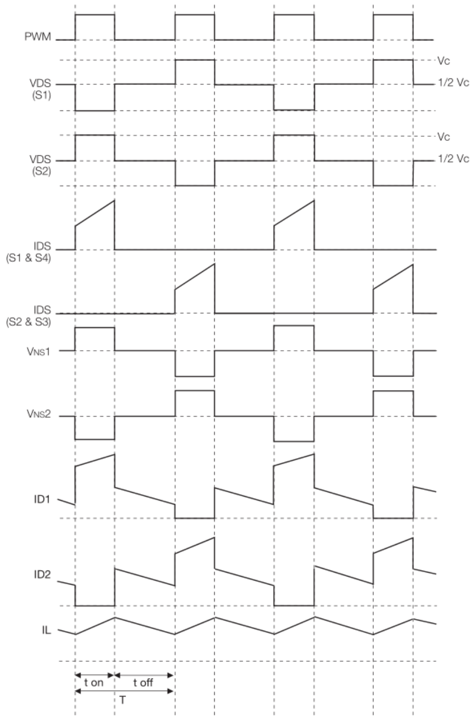


Figure 4.11: Full bridge converter waveforms

through the inductor L storing the energy in a form of a magnetic field. The diode D is reversed biased and prevents discharging of the output capacitor into the S1. When the S1 is off, the energy stored in L will be discharged to supply the current and voltage, in combination with the output capacitor, to the load. During the second subinterval both the input source and the L are connected in series increasing the voltage passing through the D. This voltage charges the output capacitor which maintains the constant output voltage level. Typical Boost converter waveforms can be seen in Figure 4.16.

The switching frequency should be fast to prevent the overdischarging of the inductor. This will provide always the output voltage greater than the input. The output current is limited by the inductor capabilities and, ideally, is lowered proportionally to the increased output voltage. This is given due to the power conservation law, $P = VI$. In practice, the Boost converter can increase output voltage up to five times the input voltage.

Often, buck and boost converters are combined into one topology called buck-boost converter. This topology comprises functionalities of both converters and can step up or step down input voltages.

4.2 Linear Topologies

Switching power supplies got popularity and their rapid development after the creation of the first switching transistor. It was back to the 1950s. The voltage regulators existed before were linear regulators.

Linear regulator is based on the principle of variable conductivity of active electronic

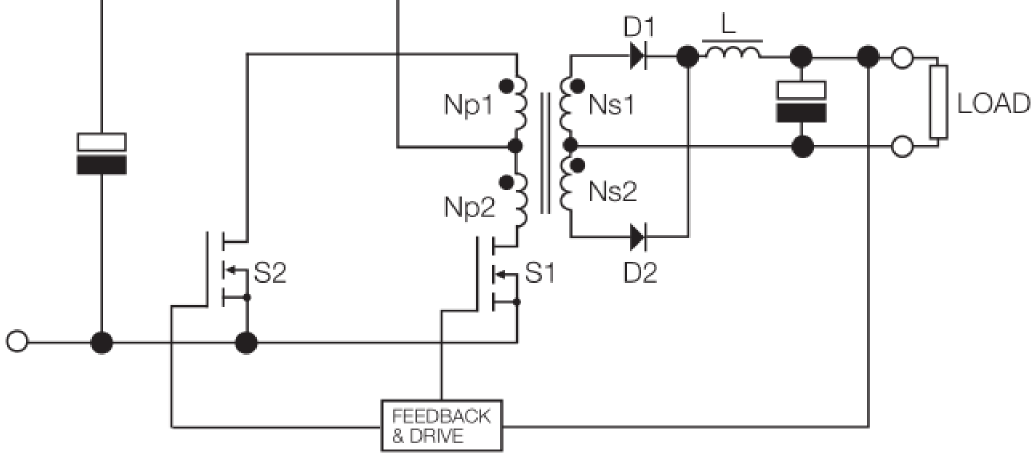


Figure 4.12: Push-Pull converter circuit

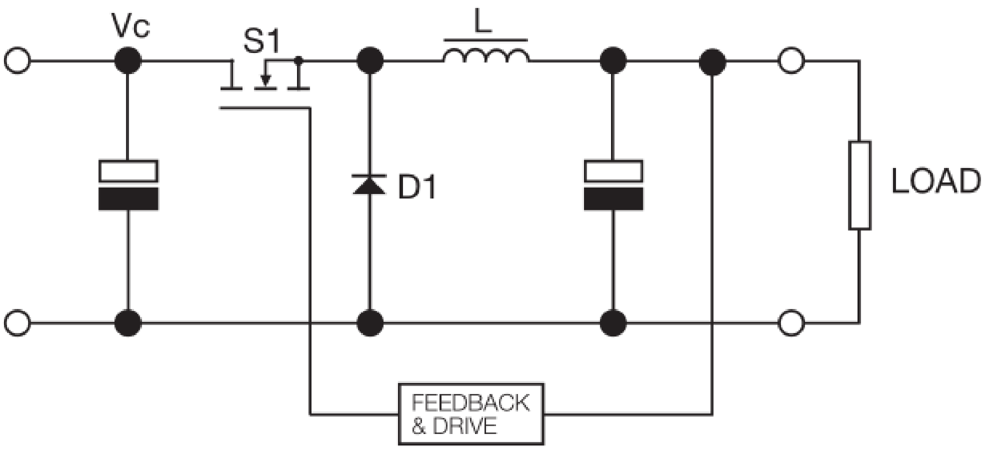


Figure 4.13: Buck converter circuit

component (Danzer, 2002, Chapter 2) which reduces voltage to desired level. The voltage drop generated by the regulator creates considerable power dissipation, usually through the heat. This is why these types of regulators are so inefficient. A benefit of this kind of regulators is that they produce extremely low levels of noise.

The linear regulators find many applications when the power inefficiency is not a concern, i.e. general purpose grid-powered electronic devices. Due to their low levels of noise they find a strong niche in audio and video amplifiers and Radio Frequency (RF) analog devices. This kind of regulators is useful in applications which require less than 10 W of output power. If applied to higher power requirements an excessive amount of generated heat has to be managed what becomes expensive.

Linear regulators are step down regulators only. There are only two types of linear regulators: the Shunt regulator and the Series-pass regulator. The shunt regulators are usually placed in parallel with the load. They draw an excessive output current maintaining a constant voltage across the load when source voltage and current are variable. A

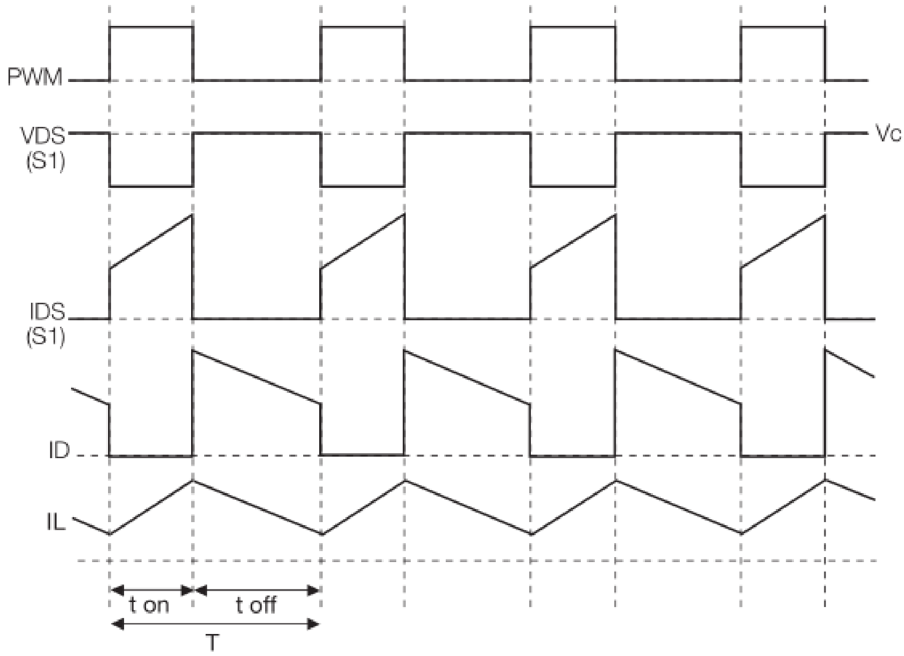


Figure 4.14: Buck converter waveforms

typical example is Zener diode regulator. The Series-pass linear regulators use an active semiconductor as the series pass component between the load and the input. Therefore, they tend to yield regulation more efficiently.

