Basic Power Conversion Technologies

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Contents

Foreword

In electric power conversion, both the input and output are either DC or AC. Thus there are four kind of power conversion technologies as shown below.

DC to DC, DC to AC, AC to DC, AC to AC

In any conversion, energy storage device such as inductors, capacitors or transformers are required. (Let's not call voltage drop by resistor a voltage converter.)

That is, power conversion is performed by the combination of inductors(transformer inclusive) and capacitors and switches. Thanks to semiconductor technology, the switches are made by semiconductors.

Since we are now reasonably well equipped with those devices, it will be necessary for the engineers to understand fundamental philosophy how they are utilized.

In case of AC to AC power conversion, transformers in commercial frequency have been used in these hundred years and the technology is well established, but how transformers are designed is generally not well described because of (perhaps) lesser needs by engineers. Moreover, how transformers are understood by Maxwell's equation are of even less interest in these days.

In this document, various power devices and power circuit are discussed to provide basic knowledge of power systems as well as how transformers are designed both for commercial frequency and for switching operation with higher frequencies.

The original document was written in 2013, and some of the items may require updating.

January, 2021 S. Tajima

Chap1 Basic power conversion technology

In this chapter, only basic conversion technologies are discussed.
The input and output of conversion is either AC or DC and there are four combinations. Technologies are called as follows by the input/output combinations.

Input	Output	
DC	DC	Chopper, Chopper converter, DCDC converter
DC	AC	Inverter
AC	DC	Converter, Rectifier (rectify circuit)
AC	AC	Cyclo converter[1]

Electric power conversion does not necessarily mean that the output is regulated; that is, the voltage or current is kept constant in regard of the fluctuation of the load. In particular, the big scale power conversion used for power transmission does not include output regulation, because of the efficiency problem. The efficiency of big AC transformers are above 99 % and no regulators can achieve that efficiency yet.

On the other hand, application for smaller power handling used in homes and offices, most of the power converters include output regulation as well.

We will discuss power conversion principle without regulation in this chapter. Since DC/DC converters are generally incorporated with regulators, it will be discussed in Chapter4.

1.1 Inverter

1.1.1 Principle of voltage type inverter

Fig1.1 shows the simplest way to convert DC to AC[2]. Switches Sa, Sy and switches Sb, Sx are turned ON/OFF alternately and apply input voltage V IN to the load. In this control, Sa, Sx and Sb, Sy must never be turned ON simultaneously.

In this type, (square wave) voltage is applied to the load by inverting the polarity and called voltage type inverter.

Understanding the voltage inverter, it is necessary to observe the type of connected loads. It is obvious that when the load is pure resistance, square wave voltage is applied and square current flows.

[1] It must have started as rotating machine.
[2] This circuit is identical with cw/ccw control for DC motor.

If the load is reactive, it is expressed by the series connection of L and R[3] and the load current looks like rounded shape for both rising and falling edge as shown in Fig1.2.

Since both load voltage and current are AC, there is no DC component and the center is zero. That is, there is phase difference between voltage and current like AB as shown in the figure, and during this period, diode Da, Dy or Db, Dx turns ON and send back energy to power source (capacitor). This is the major role of the diodes Da, Dy, Db, Dx, and necessary when thyristors are used as shown in Fig1.1.

Similarly, bipolar transistors or IGBTs with no internal diode, the external diodes are used.

MOSFET or IGBT with internal diode, the diodes are not mandatory, but they may be used to improve the current characteristics for the internal diodes.

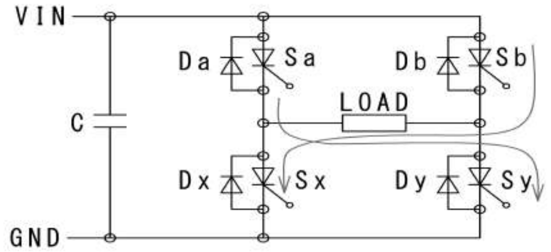

Figure 1.1: Single phase inverter

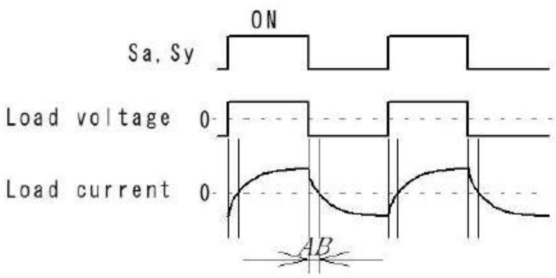

Figure 1.2: Switching timing of inverter

When the load is an LC resonant circuit, and the switching frequency is made equal to the resonant frequency, sinusoidal current flows through the load reducing the switching loss of semiconductors. Therefore, replacing L with a transformer and connect resistance to the secondary winding, sinusoidal wave is applied to the load and sinusoidal inverter may be constructed with simple circuit.

However, if commercial frequency sinusoid is required, the size of the capacitor and the inductor becomes too big to be a reasonable design.

Thinking about just the combination of square wave inverter and load, RC parallel load can be connected. In this case, current form becomes the differentiated square wave and produces big peak current at both edges. Therefore, if the inverter can sustain this peak

[3]An AC motor becomes a load like this.

voltage, it may work, but driving capacitors with constant voltage is fundamentally wrong (see Sec 2.1.1). In this case, constant current inverters shall be used

Some of the simple cheap inverters that produce AC from DC source (eg.auto-mobile battery), the output is square wave with commercial frequency. It is only usable by carefully choosing the load, but for general AC home appliances, it will cause too much ripple to the internal electrolytic capacitor and may well destroy (see Sec 1.3) the appliance. Because, electrolytic capacitors commonly used for ripple filter, the nominal frequency ripple is defined by those from half wave or full wave rectification of commercial frequency. That is, the frequency is 100/120 Hz, and for higher frequency ripple, electrolytic capacitors designed for those purpose must be used. But if the product are designed for AC 50/60 Hz, it's most likely that conventional electrolytic capacitors are used for lesser cost.

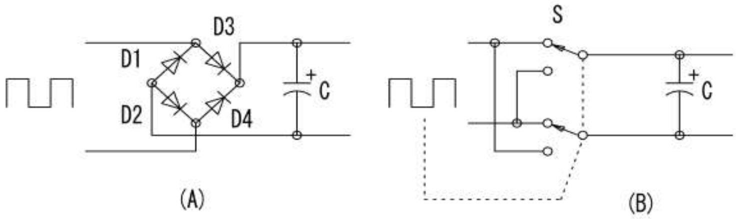

Figure 1.3: rectifier and ripple filter of electronic equipments.

Not only limited by the case mentioned above, power AC output should have sinusoidal waveform. By the sinusoid, the waveform does not change by differentiation nor integration and has single spectrum producing least noise.

One of the commonly used technology utilizes PWM control in which high frequency switching is used to produce sinusoid. As shown in Fig1.4, compare the reference sinusoid and triangular wave to modulate pulse width and control the main switch so that the the average area becomes sinusoidal. Output is filtered by LC filter and remove carrier of PWM. Then the load is driven by sinusoid. Practical technology is quite similar to that of PWM chopper regulators.

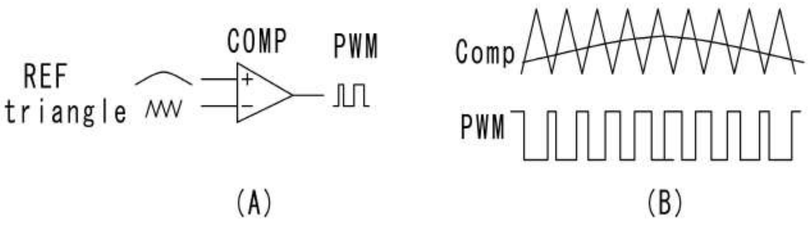

Figure 1.4: PWM control inverter

For the voltage type inverters, there are two ways about the status of switches when the voltage is not applied to the load. One is to turn the all switches OFF and float the load. The other is turn Sa, Sx or Sb, Sy ON at the same time and make a short circuit to the load. For the resistance load, either scheme should work presenting little problem. In case of motors, floating means to permit continuous rotation by inertia, ad short circuit means to apply sudden break.

1.1.2 Current type inverter

When the power from solar panels is interconnected to grid, DC/AC inverters are used to produce AC output with the same frequency, and the output is phase locked to the grid. Basically, the grid is constant voltage type power source (not regulated, but supplied by the estimated load) and it is no good to merge them by voltage in principle. Because, plural outputs of voltage source must be added by current. For instance, even the parallel connection of manganese dry cells is not recommended, and the parallel connection of Li-ion batteries are basically forbidden[4]

In this case, current(not voltage) of the inverter output must be controlled. Inverters used this purpose is called current type inverter[5].

Uploading power to the grid, the inverter must produce sinusoid, but here, to understand the current type inverter, we discuss about a current inverter that corresponds to Fig1.1 which is a square wave inverter.

Even supplying constant current to the load, the constant voltage DC power source is used in general. Trying to fake the constant voltage source to current source, reactor L is inserted to the input as shown in Fig1.5.

The diodes D1 to D4 in Fig1.5 are to prevent inverse current to DC power source (refer to Sec 1.1.3), and IGBTs are used for Q1 and others. Also, diodes that are equivalent to DQ1 etc. are connected in parallel for inverse voltage protection when necessary.

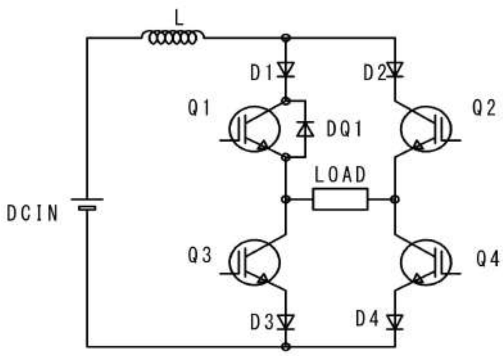

Figure 1.5: Current type inverter

Current type inverter is a dual device to voltage type inverter and CR load is appropriate as a reactive load. In this case, the load voltage is square wave and the load current is rounded shape. Just exchange voltage and current in Fig1.2.

Likewise, the current type inverter switches current between a closed circuit formed by D1-Q1-load-Q4-D4 and another closed circuit D2-Q2-load-Q3-D3.

[4]Some battery packs using Li-ion batteries do connect in parallel, but the battery cells are specially matched not only by voltage but manufacturers. Also, very careful protection circuit is incorporated.

[5]In reality, the voltage inverters are used because of current type demerits mentioned later.

Therefore, in principle, this type of switching must not break those closed circuit open at any time. This means that the switching timing of Q1, Q4 and Q2, Q3 must be continuous and it is very difficult in reality.

Also, we need some ideas how to terminate the load current. That is, if the switches are turned off suddenly, the energy in the (power) inductor loses it's route, and charges stray capacitance around the switch producing arcs eventually. The energy in the inductor must be gradually consumed somewhere and terminate the current.

Summing up the characters of the current inverters, they requires series diodes to the main switches, and power loss is increased, large inductor is necessary (bulky), continuous switching of two current loops is difficult and needs soft switching at turn off. These are the difficulties which must be resolved for the actual application.

1.1.3 Regeneration of power

Either for voltage or current inverters, when the load generates power by the external force like a motor when turned off (power is produced by the inertia), the generated power can be returned to the power source. But when one discusses power supply system connected to load, the block diagram does not show this mechanism clearly. That is, we have a circuit diagram all right, but we generally focus forward power supply to load only. But the problem we discuss here is the power propagation to the backward direction.

When an inverter is operated backwards, it works as a converter (see Sec 1.2.1), we omit the middle part of the following configuration,

DC input - inverter/converter - DC generator

and think about "DC input - DC generator".

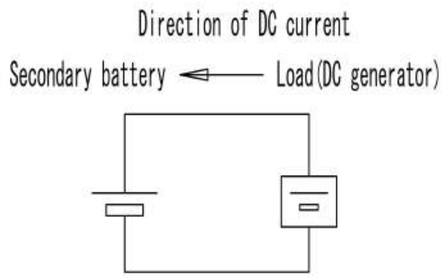

Figure 1.6: Analogy of energy transmission by DC voltage

Thinking about the energy regeneration (sending back) by voltage, we assume the DC source is a rechargeable battery and load is replaced by a DC generator as shown in Fig 1.6 at the time of regeneration. When the load side voltage is higher than the supply side, the load voltage (regenerated voltage) charges the rechargeable battery.

This is the principle of the regeneration, and it is absolutely necessary to provide the route of current from the load to power source. The diodes Da, Dy, Db, Dx are used for this purpose in Fig 1.1.

On the other hand, current mode inverter is a bit difficult to understand. We assume here that the load side produces the DC output and this is to be returned to power source

side by current.
The energy transmission by current is explained by an analogy of power transmission between two wheels driven by a belt.

Suppose the pulley of the supply side is P and the load side is L. The power transmission from the current power source to load is to drive P and transmit force to L. When load side transmit force to supply side, L drives P, and DC trans mission restricts the direction of the belt uniformly.

That is, in both cases of transmission of energy, either from source to load or the other way round, the direction of current does not change. Diodes D1, D4 and D2, D3 in Fig 1.5 ensure this.

If no diodes are quipped for the current inverter, and the load tried to flow current to change current direction, it meaninglessly consumes source energy. By the way, open circuit in a current inverter corresponds to the cutting off of the belt.

Another yet every day example may be found when applying break to a car by the engine. In this case, the wheels forcibly drives the engine to produce breaking effect. Obviously, neither wheels nor the engine rotate to the wrong direction. (But this does not regenerate energy.)

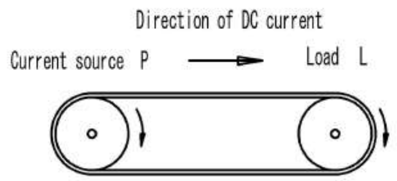

Figure 1.7: Analogy for the energy transmission by DC current

1.1.4 3 phase inverter

For the 3 phase AC, there are voltage and current mode inverters as in single phase AC. And the role of the semiconductors and reactors are same with single phase.

Fig 1.8 shows a 3 phase voltage mode inverter. The diodes connected in parallel to the thyristors are used to send back energy to supply side when reactive load is connected.