The active semiconductors are not used in complete on or off states, but rather in partially on state, so that only a desired portion of power can pass thought it. The degree of conductivity is decided by the negative feedback loop.

The foundation of the negative feedback loop is an operational amplifier which is called a voltage error amplifier (Danzer, 2002, Chapter 2). The role of this amplifier is to continuously sense the output voltage matching it to the the established voltage reference. The voltage reference usually fixed by a voltage divider. Internally, the amplifier produces a voltage gain which represents highly amplified difference between the input and the reference voltages. Further, this difference directly controls the conductivity of the semiconductor.

When the load suddenly consumes more power, the regulator output falls. This will provoke an increase of the voltage error amplifier what, in turn, will let more current from the input source to the load. And, the other way around, if the load decreases, the error rises and the output voltage is reduced. The transient response time characterizes the response time to the load changes.

Further the most common linear regulator topologies are described in detail.

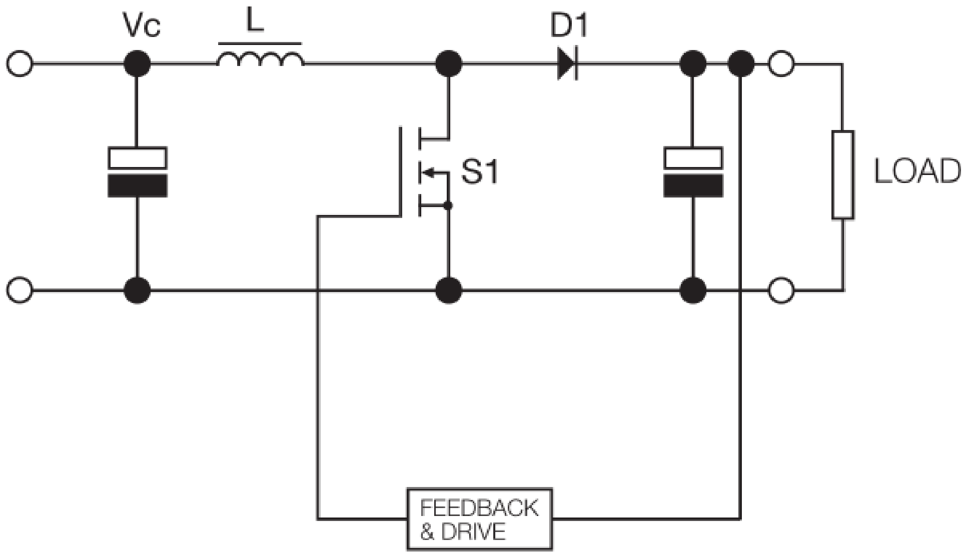


Figure 4.15: Boost converter circuit

4.2.1 Zener Shunt Regulator

Zener Shunt regulator is used with for loads requiring power less than 200 mW. The unregulated input voltage and current are limited by the series resistor connected to Zener diode. The diode has the property to compensate the variations in load current. One disadvantage is that the output voltage can drift depending on temperature. The Zener diode regulator is suited to supply voltage to Integrated Circuits (IC), however is has significant power losses what converts it to undesirable option for low-power electronic devices. The typical Zener diode circuit can be seen in Figure 4.17.

4.2.2 One-Transistor Series Pass Regulator

This regulator presents an improved version of the Zener Shun regulator. The regulation is achieved by integrating the Bipolar Junction Transistor (BJT) to the scheme and taking advantage of the gain it offers. The BJT is hooked as an emitter follower allowing much current to the load than the Zener Shunt regulator. It performs a function similar to the voltage error amplifier. When the load requires more current, than the voltage on the base rises allowing more current to pass through BJT to the load. Typical One-Transistor Series Pass Regulator circuit is presented in Figure 4.18.

4.2.3 Three-Terminal Positive Regulator Design

In this section will be illustrated basic design considerations which should be concerned during the design of a linear power supply. These considerations are common to the the majority of the ICs.

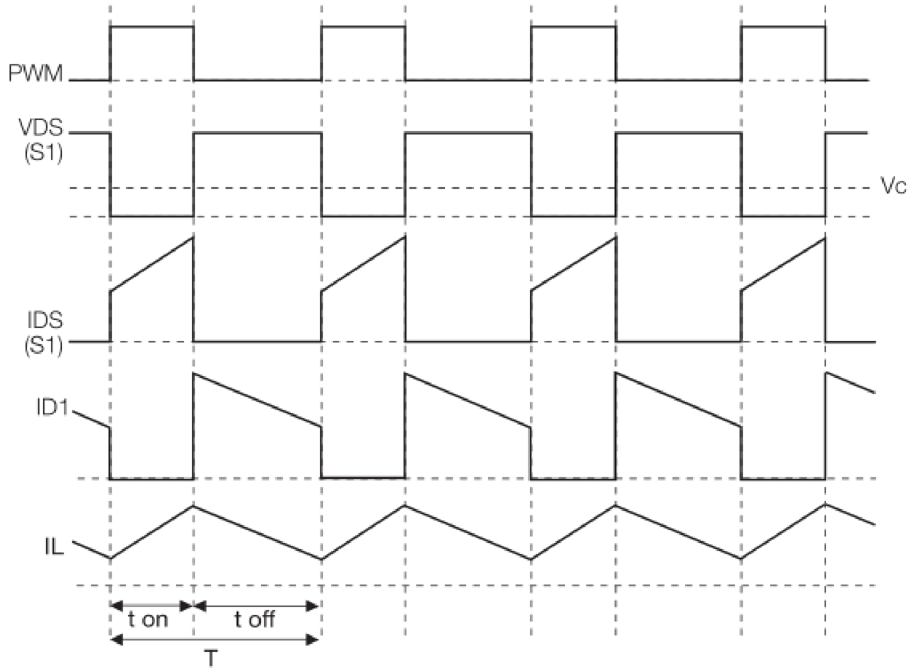


Figure 4.16: Boost converter waveforms

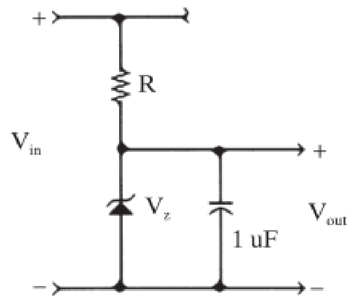


Figure 4.17: Zener Shunt regulator

Output voltage

This feature should be selected primarily based on the application power requirement. Typically used values are (24, 12, 5, 3.3) V.

Line regulation

It characterizes the variation of the output voltage to the input voltage changing.

Load regulation

The variation of the output voltage due to changes in the load.

Quiescent current

The current drawn for the operation when no load is present. It sometimes referred as standby current.

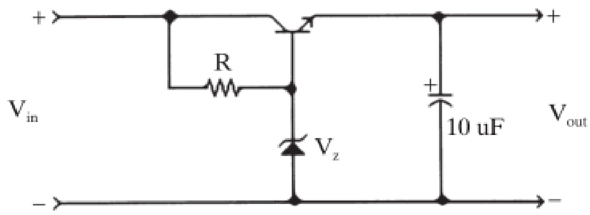


Figure 4.18: One-Transistor Series Pass Regulator typical circuit

Output noise voltage
Given as a Root Mean Square (RMS) of noise ripples present in the output voltage.