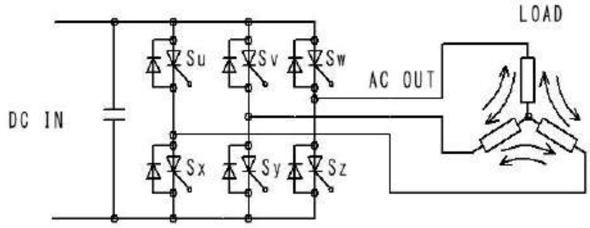

Figure 1.8: 3 phase voltage mode inverter

Su, Sv, Sw, Sx, Sy, Sz are semiconductor switches like thyristors and controlling these devices produce square wave voltage to the load. By the output point, the direction of voltage alternates and an AC is obtained.

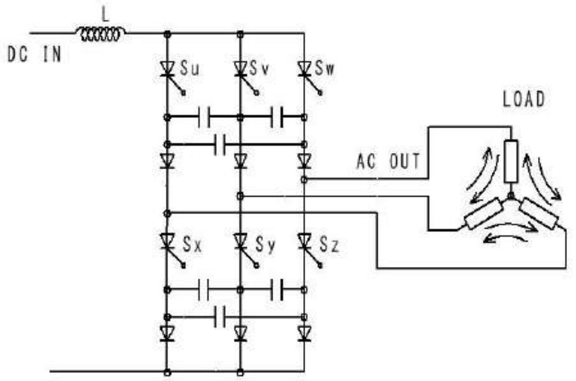

Figure 1.9: 3 phase current mode inverter

Point of the circuit shown in Fig 1.9 is, like single phase inverter, a reactor is inserted at the input line and constant current supply is intended. Diodes prevent the inverse current from the load to power source.

1.2 Converter

1.2.1 Duality of converter and inverter

Converters are circuits or devices that transform AC to DC, and in small power application, it is generally called rectifying circuit.

Just observing a rectifying circuit by a diode bridge, it is not obvious that the inverse operation yields an inverter.

Here, we show how the inverter is derived from diode bridge rectifier.

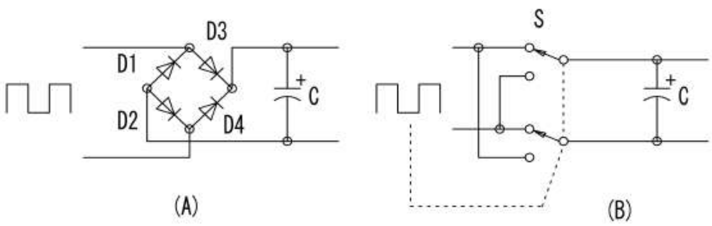

Figure 1.10: Switching in rectifying circuit

In Fig 1.10, the (A) shows a very common diode bridge and for simplifications sake, assume that the input is square wave AC. (B) shows a symbolic operation of switching of the diodes. When the switches in (B) is controlled synchronously to the input square source, DC appears to the capacitor. This is the AC/DC conversion.

On the other hand, the Fig 1.11 shows a circuit that is exchanged right/left of (B), and replaced the capacitor with a battery and load is connected. If the switch S is driven by some timing signal, AC with the same timing (frequency) appears at the load.

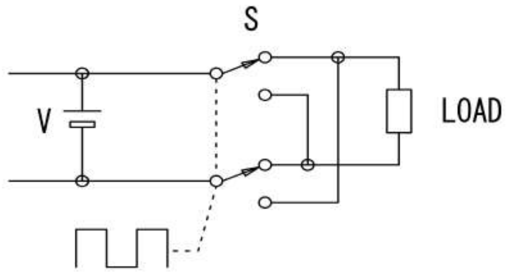

Figure 1.11: Morphing to an inverter

These are the principle that converter/inverter can be bidirectional, and when semiconductor switches are used, external control is necessary, and thyristors are the required simplest devices.

1.2.2 3 phase converter

Fig 1.12 shows 3 phase half wave rectifying circuit. The 3 phase circuit generally handles large power, capacitor input rectification in which capacitor is connected after diodes are not appropriate. And reactors are used for filtering. Even by the half wave rectification, the ripple is inherently small for 3 phase rectification.

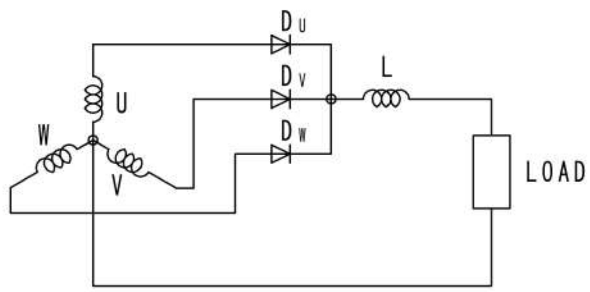

Figure 1.12: 3 phase half wave rectification

Similarly, full wave rectification is shown in Fig 1.13.

1.3 Cyclo converter

Cyclo converters are used for AC frequency conversion and the original idea does not contain energy storage device in it. And this is advantageous for large power application, but the voltage/current shape after conversion contains many high frequency harmonics and may cause various troubles.

Fig 1.14 shows the original idea of a cycloconverter that produces 1/3 of the original frequency. In this scheme, part of the input AC is rectified and makes hesitant to call this a frequency conversion, but the principle is very clearly shown.

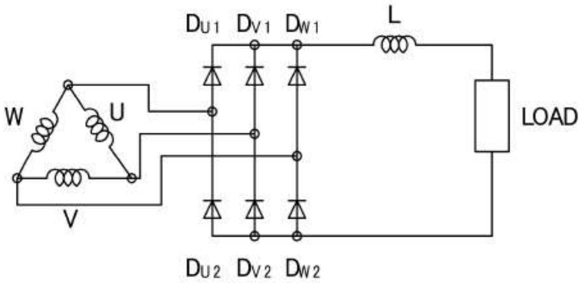

Figure 1.13: 3 phase full wave rectification

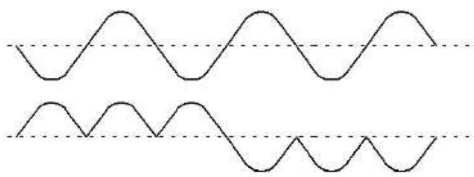

Figure 1.14: Wave form of a constant ratio cycloconverter

In real application the Fig 1.14 is improved and by using multi phase AC for the input and the switching timing is controlled by high granularity (use many switching device).

For instance, by the configuration shown in Fig 1.15, 6 phase AC is produced from 3 phase AC which is switched as shown in Fig 1.16, and convert 50Hz to 60Hz [6].

That is, skipping the phase in between and output waveform is faked. The cycloconverters require many switching devices and progressed with thyristors[7]. The OFF switching of a thyristor is carried out by itself, it suited for high voltage and high power application.

The cycloconverters are used for power supply for metal rolling mill, grid connection between different frequency systems and power supply for magnetic levitation systems.

On the other hand, power factor to the input is low, contains many high harmonic components as well as other problems. Observing the trend of AC/AC conversion, the AC-DC-AC conversion will be the emerging technology.

Shin-shinano converter station exchanges power between different frequencies by converter-inverter style. And in this case, the power is converted

AC→DC→AC

if the middle part is extended, it becomes an HVDC system.

[6]By this scheme, the phase of the output is always in syc with the input and this may be a problem depending on the application.

[7]Historically, mercury arc rectifiers are used. And, thyristors are sometimes called valves.

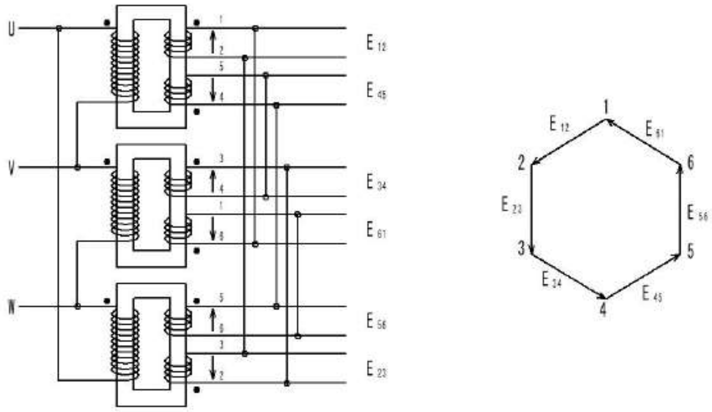

Figure 1.15: 6 phase connection

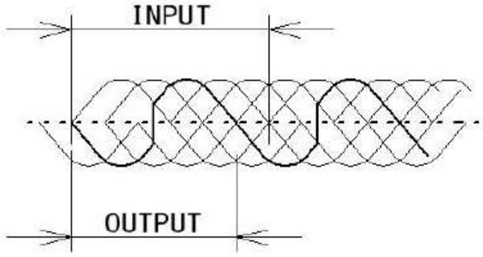

Figure 1.16: 50Hz-60Hz conversion

Chap2 Principles of power conversion devices

In this chapter, principles of component operation for power system is described. This will help to understand circuit diagram of many power conversion system, as well as the different topologies in power conversion circuits.

2.1 Energy storage devices

The energy storage devices in this section refer to capacitors, inductors, motors and speakers that react to dynamic change of voltage and current excepting chemically reacting devices like batteries.

It is not easy to understand or recognize the operation of energy storage devices in a circuit regardless the circuit is dealing with power or signal. This is caused by the physics that it takes time for charging and discharging of energies, and accompanied time delay makes it difficult to understand.

In AC transmission, the inductive and capacitive components in the system cause phase difference between voltage and current. And this is one of the concerns for AC transmission. For instance, the phase difference between voltage and current not only reduces the efficiency of the power transmission, but it may produce unexpected surge voltage on the transmission line and requires compensation devices of reactive current.

In principle, reactors or capacitors are added to the node where the troubles are observed, and try to reduce the phase difference between voltage and current. However, the voltage and current are large, a large reactor or capacitor is required, and the value depends on the situation of the node.

In case of automatic control system, these devices work as a differential or integration component and increase the order of system transfer function. Between the input and output relationship of the differential and integration components, the similarity of wave forms is lost[1]. And becomes difficult to anticipate system behavior.

For instance, for a novice driver meandering may happen. This is caused the by the time lag between the output (direction of the car) and the input (steering wheel handling) in a feedback loop. Feedback control with a higher order transfer function, many ideas are required to stabilize the system.

Another instance is found in switching regulators. Switching regulator is also a feedback,

[1]Differential and integration are linear operation, but the wave form changes between input and output and simple proportion is lost(see Sec 8.2).

automatic control system and it comprises inductors and capacitors in the main feedback loop and present difficulties in design for stable operation.

Speakers also charge energies. It is made of mechanical components like cone (mass) and damper (spring with damping) and is driven electrically by voice coil which is inserted in the gap of magnet. Since the voice coil generates electricity by the inertia of the cone, when the impedance of the driver (amplifier) is not low enough, it produces sound that is not "well damped" [2].

As stated above, the energy storage devices are the origin of many troubles, but without them, nothing can be achieved and present many interest in system analysis and design.

2.1.1 Capacitor

Capacitor charges energy by voltage and must be driven by current in principle. If constant current is supplied to the capacitor, a charge proportional to time is stored and appears as a voltage. In theory, the charge will be stored forever unless it is discharged externally by intention. In reality, because of the leakage current between the electrodes, the charge is gradually lost. In particular, the electrolytic capacitor has bigger leakage among various capacitors.

If voltage is applied to a capacitor, instantaneous big current flows and this is prohibited action in general. Similarly, never short the two terminals of the charged capacitor. To consume energy stored in the capacitor, resistance must be connected to avoid infinite level of current flow.

In case of sawtooth generators, the capacitors are charged by constant current up to some level and then shorted by a switch as if zero ohm shorting is done, but the current itself is very small and it assumes the resistance of wiring and internal resistance of switch. See Fig 2.1.

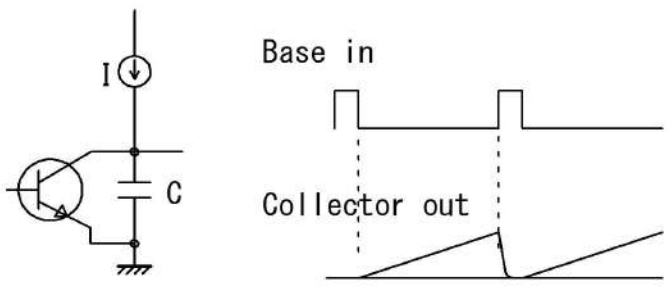

Figure 2.1: Sawtooth generator

Excepting batteries, the electric charge is only stored by the capacitors. If the charge

[2]The analog amplifier by semiconductor has very low impedance and the boomy sound belongs to the past.

in a capacitor is moved from one to the other, what happens ?

In Fig 2.2, there are two capacitors with identical capacitance C1, C2, and C1 is charged by voltage V and C2 is empty (A). When the switch is closed, the voltage of both capacitors will be $\frac{1}{2}V$ as shown in (B). The total energy in (A) is $\frac{1}{2}CV^2$ and that of (B) is

$$\frac{1}{8}CV^2 + \frac{1}{8}CV^2 = \frac{1}{4}CV^2$$

Where has the half of the energy gone?

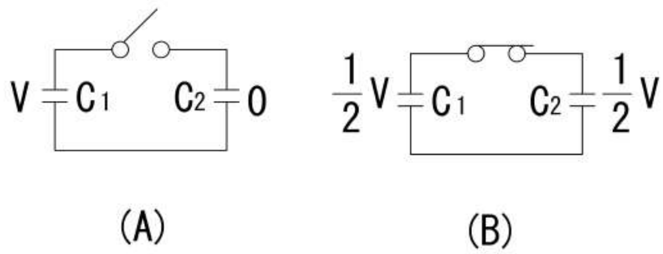

Figure 2.2: Flow of charge between capacitors

This is explained like this. When the switch is closed, huge pulse current flows and produces magnetic field $\frac{\partial \boldsymbol{B}}{\partial t}$ which is scattered into the air. Considering the resistance, the heat loss also exists.

2.1.2 Inductor/reactor

An inductor (or coil, reactor[3]) is a dual device to a capacitor and current energy device. Inductors store energy by current (or magnetic flux), but not by voltage. Therefore, they can store energy only when they are in a closed circuit.

Since inductors are the dual devices to the capacitors, when charging energy to an inductor, voltage should be used. In practical closed circuit, nonzero initial current becomes zero very quickly when current source is turned off because of circuit resistance. When a closed circuit with nonzero current is cut off (open; not to do in principle), the current become instantaneously zero producing high voltage between the inductor.

The only device that can store energy indefinitely is the super conductive inductors only. Starting current in the closed circuit of super conductive inductors, the current keeps flowing and makes a powerful magnet.