Ripple rejection
The output voltage variation due to the input voltage variation at a given frequency.

Dropout voltage
The difference of voltage between the source voltage and regulated voltage needed for proper work of the regulator.

Power dissipation
It characterizes the amount of power turned into heat. Normally, it complies to the next equation $\Delta V * I = (V_{in} - V_{out}) * I_{out}$

There are additional concerns regarding the output filter capacitors and methods for determining their values which are not covered by the present work.

5 Power Supply Protection

Power supplies in normal conditions are continuously exposed to different hazards from the power sources and, at the same time, they may exhibit a hazard for the load. A well-designed power supply has to be protected from external hazards and protect the load from possible failures. Since the electric power has two components, current and voltage, these two a the sources of possible nuisance.

This section will consider protection strategies, related to current and voltage, and measures to be taken for both, input and output power.

5.1 Input Protection

Before the power supply system provides specified power to the load it draws an input power from external sources, may they be AC primary supplies or batteries. There exist several considerations which must be contemplated related to the input current and voltage.

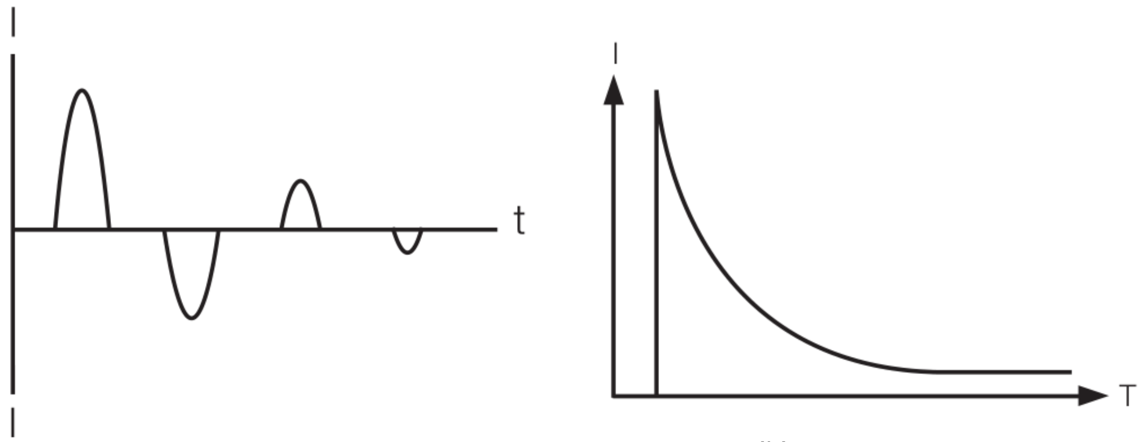
5.1.1 Input Current

The simplest and must-to-be form of current protection is the input fuse. Though, it will fail only when some fatal power supply failure happens. Fuses can be integrated in several ways: directly soldered on PCB or used as replaceable cartridges.

In fault conditions, hundreds of Amperes can flow through a circuit. This will cause the cables and other conductors increase their temperature very quickly creating a serious fire hazard. This is why the fuse is so critical and basic form of input current protection. It will quickly clear preventing the fire hazard on one side and the short circuit to the AC primary on another.

Inrush Current

At a moment when a power supply has been connected to a power source, the input reservoir capacitor is completely discharged. In this condition it will require a rapid charge. This rapid charge has appearance of a short circuit and provokes the inrush current. As the AC primary or a DC battery are used as power sources with low impedance, they will offer necessary power. The input current will be very large, typically in range of 30-40 A, for a short period of time, about 1-2 ms. This will cause disturbances on the supply line and may damage any switches, relays or fuses and other circuit breakers. The input current vs time curves in described conditions for both, AC and DC sources are shown in Figure 5.1.



(a) AC power input

(b) DC power input

Figure 5.1: Input current vs time curves for AC and DC power supplies. Typical peak is about 30-40 A

The most common technique used to tackle the inrush current is to use a Negative Temperature Coefficient (NTC) thermistor. It has a low resistance on high temperature and high resistance when it is cold. Thus, on cold plug-in it will smooth the current, gradually increasing its temperature.

Sizes of fuses and circuit breakers have to be determined according to the input power. Fuses are characterized by the current limit and a time lag, time for a fuse to be cleared at a specified current. The time lag is ranged as very fast to very long with the next marks: FF, F, T, TT. They have to be chosen according to a degree that the disturbances can be accepted.

Thermal Circuit Breakers

Thermal circuit breakers have similar to fuse characteristics, the current limit and the time lag, as well as selection criteria.

These devises have significant advantages over conventional fuses. They are not destroyed when an overload or a short circuit occurs and can be reset. They utilize a bimetallic strip placed in series with the circuit. On failures, the generated heat deforms the bimetallic strip and triggers the breaker. Another advantage is that they can be used as main on/off equipment switches.

Magnetic Circuit Breakers

Magnetic circuit breakers are significantly faster and more accurate. They are manufactured allowing different time lags what brings useful benefits for different applications. The main characteristics and the selection criteria remain the same as for standard fuses and thermal circuit breakers.

Magnetic circuit breakers use electromagnets which polling force vary depending on the current. As the current reaches the limit the electromagnet's pull releases the latch. Finally, a spring triggers the contact to open.

It became an industry standard to combine magnetic and thermal mechanisms creating a thermal-magnetic circuit breaker. This breaker is commonly used in Europe.

5.1.2 Input Voltage

Input voltage can vary creating under- or overvoltage conditions. Overvoltage conditions include fast transients, surges, and spikes. Fast transients are generated by connected motors and fluorescent lamps, surges are produces by lightning strikes, and spikes by switching different loads.

There are well-defined location-dependent standards for creating and testing fault conditions.

Transient Voltage

Electronic Fast Transients (EFT) are voltage disturbances created sporadically or periodically. Motors and fluorescent lamps generate periodic EFTs, while lightning strikes do sporadic EFTs.

Transient voltage hazards differ for AC and DC power supplies. Therefore, the measures to tackle fault conditions will vary.

For AC power supplies Metal Oxide Varistors (MOV) in combination with Gas Discharge Tubes (GDT) are used. MOV is a voltage-dependent non-linear device. Its resistance changes depending on the input voltage. It functions, similarly to Zener diode discussed in Section 4.2.1, limiting the voltage to a specified value. When EFTs are applied, it maintains the voltage provided to the load increasing the outcoming current.

A GDT is a bulb or tube filled with gas or gas mixture and with two or more electrode contacts inserted into it. When a voltage applied to the electrodes reaches breakdown level, the gas ionization initiates an avalanche process through the tube. Changing spacing between electrodes and gas composition allows to obtain various breakdown configurations.

Since it has very similar current vs voltage characteristics as the MOV, it produces the same effect and serves as another component for power supply protection.

Another typical component used for circuit protection of both, AC and DC supplies is the Transient-Voltage-Suppression diode (TVS or Transorb). Transorb is a clamping device which suppresses all overvoltage potentials greater than its breakdown voltage. The advantage it has over the MOV and GDT consists in its fast response measured in picoseconds. It is highly useful for protection against fast EFTs.

And the last protection technique used only in DC power supplies is called active electric protection. It consists in inclusion of a DC/DC converter (with output voltage less or equal than input voltage of the main voltage regulator) prior to the main voltage regulator or a circuit (MOSFET) which disconnects the main voltage regulator when EFT applied, supporting the load with capacitors. An example of such circuit is shown in Figure 5.2.