Inductors used in a circuit always keep current continuity but the current may vary by time. For instance, resonant circuit is comprised of an inductor and a capacitor and forms a closed circuit.

However, there are some inductor usage that sounds a brutal way[4].

[3] Coil refers to winding of wire, inductor is used in circuits and reactors used in power electricity; but we use this term loosely.

[4] Brutal way here means to make an open circuit in which inductor is comprised.

One of the examples is an old device found in schools called induction coil. A primary coil wound over an iron core is equipped with a mechanical iron switch. When the switch is attracted, it turns off the coil voltage thus releasing the switch. This continuously works like a buzzer. The secondary winding has many times more turns than primary winding and produces very high voltage.

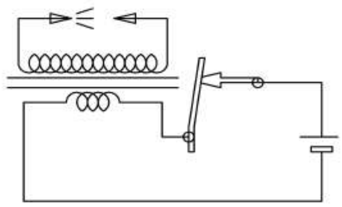

Figure 2.3: Induction coil

Another example is for the ignition of old automobile engines. This ignition system was made of coil and contact that turns the coil voltage ON/OFF, generating very high voltage which was used to produce sparks.

When this was commonly used, not enough attention was paid for the electromagnetic interference, and it's been replaced by electronic system (but the idea still is some brutal usage of inductor, only mechanical switch is replaced by semiconductor switch).

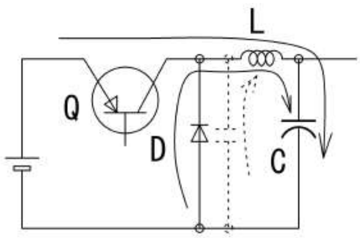

Figure 2.4: chopper down converter

In electronic circuit, flyback converters use the same principle with that brutal usage of inductors, but by carefully designing the load circuit, ON/OFF of the coils will not produce sparks, but just high voltage.

As an example of proper usage of inductors, Fig 2.4 shows a part of chopper down converter in which L is supplied voltage via switch Q and supplies current to C. When Q is turned off, diode D keeps the closed loop for the inductor.

Observing from the inductor, the value of current changes but the current path always exists. But in case the output current is small, there is a timing that both Q and D turns OFF and closed path is lost. In this timing, the current charges stray capacitance and produces big ringing. It is not the proper usage of inductance, but generally not much harm is expected and used commonly. Even in this instance, if the stray capacitors are taken into account, the current path still exists.)

An inductor is a dual device to a capacitor. Therefore, somewhat strange phenomenon happened in a capacitor circuit should happen for an inductor circuit. Suppose a circuit in which same inductors L_1, L_2 and external component (a copper wire) are connected in series as shown in Fig 2.5. Switch is closed first and the current I is flowing through L_1 only. Initial current of L_2 is zero. In practical circuit, current I is consumed by the resistance of wire and instantaneously becomes zero.

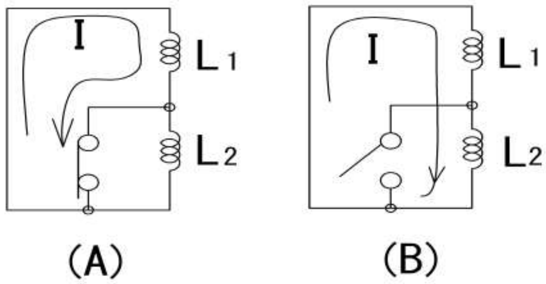

Figure 2.5: energy transfer between coils

Here, we assume that all the circuit is made by super conductors (which is possible). The energy in the circuit in (A) is $\frac{1}{2}LI^2$. When the switch is opened, the current start flowing through L_2 as well. Then the current becomes half because the inductance is doubled, overall energy will be

$$\frac{1}{2}L(\frac{I}{2})^2 + \frac{1}{2}L(\frac{I}{2})^2 = \frac{1}{4}LI^2$$

When the closed circuit of L_1 is opened, infinite voltage appears between two ends of L_1 which drives L_2 to infinite for an instant, and infinite current flowing through the circuit produces electromagnetic wave that emits energy into the space.

This is a problem associated with the transfer of current from inductor to inductor, and is a dual phenomenon to capacitor.

2.2 Transformer

Ideal form of inductor is toroidal coil. In this form, the magnetic flux made by the current through coil is all enclosed within inductor and no leakage exists.

If secondary winding is prepared for the toroidal coil, it makes a transformer. In practice, the coils are wound over toroidal core and increase magnetic flux density so that larger power is handled by smaller size of transformer.

However, there are two ways to use transformers and the characteristics are fairly different.

(1) No magnetic energy is stored in the core by the primary winding. Good example is a common AC power transformer. When nominal load is connected to secondary winding, all the power put into primary winding is transferred to secondary without time delay. And no energy stored in the core (except, magnetizing energy of core). If the load is resistive at the secondary winding, impedance looked into primary becomes also resistive.

(2) Primary winding is used for charging magnetic flux to the core with certain period and the secondary winding is putting out the energy stored in the core at the next period. That is, the energy is stored as magnetic flux. Primary and secondary winding works alternately and good example is found in transformer for the flyback converters[5].

For details see sec 6.4.4.

2.3 Conversion of charge and current

In Sec 2.1, instantaneous transfer from current to current or charge to charge will emit energy into space. This point must be avoided for the energy conversion devices and fundamental solution is to transfer energy between current and charge.

That is, energy should be transferred between capacitor and inductor in which case, transfer never occurs in zero time.

Good example is the resonant circuit in which inductor and capacitor is combined. In resonant circuit, if the resistance is zero, the oscillation continues for ever. If there is resistance - and this is actual case - but when it is small, the resonance lasts longer. Because the energy transfer between inductor and capacitor is loss-less in principle.

For practical example, chopper DCDC converters supply energy into a closed circuit of inductor and capacitor, and supply converted energy to loads. Common DCDC converter does not utilize resonance, but it does not emit energy into space needlessly[6].

Fundamental scheme to supply energy to inductors or capacitors, inductors (current energy device) should be driven by voltage and capacitors (voltage energy device) should be driven by current.

2.4 Fundamental scheme in power switching

Regardless of AC or DC, power switching is one of the fundamental problems. In case of AC, zero timing of voltage and current occurs periodically and the troubles of arcs are reduced comparatively, only the DC switching tends to attract attentions, but they are the same in principle.

For the simplification's sake, we discuss the case of DC. Switching is defined to be a measure to connect or disconnect power to loads. If there is no energy storage components like inductor or capacitor in the connection wire, there will be no problems.

That is, the problem is caused by the fact that all related devices like power source, load and wires contain inductance and capacitance.

For instance, home equipments generally converts input AC to DC. In order to filtering the AC components, large capacitors are used after rectifying circuit which causes rush current at power ON. On the other hand, the AC supply is designed to make the voltage at the wall outlet constant -constant voltage supply- and this means the supplying capacitor by voltage.

[5] Another good example is a flyback transformer for CRT television, but this is already a past application.
[6] The loss caused by leakage inductance is another story.

In principle, if we accept that the equipment input is capacitive, the power source should be current source. In real world, neither prohibition of capacitor usage nor constant current AC is practical.

Fundamental and intrinsic solution of power supply to inductive/capacitive solution is taking time when applying power - slow start switching. This is how constant voltage style outlet [7] and design with freedom [8] can exist peacefully.

Now, be aware the above discussion is for idealism, and reality is not that simple. Many equipments assume rush current when turn ON.

2.5 Switching device

We discuss only semiconductor switching devices. As switching devices, transistors and MOSFETs are commonly used for home appliances, and for large power application, GTOs and IGBTs are used. In both cases, lower ON resistance, switching speed, voltage rating and easy control are the concerned issues and technologies progressed to full fill these requirements.

2.5.1 Diode

One of the fundamental switching schemes is the flow control of current. Most common device for this purpose is the diode in which current flows only from anode to cathode. This character is used for conversion from AC to DC[9].

Diode as a switching device, it conducts only when the voltage at anode is higher than cathode by Vf, and turns off when the cathode potential gets lower than anode. That is, the diode is a self-controlled switching device.

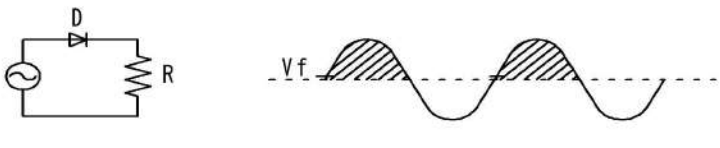

Figure 2.6: Rectification by diode

Silicon diode is the most common device and used for rectification in general. Simple structure and low to high voltage, high current rating diodes are available, but the biggest problem is the forward voltage drop which is determined by physical property. Silicon medium power diodes (several amps) goes up to approx.1V and it will consume 1W even at 1A. The improved diodes for the Vf is the Shottky diodes, and Vf is 50% to 60% of the silicon diodes. But the high rating diodes are not available and maximum voltage rating is around 100V.

[7] In case of constant current type outlet, voltage goes up at no load and this is impractical, let alone all the loads are connected in series.

[8] For big capacitor input equipments, a current limiter may be used.

[9] In case of single phase AC, ripple is big without filters and hardly called the DC, but for 3 phase AC, only diodes alone can yield DC with small ripple.

The improvement of Vf is not much expected, and MOSFETs are replacing the diodes, but obviously gate control signal is necessary.

2.5.2 Thyristor

Thyristor is a device that the latent control terminal of the diode is made explicit. Semiconductor structure is of course different, but looking at it as a black box, thyristor looks like a device that a control electrode of the diode is getting independent (form the current flow) and controllable at any time. But still turn ON only and the OFF is carried out when the forward current is extinguished.

Replacing the diodes by thyristors shown in Fig2.6 yields Fig 2.7. Then while monitoring the input AC and control the ON timing of the thyristor, average DC output voltage can be smoothly changed from zero to maximum voltage for half cycle as shown in Fig2.7. That is, a variable DC power supply is constructed by using thyristors. When the gate is always ON, the device just works like a diode.

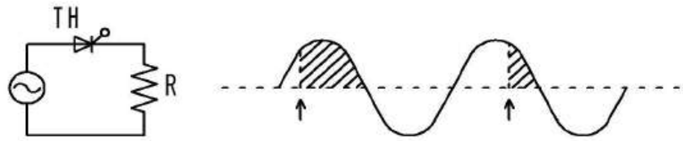

Figure 2.7: Switching by thyristor

One of the large power applications of the thyristors is the AC electric locomotives. The history of progress in AC locomotives clearly shows how thyristors are utilized. One of the ways to design an AC locomotive is to use DC motors. In the early design, mercury arc rectifiers are used to produce DC and this drove the DC motors by using resistance as current limiters. Then mercury arc rectifiers are replaced by silicon diodes(therefore, still resistance control) and improved the reliability. And when thyristors became available, variable voltage by thyristor drove DC motors (For instance, 100 series Shin-kansen, 1996).

The problems with the thyristors are the ripple of DC and the noise associated with the chopper control. Of course, ripple filters and noise filters are required and looking from AC supply side, the power factor gets lower. In these aspects, the electric locomotives and train sets are progressing to use variable voltage, variable frequency (VVVF) inverter. And in this technology, AC is converted to DC first, and then voltage and frequency controlled AC is produced to drive AC motor.

Another interesting application of the thyristor is DC to AC conversion. In case of diode, the switching timing is only determined by the AC input itself. Hence, for the DC input, there is either ON or OFF state.

But in case of the thyristors, ON timing is controlled externally. As shown in Fig 2.8, when thyristors S_a,S_d and S_b,S_c are turned ON alternately, the current through load L changes direction. However, a scheme to turn off the thyristors is necessary and there are several ways to do this.

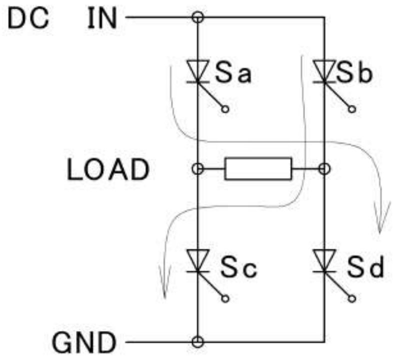

Figure 2.8: AC conversion by thyristor

2.5.3 GTO

Thyristor control electrode cannot turn the thyristor OFF which obviously is inconvenient and this capability is relized by the GTO - Gate Turn Off Thyristor and it enabled high speed (at the time of introduction) DC power switching. Bipolar transistors are available for the DC switching device, but GTOs had better voltage rating (around 1980, the voltage rating of bipolar transistor was aprox. 1400V, whereas the GTOs had aprox. 4500V[10]. But the switching speed was limited around 500 to 1000Hz.

Introduction of GTOs gave big impact to electric railway trains. Series 300 Shin-kansen by JR-Tokai developed in 1990 is the first series that used AC motors, and 4500V, 3000A rating GTO inverter was used. In this train set, the catenary voltage (25000V) is stepped down by a transformer to 1220V, and converted to DC (2400V) which is converted to variable frequency, variable voltage (VVVF) AC and drove motors. Series 500 by JR-Nishinihon is also equipped by GTO VVVF inverters.

But now the IGBT is replacing GTO by the switching speed, and as of 2012, GTO is considered to be a past device.

2.5.4 IGBT

IGBT has a structure that MOSFET is combined to the base of bipolar transistor as shown in Fig 2.9, and has characters of high voltage rating, low Vce, voltage drive and high switching speed.

Rn in the equivalent circuit means that the conductivity is modulated.

IGBT has higher switching speed (5kHz - over 10kH) with smaller power loss than GTO. Compared with MOSFET, MOSFET has lower ON resistance in low voltage switching devices (up to approx.100V), but the IGBT has lower loss in high ratings (over 500V). Therfore, IGBT is suitable to high voltage application. In home appliance applications,

[10]Because the bipolar transistors use either electrons or holes and for high voltage, the resistance becomes high.

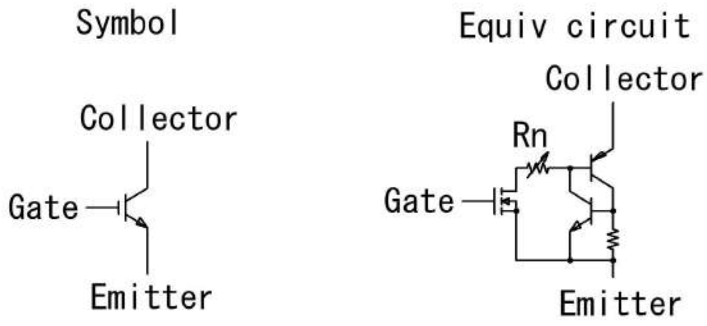

Figure 2.9: IGBT

IGBT is used for the inverters in air conditioners, microwave ovens and washing machines. These inverters operate under DC 350V-400V converted from AC line voltage [11], IGBT is better than MOSFET.