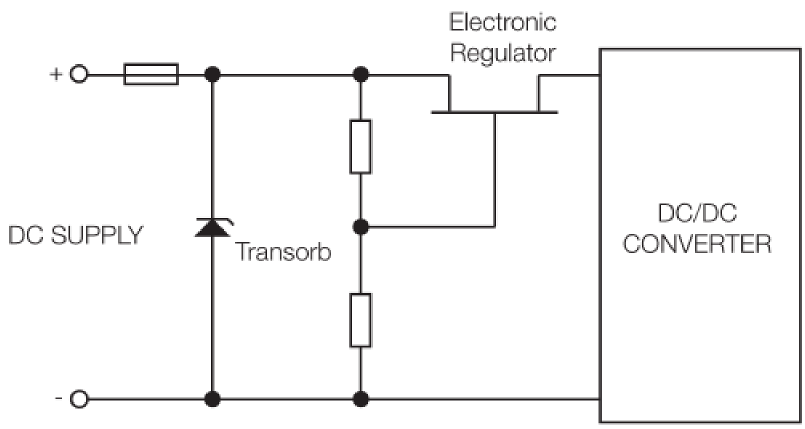
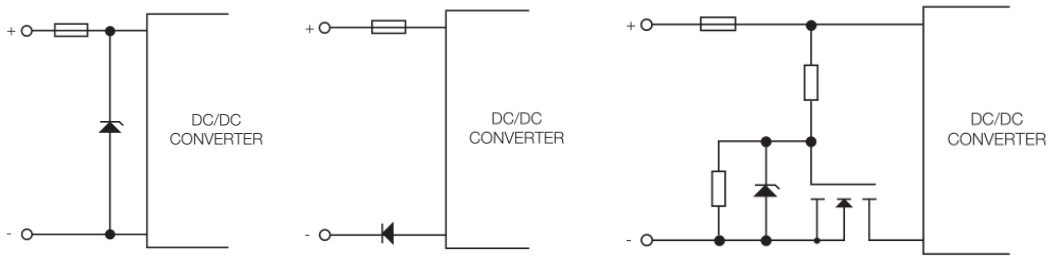


Figure 5.2: Typical DC input EFT protection circuit

Reverse Polarity

For the reverse polarity protection there are three widely used techniques: shunt diode, series diode, or MOSFET.

When the shunt diode is used, on reverse connection it will become forward biased and rapidly clear the fuse preventing the AC primary from being shorted. The DC/DC converter will be saved, but the fuse will have to be replaced. A typical circuit is shown in



(a) Shunt diode (b) Series diode (c) Series MOSFET

Figure 5.3: Common types of reversed polarity protection

Figure 5.3a.

Another option is to include a series diode or MOSFET. In these cases, when a DC Source has been reversely connected the current flow is prevented. The biggest disadvantages are permanent power losses and minimum operating voltage limiting the DC/DC converter operation. Typical circuits for series diode and MOSFET protection are shown in Figure 5.3b and Figure 5.3c correspondingly.

5.2 Output Protection

The output protection should be designed not only for the load but also for the power supply protection. Main types of protection can be separated in different groups. Overload protection cares about the power supply, while overvoltage and fault current protection do about the load.

Overload Protection

The load also can be a possible source of hazards. It can fail presenting a short circuit or simply create overload conditions. The most common overload protection techniques are discussed below.

Constant Power Limit

This technique is used in multiple output as well as single output power supplies. The power from a management circuit is constantly monitored and limited when necessary. It is extensively used in battery charging circuits. As have been discussed in 2.3, the charging cycle requires a constant current or constant voltage depending on a charging phase.

When the current output reaches a critical point, established by engineers, the supply must manage this situation. A constant current limit mode, discussed in the next subsection, can be enabled or the supply will go off and, after some time, on, monitoring the output conditions.

To implement this behavior, a designer has to consider available Power Management Integrated Circuits on the market and choose the one satisfying the application requirements.

Constant Current Limit

The idea behind is very simple: when the load requires a current which exceeds the established limit, the actual current will remain constant at a predefined level. The technique has many advantages in applications including motors, lamps, or loads requiring inrush capacitors charge.

Fold-Back Current Limit

In this strategy, when the overload condition is detected the output voltage and current are reduced simultaneously. It is very useful for linear power supplies and applications with Crowbar overvoltage protection, otherwise the circuitry will dissipate an excessive heat. As in the Constant Current Limit protection, the normal power output will be recovered when the overload condition disappears.

Fuses and Circuit Breakers

It is not a general case when fuses or circuit breakers are used for the power supply output current. Only large battery systems or massive power output distribution with multiple branches will require this measure of protection. An excessive current flow has to be limited. In battery applications, due to its low impedance circuit breakers can be employed. The main disadvantage of both techniques, consists in human intervention for the recovery.

A Positive Temperature Coefficient (PTC) thermistor can be used in a power supply with multiple branches as a resetting measure of protection. The PTC will heat up on the overload condition increasing the resistance and, this way, limiting the current flow to the load. Normally, the system has to be powered off after the incident for a complete recovery.

5.2.1 Overvoltage Protection

There are two major overvoltage protection techniques: use of the crowbar or electronic protection.

Crowbar Protection

The Crowbar protection can be implemented with an active component being a tyristor or a Silicon Controlled Rectifier (SCR). A basic crowbar circuit has tree elements: Zener diode, resistor and the active element. It can be seen in Figure 5.4.

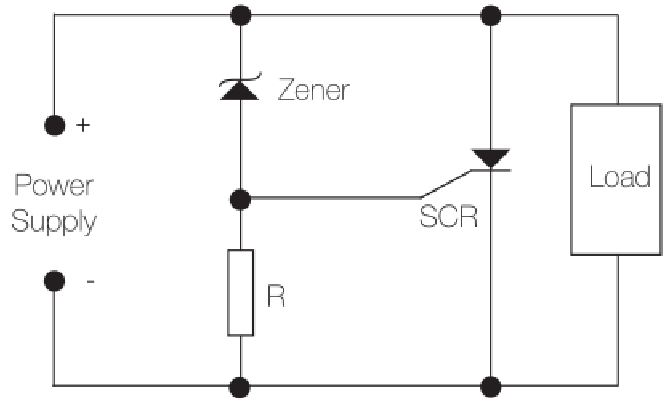


Figure 5.4: A basic Crowbar protection circuit

The Zener diode sets the output voltage limit. If the output voltage surpasses the limit the SCR goes on, inducing the power supply to enter the overload state. In this state the output voltage can be clamped to a predefined low value or short circuited.

The crowbar protection often combined with Fold-Back current limit protection.

Electronic Protection

It consists in addition of a second feedback loop which is employed on fault condition. If the main feedback loop fails, the second one turns it off. In order to recover after the fault, the system will need a reset. Most switching power supplies today use this kind of protection.

6 Combining Multiple Power Sources

Purposes of combining multiple power supplies can be different. Applications can require higher voltages, greater power, fault tolerance and redundancy, or power switching. Each of these requirements can be satisfied employing different techniques. This section provides an overview of the most common techniques.

6.1 Parallel Operation

Parallel operation is designed when greater power requirements are posed. The connection can be easily made with just several considerations. The connection topology is a star formation with the load in the center. Typical parallel power supply connection is shown in 6.1.