For the large power application, IGBT is the best choice right now, and for Shin-kansen application, it is introduced in 1996, by JR-Tokai, for series 300 (2500V,1000A) and in 1997, series 700 (3300V, 1200A) and GTO is no longer used.

2.5.5 Bipolar transistor

For the power switching applications, this is getting a past device. Transistor is a current controlled device with three terminals with the structure of either NPN or PNP. Applying current to base, larger current flows between collector and emitter (make the impedance between collector and emitter small).

By the character of the current control device the base current is required that is proportional (although, the amount is 1/Hfe) to collector current [12], and this renders cumbersome for driving. Also, base excessive carrier lengthen the switching off time (increasing power loss at high speed switching), minimum Vce cannot be made smaller than aprox. 0.1V.

Above are the demerits of bipolar transistor particularly used for the switching applications, but when turned off, between collector and emitter becomes high impedance in inverse direction as well. And base is stronger than gate of MOSFET against static electricity.

Bipolar transistors have been long used to mainly small power electronics but, as of 2012, almost all switching applications can be replaceable by MOSFETs or IGBTs.

2.5.6 Static induction transistor

An FET developed for high power, high frequency switching applications, but seems to be not much used; only some examples are found in audio amplifications (presumably because of triode characteristics).

[11] AC 100V-230V is converted to approx. 400V DC for power factor correction and world wide unification.

[12] In case of switching operation, excessive base current is applied to reduce the collector-emitter voltage - Vce(sat).

Also, a leading manufacturer Tokin has stopped production and is difficult to apply for new designs.

By the data sheet of THF-51S, switching of 600V, 20A by 1MHz seems to be possible, but the gate requires negative pulse of -30V and the gate capacitance is more than 500pF, making driver difficult.

This device can operate with faster switching than IGBT or MOSFET, but the current power design technology and devices (ferrite core, for instance) are not adapted to this speed, and combined with the difficulty of drive, small number of manufactures, this device has been little used.

As of 2012, this type of device is unavailable, but there is a report of SIT by using SiC from Sansoken, it may revive again.([4])

2.5.7 TRIAC

Turning on of the thyristor is limited during the half cycle of input AC and turn off occurs only when the voltage of the thyristor is zero. TRIAC is a device that turn on timing is made possible to full cycles of the AC input enabling phase control in full cycle.

Most common application of TRIAC is light control for incandescent lamps. Since the illuminance of the incandescent lamps are determined by the integration of power, the AC input can be switched by high frequency. Similarly, this technology is effective for heaters by nichrome wire, it is widely used for thermo control applications as well.

Fig 2.10 shows a control circuit for light or thermo control by TRIAC. TRIAC turns on when G becomes either positive or negative to T1, T2 electrodes and turns off when load current becomes zero (a four quadrant device). Device connected to G of TRIAC is called DIAC, and has characteristic shown in Fig 2.11. That is, it turns on when the voltage of both terminals becomes $+/-V_{B0}$. To the DIAC, delayed phase voltage is applied by $R1$, $R2$ and C and the delay time can be controlled by variable resister R2. Then, TRIAC turns on at $TRG1$, $TRG2$ and the hatched part is applied to the load.

Control by TRIAC is simplified by combining a dedicated control device DIAC, and the circuitry is complete in the line operated AC circuit (without using DC power). TRIAC and DIAC are interesting examples of semiconductors that require no DC voltage for their operation.

On the other hand, switching of AC produces noise and power factor is decreased. Also, because of the interface to microprocessor is not easy, and different light control is necessary for LED lamps, the application of this device is narrowing.

2.5.8 MOSFET

MOSFET has a structure that the drain - source resistance is controlled by the voltage applied to the gate. Main parameters are the ON resistance between drain and source, drain voltage rating, drain maximum current, switching speed and gate input capacitance. There is no semiconductor junction between drain and source, which enabled to produce very low ON resistance devices; in recent design for low voltage ratings, several $m\Omega$ devices

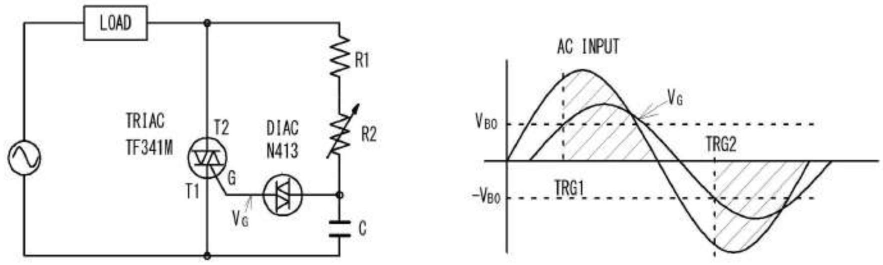

Figure 2.10: AV pase control by TRIAC

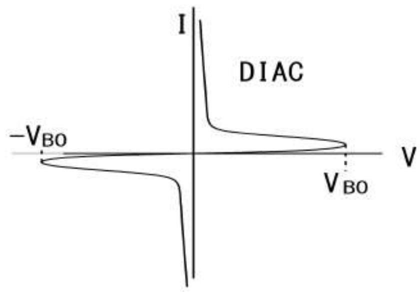

Figure 2.11: Characteristic of DIAC

are easily available, and without careful printed circuit board pattern design, the latter may present bigger resistance.

However, for high voltage rating devices, the ON resistance becomes higher and still not suitable to high voltage, high power application like electric railways.

One of the interesting characters of MOSFET is that the turn ON gate voltage of the device is determined by a parameter of design providing wider threshold voltage choice. This character may be the first for the long semiconductor development history. And this character enabled to produce 2.5V threshold device suitable for 5V logic application, 1.6V threshold device suitable for 3.3V logic application and so on.

This is very advantageous to incorporate MOSFETs with microprocessor controlled system.

Also, as is well known, to decrease energy consumption in microprocessor design, decreasing the logic level to around 0.5V [13] also became possible.

Because of the structure of the MOSFET, there is a parasitic diode between drain and source and the current switching is unidirectional. Since the control is by voltage, it is easy for low frequency applications, but for the higher switching speed applications a driving circuit will be necessary because the gate capacitance (and this is function of applied voltage) is charged and discharged accordingly.

Power MOSFET is designed to be normally OFF device and easy to use, but it is

[13]When bipolar transistor is used for logic device, the minimum base control voltage is about 0.7V which limited the logic level. And since bipolar transistor is a current control device, the reduction of over all current is difficult. Under these constraints, there was a type of logic called IIL in which logic is defined by current.

vulnerable against static electricity and has short failure mode which requires care when design and handling.

The drain - source path is ohmic and parallel connection is possible with no particular care making this device useful for power application.

Both N add P channel devices are available, but for higher rating and lower ON resistance, the N channel devices have wider choice.

Although this is not the basic problem, the symbol of MOSFET is complicated and difficult to recognize between P channel and N channel[14], and without explicitly showing the parasitic diode, some fundamental error can happen at design.

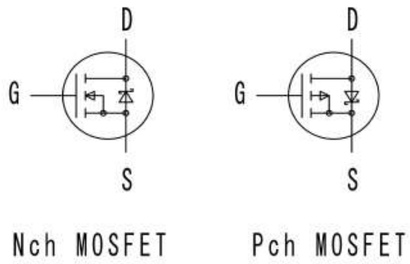

Figure 2.12: Symbol of MOSSFET

2.5.9 SiC device

The most popular Si-MOSFET is said to be approaching it's physical characteristic limit. On the other hand, SiC devices have better potential for power MOSFETs and currently development and production are in progress.

SiC has 3 times wider band gap, 10 times higher destruction electric potential. Also it can operate under high temperature (there is a report of 650 operation, having high thermal conductance nearly equal to that of Cu). And this means that a device with low ON resistance and high operating temperature is expected by SiC.

In particular, along with the progress of hybrid vehicles (HV) and electric vehicles (EV), the device is expected to find wide usage in the inverter applications.

SiC is known from old days, and had to wait for better production technology of wafer that can eliminate lattice defects, and processing technology as well.

As of 2012, mass production of SiC-MOSFET SCH2080KE commenced by Rhom; voltage rating 1200V, over 50KHz switching is possible (which was not possibel by IGBT).

The remaining problem is the cost of the wafer (several tens of times expensive), but this is expected to be reduced to several times more expensive in 2015.

[14]Comparing that of bipolar transistor, the center arrow looks like the inverse and direction of ON current is inverted.

2.6 Relays for small power

Relay is an old and very much used device. Because of it's mechanical structure, it is not suitable for high speed switching, but it's usage covered very wide range of voltage and power.

By power switching with a relay, the structure of relay differs according to AC or DC, careful selection is necessary for even relatively small power operation [15].

Particularly, power relays for the DC switching , some type encapsulates hydrogen gas and other specific design care are applied, careful selection is necessary and the size may become larger in general.

And the arcs are expected between the relay contacts, varister or CR spark killer are necessary to prevent potential mal operation of logic circuit etc..

Planning to use those power relays, it should be thought as a necessary evil, and try to find possibilities to use semiconductor switches first. In this respect the short failure mode of MOSFET is inconvenient, although contact welding can happen to mechanical relays.

The control of relay is carried out by a magnetic mechanism, relay is equipped with a coil to form an electric magnet. When applying voltage to the coil, current limit works by the inductance[16], but when the coil is turned off, high voltage is generated causing possible mal effects to the circuits nearby.

The countermeasure is to connect diode so that current path is provided when the relay is turned off. The internal resistance of the diode consumes the inductance (coil) energy and suppresses noise.

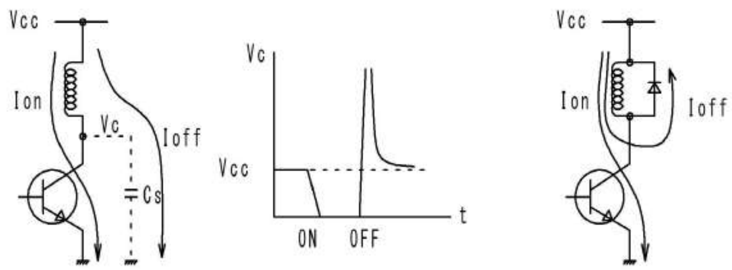

Figure 2.13: Driving of relay

2.7 Mechanical switches for power application

For smaller power applications, components that turn on/off the current is called just "switches", but for larger power operation, they are divided into several different components categories, and called by different names. We discuss these components by their design purposes here.

[15] When an AC 250V, 7A relay is used for DC 200V, max 2A switching, it was destroyed within a few times on/off because of the arc produced internally.

[16] To some extent, because the mechanical load makes the coil to look like a resistance.

2.7.1 Knife switch

Oldest and most typical switch made of a pair of knife like electrodes and receptacles made of copper alloy. It has simple structure and has self cleaning character by insertion of the electrodes, but non insulated electrodes are exposed which is hazardous.

Generally, fuses are housed inside the switch, but for application for 3 wire single phase wiring, never to use fuse to the neutral line. Because if the neutral line is cut off, voltage of the other lines may go up and destroy connected equipments.

2.7.2 Electromagnetic contactor

This is the standard component which replaced the knife switch and called MC as well. The basic structure is identical to conventional relays, and made of main contacts and electromagnet for control, but is equipped with small capacity contact that works simultaneously with the main contacts.
This auxiliary contact is used as shown in Fig2.15, enabling manual turning on/off.
The make and break contacts are called a-contact, b-contact respectively.

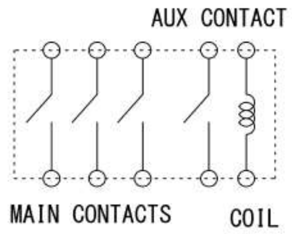

Figure 2.14: Electric structure of magnetic contactor

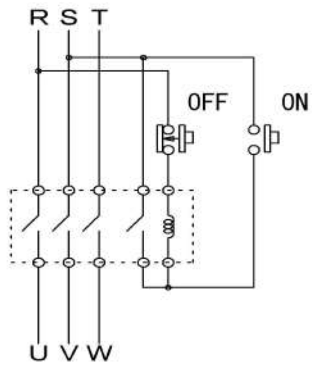

Figure 2.15: Control example of magnetic contactor

The magnetic contactors are not equipped with over current protection, and if protection is necessary, a magnetic switch is used.

2.7.3 Magnetic switch

This is a component that an over current switch like a thermal relay is connected in series to a magnetic contactor for over current protection.

When thermal relay turns on by over current, the break contact (b-contact) of the thermal relay turns off the current of main contactor coil, and keeps the off state.(Thermal relay itself returns to on state when the current is removed.)

2.7.4 Circuit Breaker, Disconnecting switch, etc.

Circuit breaker (CB) is a component to cut off the flowing current and equipped with arc extinguishing capability. There are many different type to extinguish arcs; air blast type, magnetic type, oil, gas or vacuum chamber type and so on.

The disconnecting switch has no capability to extinguish arcs, and it is connected in series with circuit breaker. If the disconnecting switch is turned off when the current is flowing, it will cause severe trouble and to prevent this, locking mechanism called "inter lock" is equipped. This component is used to cut off completely to secure the safety.

Thermal relay cuts off the current by sensing the over current by bi-metal using the heat produced by the current. Relay contacts are provided so that the cut off status is used outside.

Chap3 Storage of electricity

We will discuss the characteristics of electricity storage devices from user's point of view without getting into the mechanism of the storage.

3.1 Lead battery

This is one of the most widely used electricity storage devices that has been evolved with automobiles. Structure is simple and little hazardous of fire, but electrolyte (dilute sulfuric acid) is dangerous when leaked. The single cell voltage is 2V, but the cells are generally connected in series to produce 6V, 12V unit batteries. For the automobile application, the 12V batteries must supply huge current in these years, and there is a trial to increase the voltage to 36V.

There are roughly two different variety of lead batteries. One is for automobile application that assumes that the battery is fully charged throughout the time and is not suitable for deep energy storage/discharge. This type is most suited to supply big current at the time of starting the engine and better be understood as an impedance converter for the alternator[1].