Power supplies physical connection should not be looped. Otherwise, the connectors will be overloaded and the overall sharing be deficient. It is important to adjust output

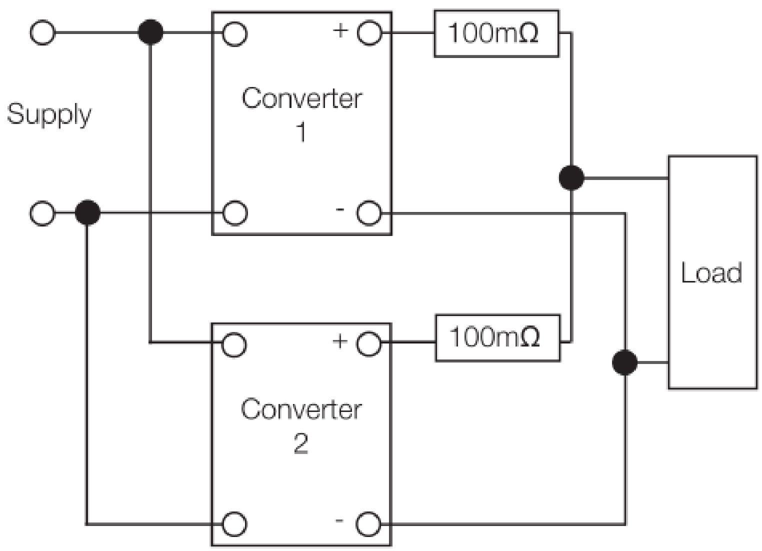


Figure 6.1: Two power supplies connected in parallel

voltages of each power supply closer as possible as well as impedance matching of the used cables and wires.

In case of unequal voltages, the power supply with the highest voltage will provide power for all the load. This puts this power supply into a hazard of running out of the maximum output capability. The problem can be handled by using series resistors which will balance the output current. However, due to the resistors value proportionality (they should match to the output voltage), there still will be a small voltage unbalance. This voltage instability will cause considerable current unbalances. Other drawbacks of this method will be degraded output due to voltage drop and a need of output capabilities foresight for each power supply. (In case of unbalance they should support the whole load) As a general rule, if the current unbalance will reach more than 50%, it will require that each power supply should be capable to support at least 75% of the load current requirements.

The improvement which solves this problem called Power or Current Share. It consists in additional input terminal in each power supply. Through this terminal the interconnected power supplies share output voltage and adjust their output. The resulting output voltage of each power supply is then maintained within error margins, typically 10%.

6.2 Series Operation

Series operation is mostly used when higher voltages are required. Some considerations have to be taken into account regarding the connection. The power supplies do not have to affect each other. This is commonly achieved placing reversed-biased diodes across the output terminals of each power supply. The reverse voltage of a failed supply will not affect the output of the other. The series power supply circuit is shown in Figure 6.2.

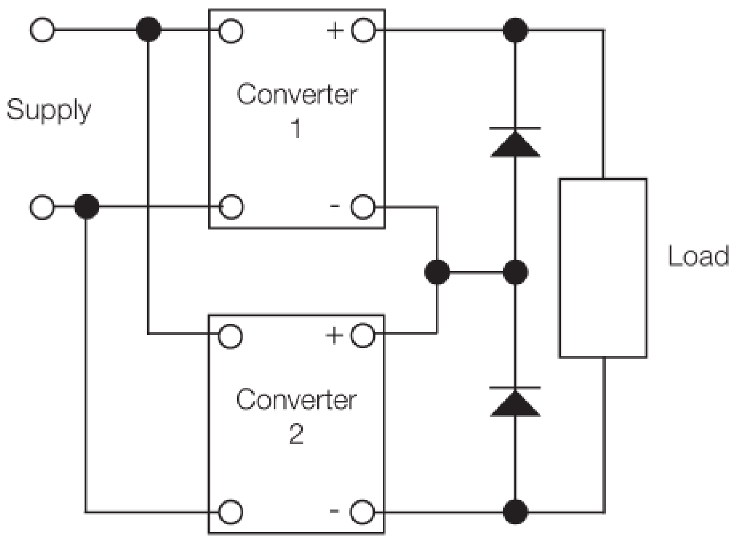


Figure 6.2: Two parallel power supplies connected in series

The most suitable topologies for series connected power supplies are constant power or constant current limit ones. When the fold-back topology is used, there may occur a lock-out during the start since each power supply has its own ramp-up time. It will create repeatable start-up inefficiency.

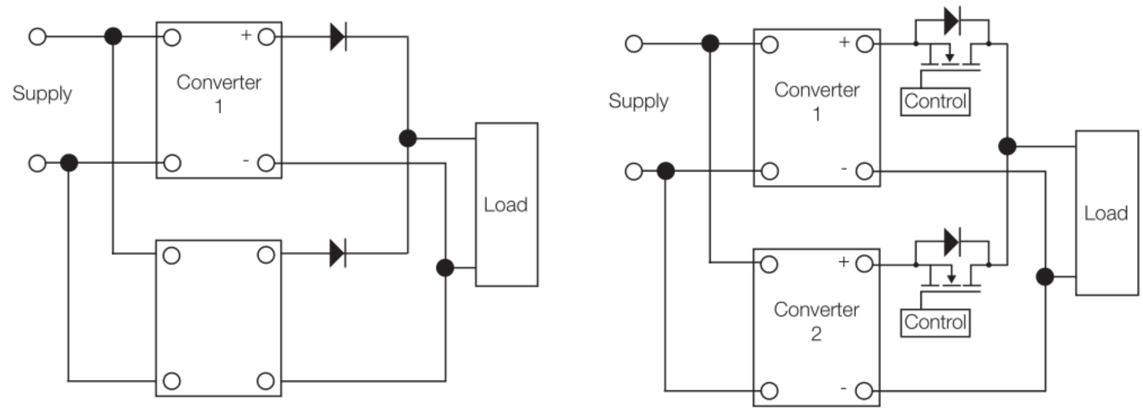
6.3 Fault Tolerance and Redundancy

Some applications require fault tolerance service which can be achieved by equipment redundancy. This implies that multiple power converters must be used. The general idea is simple, if one converter fails, another one catches up and continues the power output service.

There are two general ways of designing power supply redundancy: using diodes or using MOSFETs. One important consideration is the voltage and current rates should be rated higher than the power supplies current limits. The typical power supply redundancy circuits are shown in Figure 6.3a and Figure 6.3b, employing diodes and MOSFETs respectively.

Both methods have certain disadvantages. Diodes will degrade the output voltage due to a constant voltage drop even at different output currents. Thus, the final efficiency will be poorer. The use of MOSFETs improve the power efficiency, but a more complex control will be required. Also, the reliability is an issue. Greater components count will increase probability of a fail.

The power degradation can be handled sensing the output voltage after the diode or MOSFET. The feedback voltage will allow possible additional adjustments, and the output can be maintained at a required level compensating the voltage drop.



(a) Redundancy employing diodes

(b) Redundancy employing MOSFETs

Figure 6.3: Typical power supply redundancy circuits

6.4 Multisource combination

Previously discussed models of power combination were based on a concurrent work of each power unit. However, not all cases comply to this condition. There could be a need to combine several power sources for exclusive work, when one source can bypass the another if needed. Examples of such configurations can be powering a laptop/mobile phone from battery or DC power supply, combining AC power input with DC battery. Those combinations are a must for most portable devices and especially useful for sensor devices to be able to communicate a fail condition.

The simplest multiple power input combination can be derived from the redundant power supply techniques. Having in mind that the end device will be supplied power most of the time from one power source and only from time to time by another one proposes a design idea. The most frequently used source becomes by default option and is only bypassed when addition power supply is connected.

This idea is carried out with only three components: MOSFET, diode, and resistor. The scheme of this simple idea is illustrated in Figure 6.4.

The second power supply is by-default option. The D1 Schottky diode prevents power losses of the default supply through the resistance which pulls down the MOSFET. Once the first power supply is connected, M1 cuts off and D1 becomes forward biased. This way the first power supply bypasses the second one. This technique is employed with charger power management integrated circuits and voltage regulators always when the power source voltage is less than the maximum input voltage of the converter.

When it used as energy harvesting multisource, multiple considerations have to be taken into account. Diode forward current and maximum current rates for the MOSFET have to be checked and the components selected according to the power sources characteristics.

The second power supply can be a battery, while the first one can be a USB input, rectified input from one of the discussed AC/DC topologies in Section 4. Also a case can be made for the first power supply being a USB input, and the second a photovoltaic solar panel or other energy harvesting source.

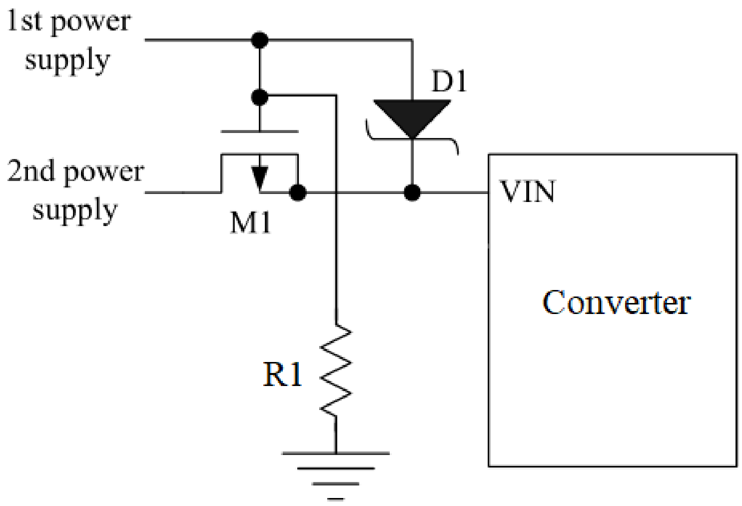


Figure 6.4: Combining two power sources using MOSFET, diode and resistor

Energy harvesting multisource techniques are taken as a separate subsection and discussed next.

6.4.1 Multisource Energy Harvesting

This section provides energy harvesting multisource topologies overview organized in order of rising complexity.

Complementary Use of Energy Sources

The simplest method, as states (Estrada-López, Abuellil, Zeng, and Sánchez-Sinencio, 2018), would be to collect energy from a primary source and use the secondary source to power up only auxiliary circuitry. This is a similar idea to the previously discussed combination. An example of this topology in practice would be a system described in (Vanhecke et al., 2015), designed for structural health monitoring of aircrafts. The system has two inputs: thermal and piezoelectric generators as active and passive interfaces respectively. The piezoelectric generator is intended to charge a small bypass capacitor. When a voltage reference is reached, the active interface is deactivated, and the passive becomes the main energy source. A block diagram of the system is presented in Figure 6.5.

In the proposed system the piezoelectric generator was supposed to supply power to the system during the airplane's takeoff, when the thermostats are still cold and energy harvested from them is not enough to sustain the system. The battery need was avoided this way and the system could achieve the cold start-up. One deficiency of the system is a lack of MPPT feature which would optimize energy harvesting efficiency.

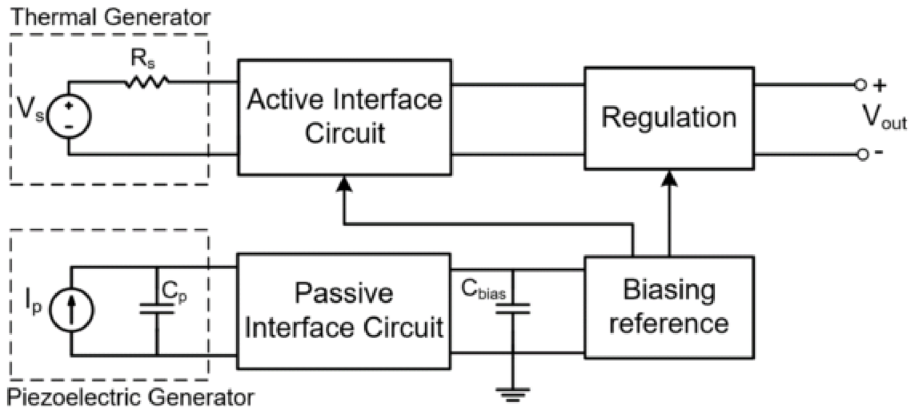


Figure 6.5: Complementary use of energy sources topology

Power ORing

An effective way of energy harvesting from multiple sources is employing a Power ORing topology, as employed in (Carli, Brunelli, Benini, and Ruggeri, 2011; Li, Zhang, Ma, and You, 2014; Tan and Panda, 2011). Some energy harvesting devices as standalone harvesters or battery chargers internally use this topology like LTC3331 from Linear Technology ("Nanopower Buck-Boost DC/DC with Energy Harvesting Battery Charger. Datasheet", n.d.) and MB39C811 from Cypress Semiconductor ("Ultra Low Power Buck PMICSolar/Vibrations Energy Harvesting. Datasheet", n.d.).

The idea behind this topology is directly derived from the redundant power supply technique using diodes. A circuit model is presented in 6.6.

This is a modular topology that can include any number of harvesting sources. The availability of dedicated MPPT units for each harvesting transducer offers a good advantage in terms of efficiency. A self-synchronized operation is assured by using the diodes what also reduces the overall complexity.

The topology also regards several disadvantages. The first one is the voltage drop caused by the diodes which will bring power losses. If the diodes were selected with poor precaution this will result in a serious performance degradation. Often, energy harvesting sources supply small power volumes and the diodes will possibly consume significant part of energy changing and maintaining their states, i.e. forward current characteristic. The input power to DC/DC converter will be, thus, limited.

Presence of multiple MPPT units will increase the size, complexity, power consumption, and the final cost of the harvesting management integrated circuit. Proposed in (Tan and Panda, 2011) solution alleviates those constraints removing all MPPT units. The DC/DC converter can be controlled in a way that the voltage at the storage capacitor will ensure the optimized power delivery from connected in parallel sources. The expense of this solution lays on considerable power degradation when many inputs used, due to the exclusion of MPPT units (Romani, Tartagni, and Sangiorgi, 2017). It is important to consider that this is complementary energy harvesting topology and the energy from sources does not summed up. Only the highest voltage is selected to deliver power. It will work well for complementary energy harvesters, (wind and solar sources) where only one source is expected to be present at a time. If multiple heterogeneous energy sources would be selected with comparable power inputs, the final performance will be poor Estrada-López et al., 2018.

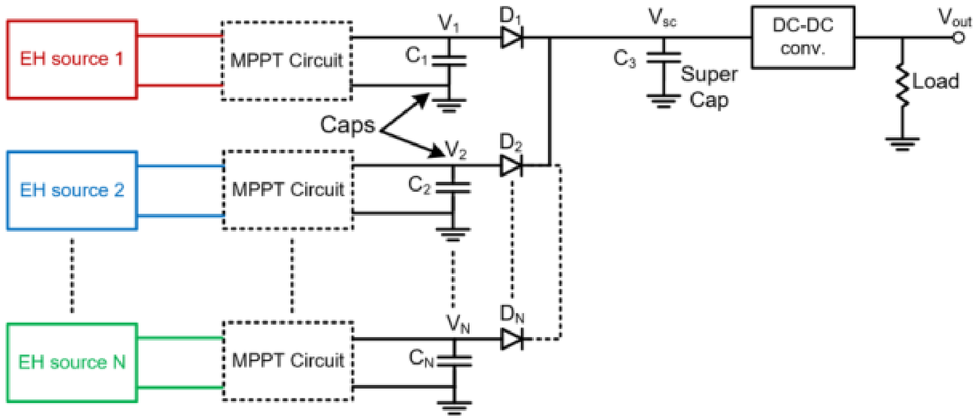


Figure 6.6: ORing energy harvesting topology circuit

Voltage Level Detection

The Power ORing topology can be enhanced substituting diodes with MOSFETs. This would reduce power losses, however, imply more complex control, but also a room for different switching strategies. The authors of (Lhermet et al., 2007), employed a voltage detection strategy. Two-input energy harvesting system has been designed based on a thermal and RF harvesting transducers. Depending on the voltage level of each power input, the source with the highest value was chosen for charging a microbattery. Researchers from (Kang, Kim, Hyoung, Kang, and Park, 2015) have gone further and connected each input sequentially for a certain period of time, while the summed voltage was higher than a predefined threshold. In (Amanor-Boadu et al., 2014), the control circuitry was designed based on the same voltage-level criteria. Since the goal was associated with a battery charger, the charging circuit was connected when at least one of inputs harvested sufficient power, charging its corresponding output capacitor. Otherwise, when the harvesters' output voltages reduced below a defined threshold, the charging circuit was disconnected until one of the capacitors has been charged again. The threshold would depend on a battery type and selected charging circuit.