The automobile batteries are very much optimized; heavy but inexpensive, requires maintenance for the electrolyte but is regularly stirred for good effect. The capacity and weight are 32Ah(11kg) - 64Ah(22kg) for passenger cars, and 52Ah (16kg) - 176Ah (61kg) for trucks and bigger cars (voltage is 12V).

The other type of lead battery is called a deep cycle type. As the name implies, it can work with the discharge/charge cycle of full energy capacity. These were originally designed for battery powered vehicles like fork lifts or buggies used for golf, but they can be used as energy storage devices for photo voltaic or wind turbine power generation. A deep cycle battery made by Panasonic (LC-XC1228AJ) (12V,28Ah) can sustain 70% capacity of the original value after 400 charge/discharge cycles. For the charging of this battery, two step constant voltage scheme is used; early stage of charging is done by higher constant voltage (cycle charge voltage), and then switched to lower voltage (trickle charging voltage) when the current is reduced to specified value.

Fig3.1 shows a block diagram of the simplest solar panel power generator system with a lead battery. The system charges the battery by the energy from photo voltaic panels simultaneously driving the DC/AC inverter to produce AC output. This satisfies the minimal requirements for solar or small wind turbine generation. The simplicity is the

[1]The situation is changing for the automobiles that support the stopping of engine idling. For this application, the work load for the battery gets much heavier because of deeper charge/discharge

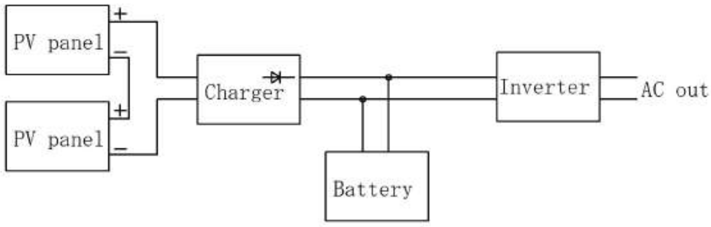

Figure 3.1: Photo voltaic energy system with lead battery

best merit and can be better suited than sophisticated systems for some applications. For instance, Fig3.2 shows an electric lighting donated by Cocoaboard [2], pictured at a community with no electricity near Yendi in Northern district of Ghana. In this case, the solar panel is mounted on top of the pole with a light underneath and charge controller is housed within the pole, the battery buried underground of the pole[3].

Figure 3.2: Solar light

3.2 Nickel cadmium battery

The Ni-Cd battery is the first practical rechargeable battery for the portable consumer equipments. The cell voltage is 1.2V nominal and a bit lower than the dry cell battery,

[2]An organization that monopolizes cocoa production in Ghana.

[3]They come up suddenly with a heavy earth-moving machine without caring the villagers' intentions at all and start digging the hole, install the lighting and are gone with the wind. No information of contact address at the time of failures nor the replacement of the battery when the life is over.

but found many applications replacing dry cells either single or serially connected cells. These secondary batteries were commercially available with compatible form factor with the dry cells. The merits of the Ni-Cd battery are that the constant discharging voltage (during discharge, the output voltage is almost constant and it steeply drops at the end of capacity) and very low output resistance. The low output resistance is most suited for driving DC motors and was best utilized for early camcorder applications. Demerits are; the self discharge is relatively big, has memory effect (if charged capacity is not fully discharged, then it will not charge up to full capacity) and toxic materials are used. They have been replaced by nickel hydrogen (Ni-MH) battery which has better energy density and has similar electric characteristics.

The good discharge characteristics means the difficulty of charging control and following schemes are used for charging. Monitoring the voltage while charging by constant current and detect the small rise and fall of the voltage at the end of full charge to stop charging or, just apply smaller quasi constant current for some specified time.

3.3 Nickel hydrogen battery

By replacing the negative electrode material of Ni-Cd battery by hydrogen absorbing alloy, the capacity as a battery is more than doubled. And the voltage characteristics are similar to the Ni-Cd battery which worked for quick replacement. Demerits are also similar to Ni-Cd battery and still has memory effect, with some self discharge. However, self discharge characteristic has been greatly improved and pre charged Ni-MH batteries are commercially available now (Eneloop by Sanyo and Evolta by Panasonic and others). These batteries have much improved charge/discharge characteristic like 1000 to 1800 cycles, and much economic considering the longevity of whole life than dry cell batteries.

On the other hand, the voltage that is determined by electro chemistry is smaller and there are applications that cannot replace dry cell batteries. For instance, the LED lamps designed for un-electrified areas[4] can work only by dry cell batteries or has very short operation by the low voltage batteries like Ni-MH batteries.

Since the Li-ion batteries are not commercially available as a cell[5], the Ni-MH is the only rechargeable battery that can be used like dry cell battery.

Also, the Ni-MH batteries are used for hybrid and electric vehicles and shall still have a good and wide application field.

3.4 Lithium ion rechargeable battery

3.4.1 Outline

This rechargeable battery is made into products by Sony and Asahi-kasei in 1991. The cell voltage is 3.7V, no memory effects and small self discharge with high energy density (155Wh/kg which is approx. two times higher than Ni-MH). These various merits found

[4] In these areas, the used batteries are just thrown away with no hope of recycling.

[5] The situation has changed as of 2020, but there is potential danger is dealing with Li-ion battery cells.

good applications in mobile phones, lap top PCs, camcorders and other mobile equipments. Cycle life is said to be 500-1000 times.

The demerits are that both the over discharge/charge may cause abnormal heating up and requires protection mechanism, not suitable for big current application and poorer characteristics at low temperature as compared with Ni-MH battery. In August 2006 and later, the battery system for laptop PCs caused a couple of accidents of smoke and fire that attracted the attention for the danger of these high density mobile storage. Also, the troubles of Li-ion battery system equipped in Boeing 787 is still green in memory. And the cost of rare metals like lithium and cobalt is another demerits for the battery.

The lithium-ion batteries are light weight and very handy to use, but they require utmost care and attention in handling, causing that the cells alone are not commercially available. The lithium-ion battery cells are made into a battery pack that are equipment specific, and treated with charging technology as a system.

3.4.2 Smart battery

This is a battery management specification made by Intel and Duracell in 1994 mainly aiming at the application for laptop PCs[6]. The batteries included are lead, Ni-MH and others, but practically lithium-ion battery is the main target right now and, hence mentioned here.

As shown in Fig3.3, information bus line called SMBus is designed connecting battery pack, equipment and battery charger. By information exchange between these three devices, calculation of the remaining capacity of battery, expected operation time of the equipment and charging control of the battery are realized. Also, type of battery, manufacturer, model, characteristics and alarm signals are read out from the battery that enables high speed charging and graceful shutdown of the laptop PC and so on. The number of charge/discharge cycles may be written into the battery pack that is used to anticipate the life of the battery pack.

Specifications and protocol are disclosed (document[25]), device drivers for PC can be down loaded.

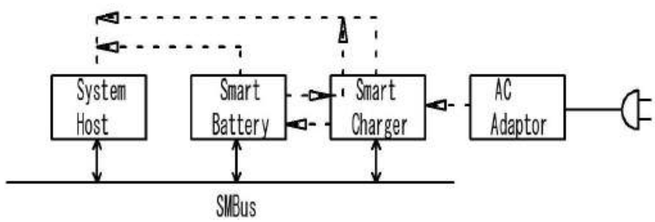

Figure 3.3: Smart battery

[6]Toshiba is calling their stationary energy storage system as "Smart battery" but this is completely different.

3.4.3 Info lithium battery

Battery pack designed by Sony in 1996 that enables to show the remaining capacity by the units of minutes intending for camcorder application. The battery pack has three terminals and used for DC outputs (+/-) and information exchange with the equipments. The contents of the data read from the battery are version, current capacity(Ah), voltage(V), current(A), internal temperature and others, and data written to the battery comprises the number of the charge/discharge cycles.

Hence, if the equipment has functionality to manage the info lithium specification, the remaining operation time of the equipment is calculated by taking account of the variety of equipments and variety of battery capacities under detachable battery systems. Also, the equipment may accept only the genuine batteries by inhibiting batteries made by unauthorized third parties. However, the discharging and charging of the battery are possible without active communication of the battery. The specification and protocol is proprietary and not disclosed, the details of the data communication is unknown.

3.4.4 Battery packs

The cell of lithium-ion battery[7] is not commercially available, but only released to consumer as a battery pack specific to the equipments. Inside the battery pack, cells are connected in serial/parallel to produce specified power output. For instance, commonly used chargers for laptop PCs have voltage of 10.5V,16V and 19.5V. These chargers correspond to 2, 3 and 4 series cell packs[8]. The cells internally connected in parallel are controlled by voltage at the factory.

The battery packs for laptop PCs are controlled by charging scheme (constant current, constant voltage), have over current protection, over voltage protection, management of battery remaining capacity, temperature, history of usage and others. Also, to conform smart battery specification, a microprocessor is generally used as well. However, the number of serially connected battery cells are limited, the cell balancing is generally not implemented (document[29]), and the charging is done for the serially connected cells.

On the other hand, the battery packs for Electric vehicles and machine tools that require higher voltage output [9], further control of cells are necessary. The single cell voltage of the lithium ion battery changes 4.2V-2.8V at charge and discharge, voltage of the 10 series connected battery pack will be 42V-28V with the nominal voltage 37V. Obviously, the failure of a single cell cannot be detected as long as monitoring the whole series cell only.

For solving the problem, the voltage of each serially connected cells are monitored (for this purpose, bq76PL536A made by TI and others are used. [31]) and voltage balancing is performed. As shown in Fig3.4, the parallel resistance and semiconductor switches are connected to each cells and the cells are discharged locally so that the voltage is made equal to the lowest voltage cell. This control is done for a couple of series connected

[7]Most commonly used cell is called 18650, whose diameter is 18mm, and length 65mm. For mobile phones and tablet devices, the battery cells are specifically designed for the equipments.

[8]Maximum voltage for charging voltage per cell is 4.2V

[9]36V by HR262DRDX produced by Makita.

cells (for instance, 6 series cells), and eventually all the series connected cells are voltage balanced.

As shown above, the utmost care is taken for the charging and managing of the lithium ion batteries. Particularly, the high voltage battery packs require significant control technology and is reflected to the cost of the battery packs.

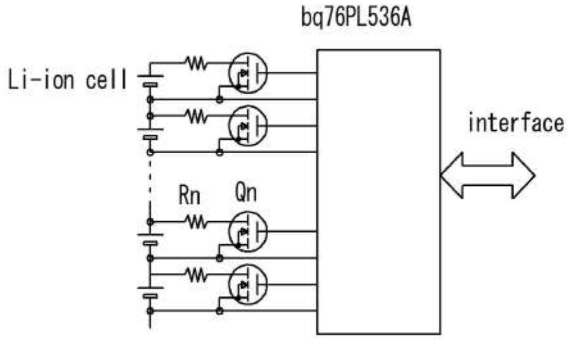

Figure 3.4: Cell balancing of li-ion battery

3.5 Iron phosphate lithium battery

One of the varieties of lithium ion batteries that uses iron phosphate lithium for positive electrode. The heating up at abnormal condition is suppressed for higher safety and drastically improved the charge/discharge cycles. After 5000 cycles, more than 80% of original capacity remains. However, the energy density is decreased to 95Wh/kg and cylindrical cell of 26650 (dia 26mm, height 65mm) weigh 40g, with capacity 1.1Ah and nominal voltage 3.2V.

The merits of this battery are best exploited for power electricity storage system and electric vehicles. The longevity of life is over quality for mobile phones and smart phones that have a life of a couple of years, and the weight and size are not competitive. Energy server system that uses this battery is released in 2011 by Sony (CP-S300 series).

3.6 Lithium titanate battery

This battery is developed by Toshiba aiming at the electric vehicles and hybrid electric vehicles. Positive electrode is made of lithium manganate and negative electrode is made of lithium titanate(Li4Ti5O12). Merits are that it can work rapid charging/discharging and long cycle life. After 3000 cycles, the reduction of capacity is less than 10%, and can work 5000 cycles. Also, it works under -30 degree Celsius and internal short circuit by external cause will not lead to thermal runaway. Longevity and robustness of this battery found applications for Mitsubishi "i-MiEV", "MINICAB-MiEV", and Honda "FIT-EV". Cell voltage is 2.4V, and energy density is approx. 67Wh/kg. It is said that the battery is expensive because of titanium.

3.7 Calculation of remaining capacity

One of the biggest concerns in using secondary batteries is the estimation of the remaining capacity. For this purpose, many schemes are developed and utilized. We discuss about this technique assuming the lithium ion battery and Ni-MH battery. But if the battery is detachable or not (with variety of capacity) will greatly affect the selection of schemes.

For the detachable battery system, the information exchange with battery (pack) will be almost inevitable for even reasonably accurate calculation. The cost of information processing and communication is small enough that both equipments and battery packs can afford, and "smart battery[10]" is the current standard of battery system.

Even communication capability is equipped, it will be almost impossible to calculate the precise remaining battery capacity including the third party battery packs[11].

Following is the discussion for several schemes for remaining capacity calculation.

3.7.1 Voltage measurement scheme

All the batteries have voltage characteristic with high initial voltage which becomes lower as discharge goes on, and at the end of discharge, the voltage drops rapidly. Therefore, when the voltage is monitored, the remaining capacity is more or less calculated. But the batteries with better discharging characteristic it is difficult to estimate the remaining capacity because of flat voltage during discharge.

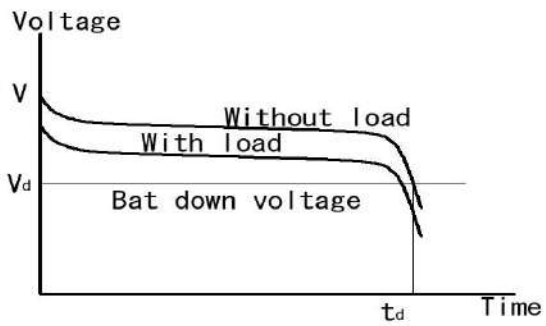

Figure 3.5: Discharge characteristic of battery

Fig 3.5 shows a typical discharge characteristic[12] of a battery which shows a steep voltage drop at the end of discharge t_d. The voltage V_d at t_d becomes the battery down voltage which cannot ensure the appropriate battery capacity. Because, the curve changes by the battery sample, number of charge/discharge cycles, with load, ambient temperature and so on.

By this reason, monitoring the battery voltage is inaccurate for estimation of remaining capacity, and this scheme was used for early Ni-Cd and Ni-MH applications or is used just for rough estimation.