The algorithms proposed by (Kang et al., 2015; Amanor-Boadu et al., 2014) First, a concurrent harvesting is not possible and there will be always a potentially associated power wastes (Estrada-López et al., 2018). When a threshold is defined, there may be a risk for some harvesting sources to never reach it, even generating significant amount of power. Having in mind that ambient conditions for energy harvesting can be unpredictable, the voltage detection method is limited for such cases.

As it could be noted none from the previously considered topologies combine concurrently and efficiently multiple energy harvesting sources. A research has been carried out to find algorithms that would effectively combine multiple power sources. Further described topologies achieve this objective in respective degrees.

Energy Combining Through Linear Regulators

According to the title, and as can be observed in Figure 6.7, three different sources of energy (inductive link, piezoelectric transducer and solar cells) are combined in parallel through the linear regulators output (Colomer-Farrarons, Miribel-Catala, Saiz-Vela, and Samitier, 2011). Since the connection is performed in parallel, the output power is effectively combined. The output capacitor called Single Storage Device (SSD) stores the energy and filters the output from regulators.

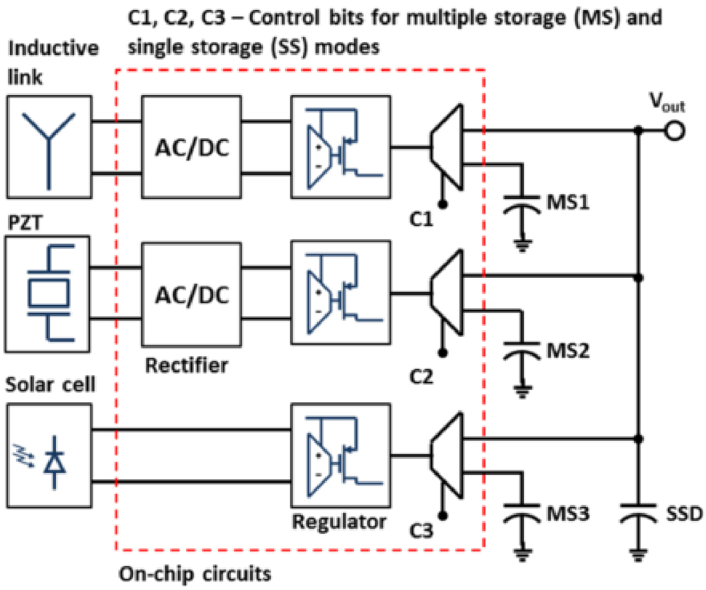


Figure 6.7: Energy harvesting combining through linear regulators scheme

The start-up mechanism is not presented in the Figure. It starts through Power-on-Reset circuit. When the output voltage reaches 0.8 V, all circuitry becomes activated. The scheme does not use any battery charging mechanisms. However, a certain output flexibility has been introduced. The topology allows to store the power in dedicated output capacitors (MS1-MS3) providing separate regulated outputs for each harvester. The outputs is managed by control bits C1, C2, and C3.

This topology is indeed capable of parallel energy harvesting from different sources. A simple control algorithm is also needed. The fact that each power input requires a dedicated linear voltage regulator makes it less efficient compared to possible switching voltage regulators use. The range of output energy for all three inputs is wide, however, the stabilization capacitor must meet, at least in average, needs of each output. The general output capabilities are reduced and the value of the capacitor becomes limited to the poorest harvesting output. Therefore, the number of possible applications is reduced.

Multiple-Input Boost Converter

This topology can be seen as a modified Dickson charge pump where each stage is fused with a boost converter (Estrada-López et al., 2018; Colalongo, Dotti, Richelli, and Kovács-Vajna, 2017). It represents four-input non-isolated boost converter shown in Figure 6.8. The energy is harvested from every source charges the capacitor employed in the next stage. The duty cycle is shared among inputs and its control complies to the Equation 6.1.

$$V_O = \frac{V_{i1} + V_{i3}}{1 - D} + \frac{V_{i2} + V_{i4}}{D} \tag{6.1}$$

Where V_O is the output voltage, V_{i1-4} are harvesting inputs and D is the duty cycle.

The multiple-input boost topology has serious disadvantages. Since each harvesting source requires a dedicated inductor, the final composition will be massive and costly. The lack of MPPT units integration assures poorer power outcome. And finally, the duty cycle equation indicates that D is shared among four inputs and inputs V_{i1} and V_{i3} have opposite effect on inputs V_{i2} and V_{i4} what results in impossibility of individual boosting ratio setting for each input.

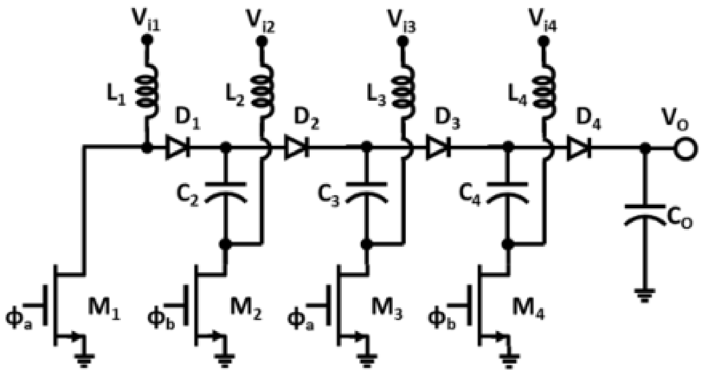


Figure 6.8: Four-input non-isolated boost converter circuit

Shared-Inductor DC/DC Converters

A general approach to achieve impedance matching for energy harvesting MPPT purposes is to use buck-boost converters. Sections 4.1.6 and 4.1.7 provide details about the working principles and possible capabilities of those converters. Switching frequency control makes possible to vary input impedance and to adjust it according to the requirements. In (Bandyopadhyay and Chandrakasan, 2012), the authors proposed a strategy for multiple input energy harvesting using a shared inductor on the buck-boost converter. One evident advantage is the reduction of external components use. The use case of this topology is shown in Figure 6.9 where five input channels are dedicated to AC and four channels to DC input types (Dini et al., 2015). This topology requires a complex controller which will orchestrate access for power inputs to the shared inductor. The MPPT of each DC input must assure that the energy delivered by individual sources to the inductor is the maximum for a given instant.