[10] battery system with communication. not limited by Intel/Duracell protocol.

[11] Depends on the technology and good will of the third party battery pack manufacturer.

[12] Either Lithium ion or Ni-MH, the curve is similar.

To get better accuracy, information concerning battery manufacturer, model, charge/discharge cycles, internal temperature and amount of load are necessary and that eventually lead to smart batteries and info lithium batteries.

3.7.2 Coulomb counter

This is based on the principle that the battery is charge storage device. That is, the current through the battery is integrated to calculate the capacity. In practice, pulses that is proportional to the current are generated and the number of the pulses are counted by an up/down counter. The up or down is controlled by the charging or discharging status and this is the reason why this scheme is called Coulomb counter (see [28]). This scheme provides better accuracy than voltage method, but still, the characteristic change by temperature and age cannot be taken into account. Also, this scheme is basically relative measurement and requires calibration by combining with the voltage method (counter may be reset by full charge).

For detachable batteries, the difficulty increases for supporting various samples. The information from the battery such as capacity of battery pack (model number), and current SOC (state of charge) must be stored in the battery pack and the equipment must know these informations.

3.7.3 Cell modeling scheme

Data base of the battery characteristics such as discharge curve and temperature characteristic are stored in the equipments and combining coulomb counter scheme to calculate remaining capacity. In this scheme, the age and temperature are taken into account yielding better accuracy. However, if the battery is detachable, data storage and communication capability is necessary in the battery pack with the corresponding functionalities in the equipments.

3.8 Redox flow battery

Redox is coined by combining reduction and oxidation and shows the principle of this battery. The charge and discharge of the battery is caused by the reduction and oxidation of two electrolytes which are sulfuric acid solution with vanadium ions. Positive and negative electrodes are made by identical material (carbon felt). The Fig 3.6 shows two serially connected cells each of which has chambers separated by ion exchange membrane with electrodes. The vanadium ion (V^{5+},V^{4+})(V^{2+},V^{3+}) solution is circulated by pumps to each chambers for charging/discharging electricity.

Electrodes themselves don't change, and the vanadium solution changes only by reduction and oxidation having no life limiting chemical reactions.

Ion exchange membrane passes through ions only. The cell voltage is 1.4V, and to increase voltage, the cells are serially connected. The function of cell is to efficiently reduce or oxidate the vanadium solution and this works as an equivalent internal resistance.

Output power is determined by the area of the cell and number of serially connected cells with pumping capability, whereas the output capacity is determined by the capacity of tanks that store the vanadium solution. That is, the output power and output capacity is separated and two vanadium solutions are stored by different tanks separately, meaning that once the pump is stopped, the self discharge is negligible.

This battery was originally intended to leveling the power demand for AC grid, and longer time discharge was assumed, but after real implementation, it was found out that it has good instantaneous power supply capability and is expected to become one of the potential technologies for big energy storage, particularly, it can operate under normal temperature. The demerits are that the energy density is small (100Wh/kg), energy to start pump is necessary[13] and the system must necessarily be big because of the tanks for vanadium solution storage.

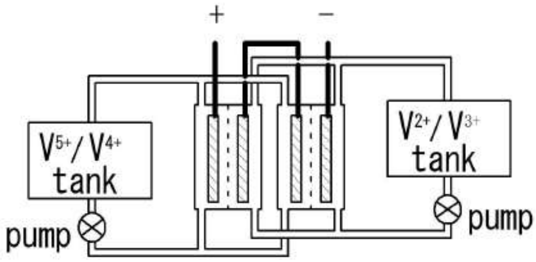

Figure 3.6: Redox flow battery

3.9 NAS battery

This is a big battery system intended to store electricity for big energy applications. The battery cell is covered by stainless steel container in which liquid sulfur with positive electrode and ceramic container in which liquid sodium with negative electrode is placed.

Energy density is very high (786Wh/kg) and has long cycle life (more than 2500 times). The structure looks simple, but the ceramic container is the key device and only one manufacturer Nihon gaishi can produce this container - and NAS battery.

The cell voltage is 2V, and the cells are connected in parallel/series to produce required output power, and the cells are then put into a container that is filled with sand and the inside of the container is kept by high temperature.

The biggest difficulty of this system is the heating of the battery cells to 300-350 degree Celsius to keep sodium and sulfur in liquid condition. Also, the sodium burns by water and in case of fire, water cannot be used to extinguish fire.

Since high temperature is kept for operation, mobile battery will be impractical and the system will be only for stationary applications with necessary energy to keep heated. The system efficiency is around 75%.

[13]Once the pumps are started, the pumps can be driven by itself.

Fire broke out in 2010 by the NAS battery system and other installed systems were also stopped operation or removed installation, but as of 2013, the troubles are resolved and new progress seemed to have started. But NAS battery hardly can be a component in a system described in this document.

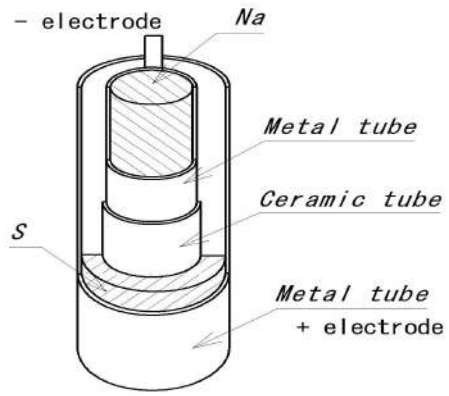

Figure 3.7: NAS battery

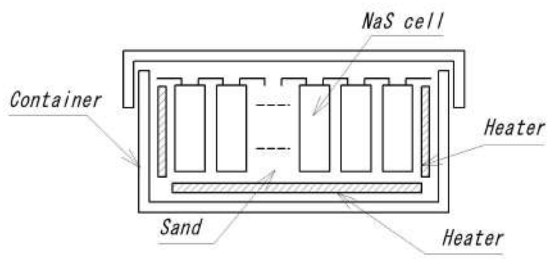

Figure 3.8: Structure of NAS battery system

3.10 Electric double layer capacitor

Capacitors store electric charges and the big capacitance can be used as a energy storage device. Even electrolytic capacitors, 100μF, 450V [14] can store nice amount of electricity for circuitry used in home electric appliances. But, as electric power, this still is negligible and cannot be of practical use.

To store energy, both capacitance and voltage works. Electric double layer capacitors are the ones that have big capacitance, although with small voltage. This is sometimes called a super capacitor, and appeared in the market around 1970s, and long used already.

The capacitance is around 1F-2000F, but the nominal voltage is as low as 3V. The mechanism of the storage is not electro chemical, but that of a capacitor and has a very

[14] Even the storage with this amount of value, short circuit by a wire causes big noise as well as arcs. Also, there is potential danger of electrocution although this value are often found in home electric equipments.

long life (several tens of thousands hours). The discharge characteristic by constant current shows linear decrease of the voltage which is apparently different from that of a battery.

Comparing with the electrolytic capacitors, the internal resistance is high and not appropriate for ripple filtering for AC applications. Mostly found the applications for memory back up, clock back up and so on. In this sense, this still is not very practical for energy storage applications, but it can be charged rapidly[15] and will find applications used in parallel with batteries.

3.11 Lithium ion capacitor

This device is made by combining negative electrode of lithium ion battery and positive electrode of electric double layer capacitor. Hence, the charging mechanism for both electrode is different. For negative electrode, charge is stored as ion inside the material just like lithium ion battery, whereas at the positive electrode, charge is attracted to the surface of the positive electrode. Because of this mechanism, the nominal voltage becomes approx. 4V and this contributes the increase of stored capacity. Other merits are that no thermal runaway expected, small self discharge and rapid charge/discharge is capable. As demerits, there is a limitation of lower voltage and over discharge degrades the device like a lithium ion battery.

The principle of charge is also a hybrid of lithium ion battery and electric double layer capacitor. Up to 3V, ion is charged into negative electrode (battery side) and 3-4V, the charge is attracted to positive electrode (capacitor side). For the discharge, the mechanism is just inversed. The electric characteristics show the combination of rapid charge/discharge of electro double layer capacitor and high energy density of lithium ion battery. ULTIMO laminated cell CLQ2200S2A by JM energy company has the cell di-

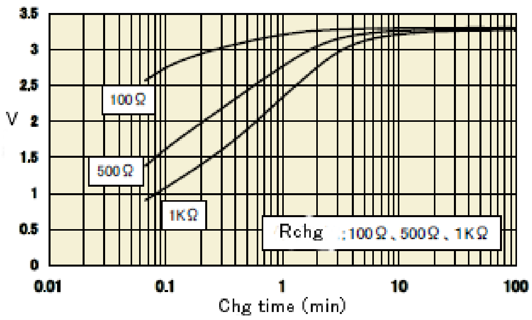

Figure 3.9: Charging characteristics of PAS414HR

mension of 180x126x10.9mm, with maximum voltage 3.8V, minimum voltage 2.2V and capacitance 2200F. Energy density is 10Wh/kg.

The charge/discharge curves remind us the parallel connection of a lithium ion battery and an electric double layer capacitor.

[15]Comparing with the rechargeable batteries. As a capacitor, charging is slow because of internal impedance which in turn, big surge current will not flow and easy to use.

Fig 3.9 and Fig 3.10 shows charging and discharging characteristics of PAS414HR manufactured by Taiyo Yuden. (From Taiyo Yuden Navigator)

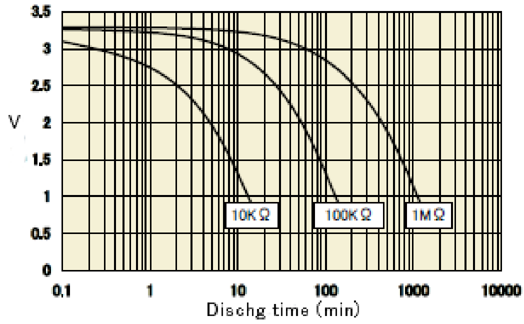

Figure 3.10: Discharging characteristics of PAS414HR

Chap4 Power conversion circuit

Power supply generally incorporates regulator, by which the voltage or current is kept constant. Therefore, power conversion more than often includes regulator which is not separable.

4.1 AC conversion

In this chapter, conventional AC conversion is not the target nor an objective. But the DC/DC converters convert DC to AC first and use a transformer inside, it is necessary to understand the principle of the transformer. We discuss the transformer as a black box here, and the seamless discussion form electromagnetic theory to a transformer design shall be discussed in Chap 5.

In case of AC, voltage conversion is easy by using a transformer. The primary voltage (current) is first converted to magnetic field, and then magnetic field is converted to secondary voltage (current). Electrically, primary windings and secondary windings are insulated in general [1].

Most conventional transformers are used for the sinusoidal voltage conversion for commercial frequencies (50,60Hz), and the first specification required is the voltage ratio. This value is determined by the ratio of windings for primary and secondary side, and when the ratio is,

$$n_1 : n_2$$

then, relation between input voltage V_i and output voltage V_o becomes,

$$V_o = \frac{n_2}{n_1} V_i$$

Power capacity of the transformer is the summation of output power, loss by winding resistance and loss by mainly eddy current in the core. These summation becomes equal to the overall input power. Therefore, at design or the specification fix, the overall power output is the first thing to consider. The power capacity determines the core size, weight and size of the transformer and roughly cost.

In principle, larger transformer can replace smaller one, but in this case, larger in size means heavier, more expensive and requires bigger magnetizing current, so it is advisable to use an adequate power capacity transformer to the load.

Efficiency of the small power transformer for home equipments, it is about 80%, and for the large transformer for grid power transmission, it becomes over 99%.

[1] There is a transformer called auto-transformer by which, primary and secondary is not insulated.

Generally, transformer is designed by a specialist, but for writing down a rough specification or even just using, it is very much advisable to understand several important characters.

First of all, never try to draw output more than nominal rating. If one does this, the output voltage will drop more than expected, but the real problem is the saturation of core and lower voltage is a secondary problem. In case of power transformers for commercial frequency, the core size (capacity) is chosen so that magnetic saturation does not occur at the rated output with minimum margin. Over loading to transformer causes core saturation which effects heavy current in the primary winding and eventually burn the winding. This tendency is known by observing the shape of primary current of the transformer[2] and if there is some peak over the top of sinusoid, core saturation is happening. Either reduce load or replace by a larger transformer.

Insulated copper wires are used for transformer and the general rated current is 105 degree Celsius. And the transformers must be used so that the deepest layer of winding has enough margin with the rated value under the highest ambient temperature. Particularly, remember that the transformers have big heat capacity and they take time to fully warm up.

Electric characteristics of a transformer becomes different without load and with (nominal) load. In case of no load, only magnetizing current flows to primary side, and looks like an inductor. Phase of the the magnetizing current lags to the applied voltage. In ideal condition this is 90 degree, but in actual case, it is less than 90 degree because of iron loss and copper loss.

On the other hand, when nominal (or design) load is connected and the load is resistive, looking into the primary side becomes resistive and no phase lag is expected.

In practical usage, the secondary side is likely to be connected to rectifier and filter capacitor, current phase lag is expected with power factor degradation. In a nutshell, looking into primary winding, it looks as a parallel circuit of R,L and C, but R should be dominant.

When the transformer is used by the rated load, input energy except loss is all transfered to secondary side and no energy is stored in it, that is, primary and secondary is wound by wires, but no inductance observed.

4.2 DC conversion

In case of DC, direct voltage conversion is not possible other than voltage drop by a resistance[3]. Therefore, it is converted to AC first and for the conversion, switching devices are most commonly used .

Simplest way to convert AC from DC is by the switching and produce square wave [4], which is fed to a transformer so that the voltage is tailored to meet specifications. Thus,

[2]Observing any winding by an oscilloscope, this will be known.

[3]There is an old way in which DC generator is driven by an AC motor.

[4]Using resonance, sinusoid can be produced from DC.

during the power conversion process a switching transformer is often used. Although the waveform is not sinusoidal, but still AC is used for conversion.

Now, complication begins here. One part is caused by the wave form that requires straight forward differential equation[5] for analysis.

Second part is the driving scheme of transformer. In case of sinusoidal AC, there is no DC components, and hence no magnetic bias for the core is expected. On the other hand, when the input power source is DC, primary side may be driven for one direction only. Because this is much simpler and less expensive. In this case, there is a DC component in the driving (square) wave, and it requires further thought than AC transformer.

4.2.1 Square wave drive for transformer

In this section, we will clarify the two driving schemes for transformer using DC.