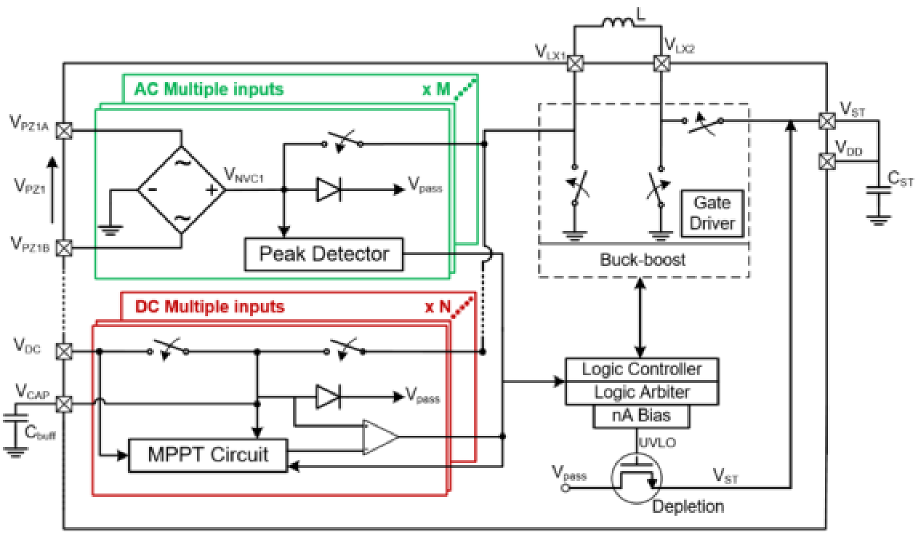


Figure 6.9: Buck-boost energy harvester based on shared inductor topology

A fractional open circuit method described in (Ahmad, 2010) is employed for each of the DC inputs. Harvesting inputs are disconnected for sampling their open circuit voltages. Small capacitors are used to store the charge for the sampling purpose. External connection of the input capacitor C_{buff} allows to reduce the time it is charged to the open circuit condition voltage. Thus, at least, two external terminals are necessary per one DC input module. The use of a monostable multivibrator reduces the sampling interval to $2 \mu s$ unfolding the complete operation in 8 energy extraction cycles. These sampling bursts are repeated every portion of the sampling period. If the period is defined to be 100 ms, the bursts can be repeated up to 6 times.

It has been mentioned that the topology requires a complex arbiter circuit design to share access to the inductor. Preset priorities are proposed for each energy harvester type. In (Ahmad, 2010), the highest priority is assigned to piezoelectric harvesters since these sources are effective only when their output voltages reach maximum, while solar or thermal harvesters have steadier in time output.

The boost converter switching speed must be controlled by comparator from the MPPT circuit, what will keep the output power as close to the open circuit condition voltage as possible. Thus, the comparators must be fast and accurate for the MPPT to provide effective tracking. These types of comparators require heavier power consumption. The problem is tackled in (Chowdary, Singh, and Chatterjee, 2016) by using a shared comparator for all harvesting inputs. The converter oscillator is then tuned to imitate the comparator's output. The MPPT procedure is then continued by the oscillator while the comparator drawn to low power sleep state or powered off to reduce power consumption. The author of (Chowdary et al., 2016) states that the energy can be harvested even down to nanowatts level.

A time multiplexing approach can be used either instead of the priority-based one. But a dedicated microcontroller will be needed to perform on-board MPPT computations to optimize the output Abouzied, Osman, Vaidya, Ravichandran, and Sanchez-Sinencio, 2018.

The greatest disadvantage of this topology is the increased number of external contacts. On the other hand, it is not a pure concurrent energy harvesting topology since only one energy source is connected at a given moment. However, the monostable multivibrator switching frequency makes it appear as one large energy harvesting source considerably improving the efficiency.

Fully Integrated Switched-Capacitor Converter for Concurrent Energy Harvesting

Another possible way to add up voltages is by using switched-capacitor circuits (*Linear circuit design handbook*, 2008, Chapter 9). The scheme for the switched-capacitor DC combiner is illustrated in Figure 6.10. The main idea consists in inverting DC input into AC waveform and superimposing it on the next DC input. The final rectified waveform will provide summed voltage from all inputs. The modular nature of this procedure is also seen in Figure 6.10.

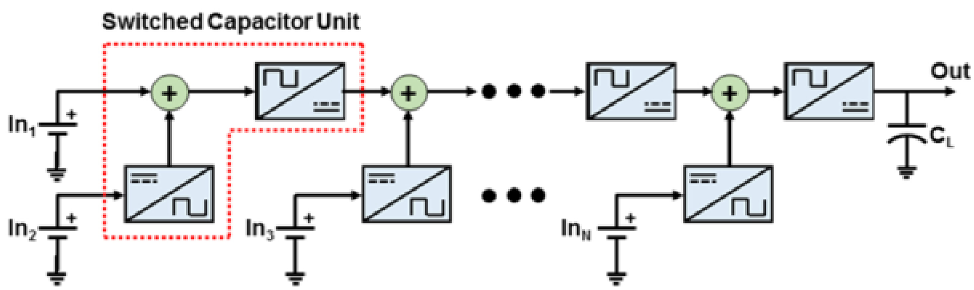


Figure 6.10: Switched-capacitor DC combiner scheme for energy harvesting

In (Abouzied et al., 2018), the implementation of the switched-capacitor block was designed as shown in Figure 6.11. The circuit effectively combines two DC input sources into one output in four stages. Each stage is described in the listing below

1. The input current In_2 is transformed into AC by a differential low-power oscillator I_0. The oscillator is composed by delay cells based on thyristors.
2. The AC waveform is transferred through the drivers I_1 and I_2 and coupled by the capacitors C_1 and C_2 respectively, ending on the nodes V_A and V_B. The difference between the nodes V_A and V_B sums up $V_{i1} + V_{i2}$.
3. M_3 and M_4 converts the power back to DC at the V_{out}.

The voltage sum of two inputs can be stored in a large capacitor at V_{out} if one connected. The actual agglomeration of voltages V_{i1} and V_{i2} is performed by means of the capacitors C_1 and C_2. First, they are charged to the V_{i1} level. Then, the voltage is summed to $V_{i1} + V_{i2}$ level.

The switched-capacitor DC combiner can be easily fully integrated what reduces its size along with the overall system costs. The true concurrency energy harvesting makes this topology highly efficient always exhibiting the maximum of the harvested energy. However, the selection of this topology has to be careful considering the application needs. The

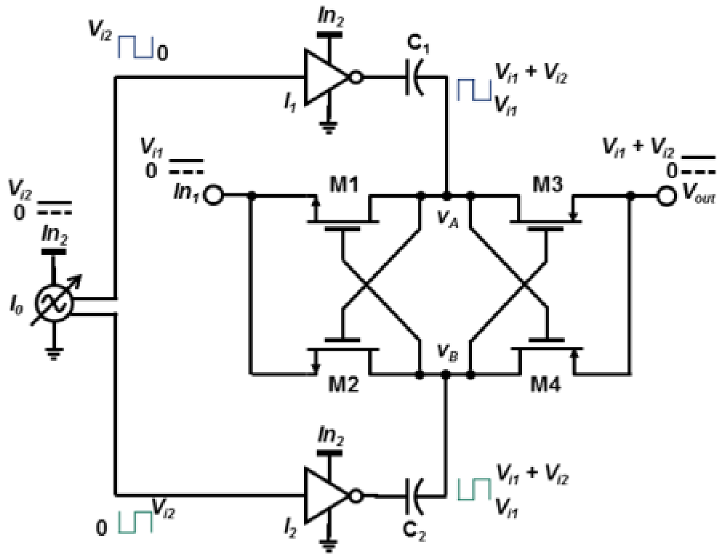


Figure 6.11: Two-input switch-capacitor DC combiner topology

sum of voltages can present a large possible range of the output power, of course, depending on harvesting sources. This can pose certain limitations on further voltage regulations.

7 Conclusions

The present work provided a wide and deep overview of the general power cycle and considered certain concerns related to the field. The reader could possibly trace two distinguished lines of research through the work: general power management and energy harvesting power management.

The sources of energy have been considered in detail for each research line. The common topologies of energy transformation have been presented with sufficient details for clear understanding. One of the most important characteristic of power supply, its protection, has been introduced. Finally, the ways of combining multiple power supply systems have been discussed.

Personally, since I am coming from Computer Engineering background where the focus has been placed on efficient computation and architectural insights, it is difficult to convey how much I have learnt during the preparation of this work. Many papers and books have been explored selecting the information of interest. This work not only laid a base for understanding power electronics, but brought the ability to have proper criteria and design a proper power supply for my future electronic systems.

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