Fig 4.1 shows a basic circuit to drive a transformer by square wave. Transistor Q switches the primary winding of the T1, and the current flow is unidirectional. Comparing with AC sinusoidal transformer, this is a big difference. In this case, the primary current has DC component causing DC magnetization bias to the core.

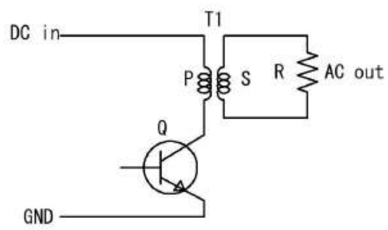

Figure 4.1: DC half switching converter

Then, if we want to drive the transformer in two directions like AC sinusoidal transformer, under the same DC input, we need a circuit shown in Fig 4.2. In this circuit, Q1, Q4 and Q2, Q3 pairs turns ON/OFF alternately. It is clear that current for the primary winding flows alternately. In this case, the primary current has no DC components.

This driving scheme is generally called "full bridge" drive and is much more complicated than the circuit in Fig 4.1. Not only the number of the transistors is increased, but control is complicated. And indeed this is the reason that the simpler form is preferred.

In above examples, the secondary output is connected to a resistive load and in ideal condition, the form of primary voltage, primary current, secondary voltage and secondary current are all same - square wave - and like AC sinusoidal transformer, the switching transformer just converts the voltage and stores no energy. Although the transistors look like to driving coils, they are actually driving resistors.

[5] In AC theory, scope is only (commercial frequency) sinusoid and differential/integration is replaced by multiplication of $j\omega$.

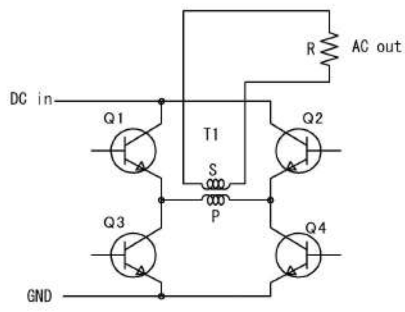

Figure 4.2: DC full switching converter

4.2.2 Forward converter

Fig 4.3 shows a simplest "forward converter".
Input DC is switched by Q (power transistor, MOSFET) and applied to the primary winding of the transformer. The current flow is always unidirectional and the windings of primary and secondary are set so that the polarity of secondary voltage becomes same with the primary voltage.

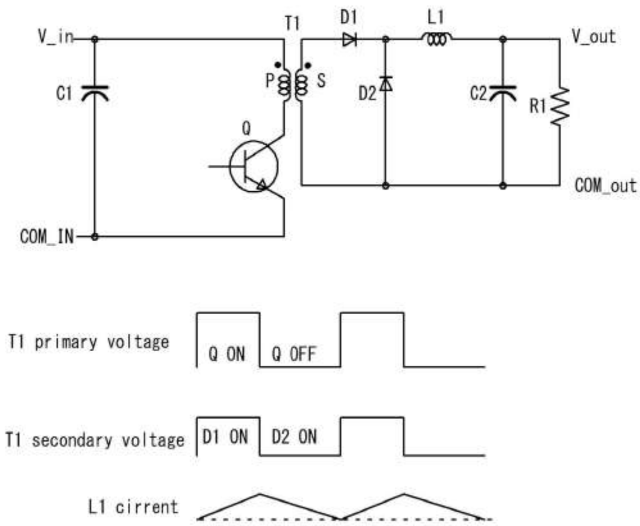

Figure 4.3: forward converter

When Q turns ON and DC is applied to the primary winding, the proportional voltage to the ratio of windings appears on the secondary side. The secondary circuit supplies energy via L1 to load R1, storing energy in L1 and C2. The input energy is only transfered to secondary side at this timing. When Q is OFF, the energy stored in L1 is supplied to R1 (and C2) via D2. The circuit is designed so that the current of L1 becomes basically continuous.

The idea of the usage of the transformer is identical with AC commercial frequency transformers - other than the unidirectional current - and it is a voltage conversion device. In principle, the transformer does not store energy and hence, no gaps are provided for the switching transformer. For details of transformer design, see Sec 7.2.

To design a regulator based on this circuit, add voltage sensing resistance at the out put and this signal is fed back to Q and modulate ON time (PWM). In the regulator, the current through L1 (DC+AC component) is either continuous or discontinuous. The discontinuity happens when the duration of Q ON is enough to increase the output voltage to specified value and no excessive power is required.

The advantage of using a transformer is that the primary and secondary side can be insulated, and for this purpose, the optical feedback is often used. Another advantage of a transformer is that multiple voltage (negative inclusive) outputs can be available. But the outputs cannot be regulated independently, generally main output is regulated.

As stated above, the ideal transformer looks resistive when nominal resistive load is connected at the secondary side. But in practice, there is always magnetizing inductance and leakage inductance, load of the switch Q is not only resistive but inductive as well. That is, when Q turns off, high surge voltage appears on the collector (identical effect described in Sec 2.6). Without countermeasures, high collector rating transistors are required, efficiency decreases and produces spike noises. The simplest scheme is to connect snubber circuit as in the case of relays, but much better sophisticated ideas are generally used.

Also, forward converters stated in this section uses only first quadrant of the hysteresis curve for magnetization and requires reset circuit.

The problems encountered in this section is neatly solved by the active clamp forward converters described in Sec4.5.8.

4.2.3 Analysis of forward converter

Referring to Fig 4.4, basic equations are derived. First we discuss when the current of the inductor L1 is continuous. Assume the voltage of the secondary winding of the transformer Vs and the current is shown in Fig 4.5. While the transistor Q is turned ON, secondary current I_1 flows via D1, L1. While Q is turned OFF secondary current I_2 flows via D2, L1. We assume the average output current is I_O and ignore forward voltage drop of diodes.

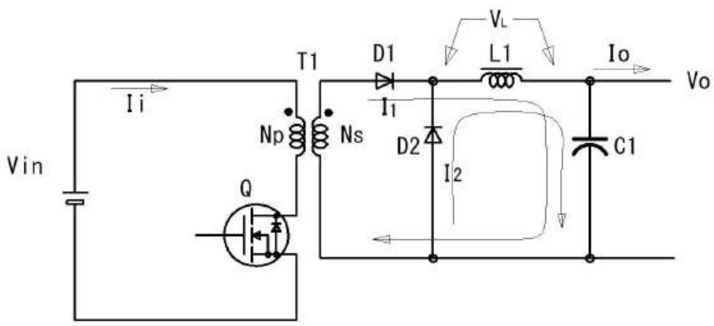

Figure 4.4: Forward converter

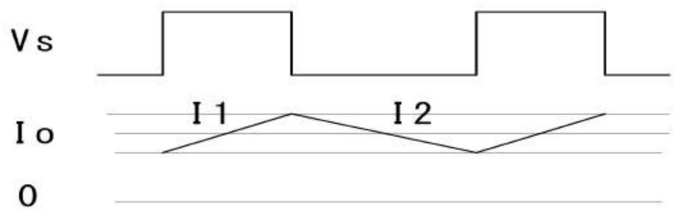

Figure 4.5: Wave form of forward converter

The output/input voltage and number of secondary/primary winding ratio of the transformer is,

$$\frac{V_s}{V_i} = \frac{N_S}{N_P}$$

When the transistor Q turns ON for t_{on} seconds, the secondary current $I_1(t)$ is,

$$\begin{aligned} V_L &= L_1 \frac{d}{dt}\big(I_1(t)\big) \\ &= \frac{L_1 i_1}{t_{on}} \\ I_1 &= \frac{V_S - V_O}{L_1} \cdot t_{on} \end{aligned}$$

When the transistor Q is turned OFF, the current flows through D2 for t_{off} second and $V_L = V_O$,

$$I_2 = \frac{V_O}{L_1} \cdot t_{off}$$

In case of continuous current mode, the average inductor current by diode D1 and diode D2 becomes identical,

$$\begin{aligned} \frac{V_S - V_O}{L_1} \cdot t_{on} &= \frac{V_O}{L_1} \cdot t_{off} \\ V_O &= \frac{t_{on}}{t_{on} + t_{off}} \cdot V_S \end{aligned}$$

The switching frequency f is,

$$f = \frac{1}{t_{on} + t_{off}}$$

The output voltage becomes,

$$V_0 = f \cdot \frac{N_S}{N_P} \cdot t_{on} \cdot V_{IN}$$

To control the output voltage, the duty ratio,

$$D = \frac{t_{on}}{t_{on} + t_{off}}$$

is modified.

When the load becomes small, the average current gets smaller and eventually, the zero current period (both D1 and D2 turns OFF) appears as shown in Fig 4.6. The peak current I_p through the inductor L1 becomes,

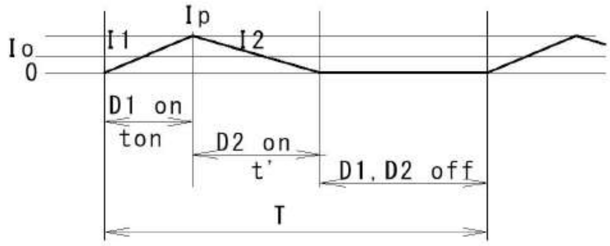

Figure 4.6: Discontinuous mode of forward converter

$$\frac{I_p}{t_{on}} = \frac{V_L}{L_1}$$

Expressing ON time of D2 by t', the voltage between L1 is equal to output voltage.

$$\frac{I_p}{t'} = \frac{V_O}{L_1}$$

$$I_p = \frac{V_L}{L_1} t_{on} = \frac{V_O}{L_1} t'$$

Average output current I_O will be,

$$I_O = \frac{1}{T} \cdot \frac{1}{2}(t_{on} + t')I_p$$

$$= \frac{I_p}{2T}(t_{on} + \frac{V_L}{V_o} \cdot t_{on})$$

$$= \frac{I_p}{2T}(1 + \frac{V_L}{V_o}) \cdot t_{on}$$

When t_{on}, $V_L = V_S - V_O$ holds,

$$= \frac{I_p}{2T}(1 + \frac{V_S - V_O}{V_O}) \cdot t_{on}$$

$$= \frac{I_p}{2T} \frac{V_S}{V_O} t_{on}$$

I_p is expressed as

$$I_p = \frac{V_L}{L_1} t_{on}$$

Therefor,

$$I_O = \frac{1}{2TL_1} \frac{V_L V_S}{V_O} {t_{on}}^2$$

Eventually,

$$V_O = \frac{V_L V_S}{2TL_1 I_O} {t_{on}}^2$$

The output voltage is controlled by the ON duration of the transistor in discontinuous mode as well.

4.2.4 Reset of transformer

Residual magnetic flux is an inherent problem of transformers which is caused by fundamental character of magnetic devices like iron and ferrite. This character shows that a magnetic material is once magnetized, it keeps on magnetized. For the transformers, the materials with smallest memory are used, but never becomes zero.

This problem manifests when a transformer is magnetized by DC biased current. In case of forward converters, the magnetizing current causes biased magnetizing (magnetic flux used for energy transfer to secondary side is completely consumed).

Fig 4.7 shows the B-H curve of a transformer. At the beginning, the magnetizing curve of the transformer starts at the origin, and reaches point C at maximum current. Then even the current becomes zero it can only get back to B. And it is necessary to set it back to point A to avoid the eventual saturation of the core. This operation is called the reset of the transformer. A is the residual magnetic flux and this cannot be avoided.

The fundamental reason of this problem is that the system uses only first quadrant, and this is the penalty to pay for using a simple circuit for the forward converters.

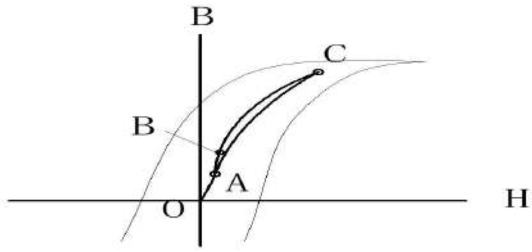

Figure 4.7: BH curve

4.2.5 Flyback converter

This circuit looks rather similar to Fig 4.3, but the operation principle is quite different. In flyback converters, the current flow for primary and secondary side has completely opposite (note the dots of T1) timings. When primary is turned ON, the secondary is cut off by diode D1 and no load is connected, only charging the magnetic flux into core.

Conversely, the secondary current flows by the magnetic energy stored in T1 when Q is OFF. That is , T1 looks like a transformer, but it works just as an inductor. And the amount of energy stored in T1 is important. For this purpose, T1 has a gap. See Sec 6.4 for detail.

4.3 Switching of reactor, capacitor

Reactors and capacitors are energy storage devices and switching these devices can convert voltage. Most commonly used DC/DC converters are down converters, up converters and inverting converters. In either converters, reactors and capacitors are used

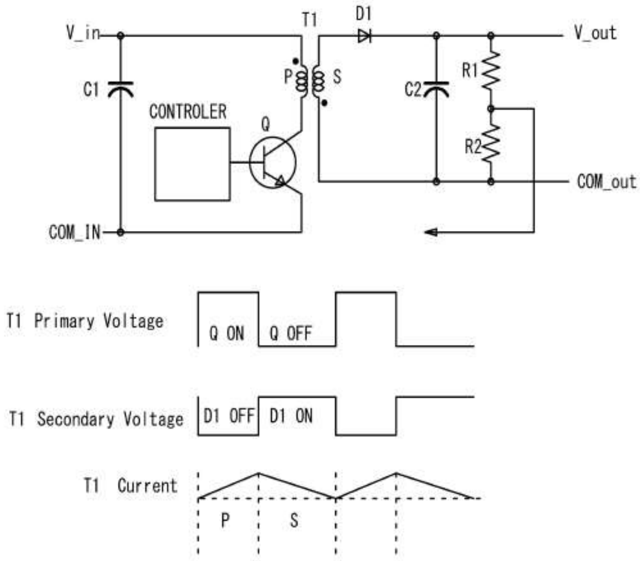

Figure 4.8: Flyback converter

and different topology gives different voltage output.

Fig 4.9 (A), (B), (C) show each basic circuit. In each circuit, reactors store energy as current (flux) and transfer to capacitors as voltage.

In general, the ON timing of the switch is PWM controlled and regulation control is carried out. Characters of these converters are;

(A) Output voltage < Input voltage,

(B) Output voltage > Input voltage and

(C) Output voltage polarity is inverted.

Particularly absolute value of output voltage of (C) may be either small or large and called up/down converter as well. This is useful for the application for which polarity inverting is permissible.

Down converters have one of the simplest configuration in DC/DC converters. And this circuit is obtained by removing the transformer and omitting the insulation from Fig 4.3.

Also, the up converter is derived by removing the transformer from the flyback converter shown in Fig 4.8.

Combining these down converter and up converter gives bidirectional DC/DC converter which will be discussed in Sec 4.4.

On the other hand, it is possible to convert voltage by capacitors only. Fig 4.10 is a circuit called "Cockcroft-Walton circuit" and used for high voltage generation. The idea is to charge capacitors in every half cycle by AC power source, and discharge in series eventually producing high voltage.

In the circuit shown by Fig 4.11, the capacitors are charged in series and discharged in parallel which is used in energy harvesting system.

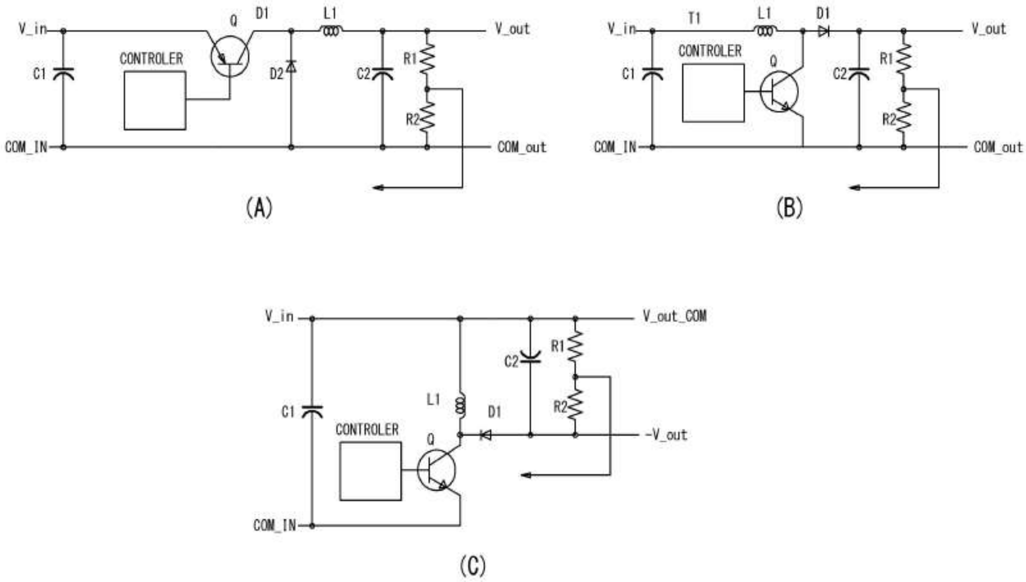

Figure 4.9: Topologies of DCDC converter

Also, conversion circuit called "switched capacitor" is used widely.

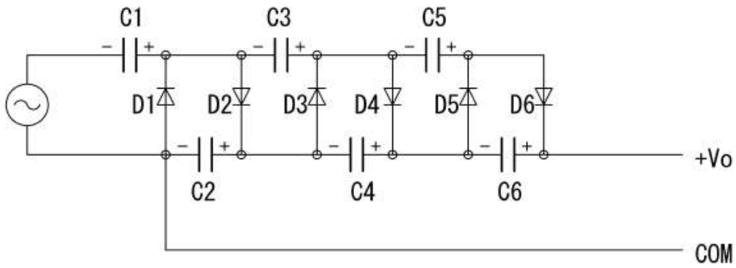

Figure 4.10: Cockcroft-Walton generator

Remembering that the reactors are dual device of capacitors, conversion circuit of reactors only must be possible, but they must become current conversion circuits and would be difficult for practical use in mostly voltage based electric engineering.

4.4 Bidirectional converter

This converter enables bidirectional conversion of voltage. As shown in Fig 4.12, down converter and up converter is combined back to back producing beautiful configuration. Principle itself is clear by the circuit diagram, but in particular Q1-D2, Q2-D1 pair became explicit bidirectional switch revealing somewhat hidden meanings of D1, D2 in up, down converters. [6].

[6] Regarding the beauty of structure, both up and down converters are incomplete, and the real perfection is found in this bidirectional configuration.

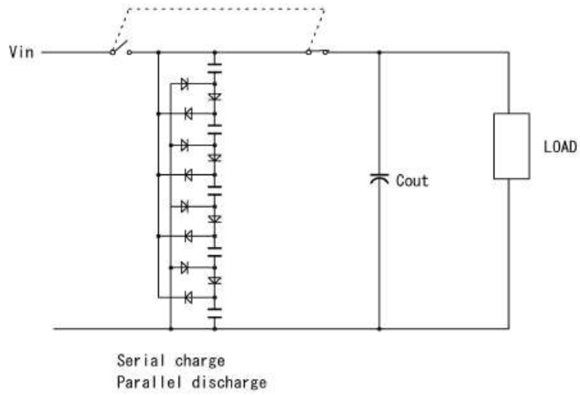

Figure 4.11: Series charge, parallel discharge of capacitors

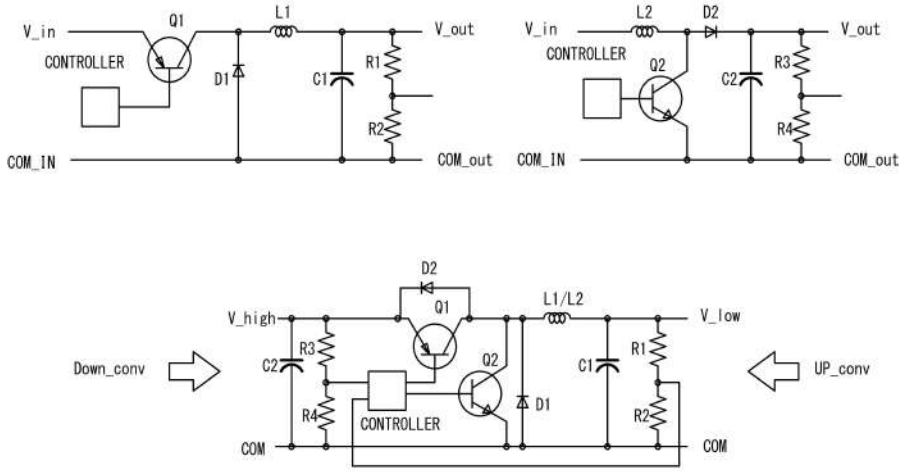

Figure 4.12: Bidirectional converter

4.5 Power conversion using resonance

4.5.1 Resonant circuit

We will clarify the characteristics of resonant circuit before discussing about the application in Sec 4.5.2.

Ideal resonant circuit is a closed circuit of an inductor and a capacitor. The configuration of the resonant circuitry is one and only, and cannot be regarded either series nor parallel. If oscillation is induced in this circuit by some reason, it will continue for ever.

For a practical resonant system, energy is applied to this system and characteristic oscillation is extracted. For instance, in a pendulum clock, a spiral spring drives a pendulum and it regulates the rewound speed which eventually indicates the time.

Therefore, in practical resonant system (circuit), there is a mechanism to supply energy and extract periodic information (this will deprive some energy from resonant circuit) from the system. And in conjunction with this information extracting interface, the distinction

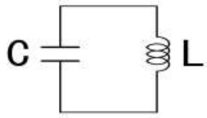

Figure 4.13: Ideal LC resonator

of series resonance and parallel resonance makes sense.

Based on the discussion above, LC resonant circuit that comprises both energy source (AC power source) and losses are shown in Fig 4.14. In general, topology (A) is called "parallel resonant" circuit whereas (B) is called "series resonant" circuit. The name and topology is self evident by the connection with energy source. R_P、R_S shows the loss of resonant circuit and R_P should be a large value, and R_S should be a small value.

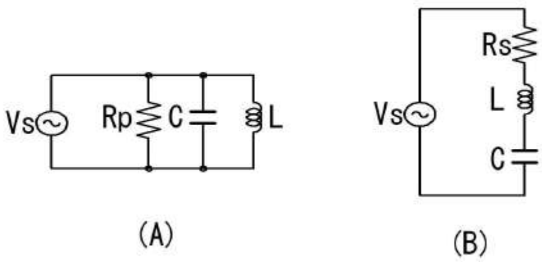

Figure 4.14: LC resonant circuit

Admittance Y_P of the parallel resonant circuit is

$$Y_P = R_P + j(\omega C - \frac{1}{\omega L})$$

Impedance Z_S of the series resonant circuit is,

$$Z_S = R_S + j(\omega L - \frac{1}{\omega C})$$

At the resonant frequency f_0, the imaginary part becomes zero and in both cases,

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

This is quite natural because there is only one resonant circuit.

Losses mean inductor DC resistance and dielectric loss of capacitor, and when these are expressed by resistance R, the Q of resonant circuit is given as follows.

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Considering the cases to supply/extract energy to/from resonant circuit, there are four topologies as shown in Fig 4.15.

The (A) shows a case supplying energy in parallel, (B) shows in series. Similarly, (C), (D) shows cases that the load is connected by parallel and series respectively.

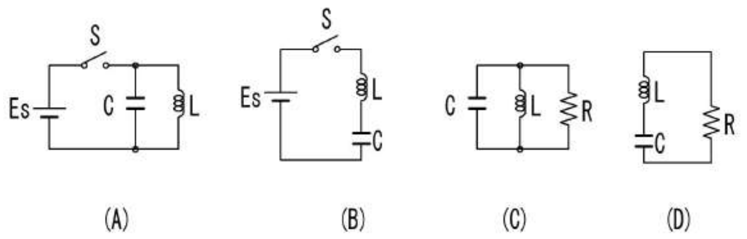

Figure 4.15: Relation of LC resonant circuit and external power supply/load

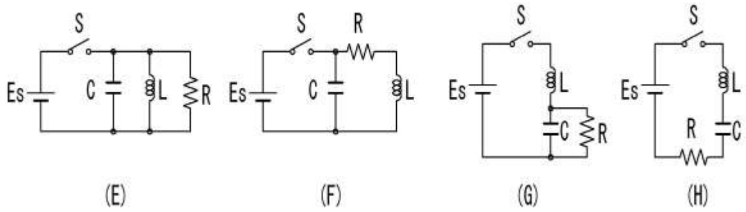

Figure 4.16: Drive of Resonant circuit with R

Supplying energy and connecting load, the topology will be shown in Fig 4.17. In (G), R may be connected in parallel with L resulting the same effect.
Parallel and series resonance makes sense only when discussed in the above context.

4.5.2 Driving the LC resonant circuit

The actual resonant circuit cannot oscillate continuously without external energy supply. Fig 4.17 shows a case that supplies energy to parallel resonant circuit by switching the voltage source by the resonant frequency.

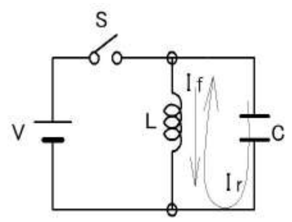

Figure 4.17: Driving the parallel resonant circuit

Fig 4.18 shows the wave form of the circuit. Switch is turned ON at t_0, turned OFF at t_1, and assuming the period $t_0 - t_p$, then the voltage of the capacitor is charged to voltage V at t_0[7]. The charging current of the inductor starts at t_0, and increases linearly till t_1. When the switch is turned OFF at t_1, the energy stored in the capacitor supplies current to inductor till t_2, then the voltage of the capacitor becomes zero and inductor start suppling energy to capacitor.

[7] Since assuming a voltage source, internal resistance is zero, and can charge up any capacitor instantaneously.

Fig 4.18 shows the very start of the resonant circuit behavior, and in this case, the capacitor is excessively charged between t_0 and t_1. Hence at time t_p, the capacitor voltage exceeds slightly over V and the current is already flowing to I_f direction.

When the resonance becomes stable, capacitor voltage becomes V, zero point of inductor current becomes the next power supply point t_p and the spike current to the capacitor will no longer exists. And the current supply to the inductance starts by zero.

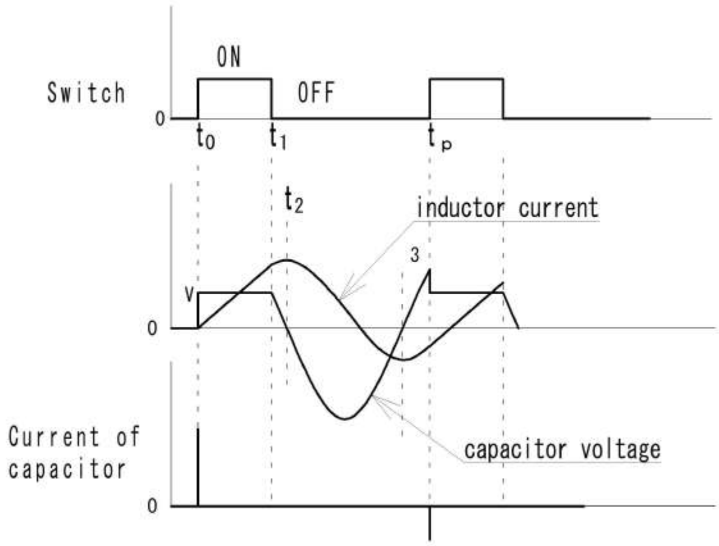

Figure 4.18: Waveform of LC parallel resonant circuit

One of the difficult point to understand the operation of the resonant circuit is that the voltage waveform is completely different from current waveform.

Although as shown in Fig 4.18, voltage across the capacitor (this is identical to the voltage waveform of parallel resonant circuit) will not be a sinusoid, but the inductance current becomes sinusoid.

Generally, passive devices (resistor, capacitor and inductor) are called linear devices, but the linearity does not mean that the waveforms of voltage and current is similar [8].

Therefore it is not surprising that the voltage and current waveforms are not similar, but extracting output to outside, sinusoid must be chosen. The example in this section provides a coil that couples with a coil (inductor) in resonant circuit and extract the energy from this coil. The coupling must be a loose coupling (see Sec 4.5.10).

Even in transient only, it will not be advisable to drive parallel resonant circuit by voltage source because of the instantaneous big peak current. On the other hand, if we consider current drive, the charge of the capacitor gradually increases, but the the coil is supplied by instantaneous big current. These scheme violates the prohibited operation stated in Sec 4.3, and on the whole, parallel resonant circuit faces difficulty in principle when supplying energy.

[8] The meaning of "linear", see Sec 8.2

4.5.3 Zero cross switching

A big problem in DC circuits is the switching OFF of the flowing current. Switching time by semiconductor is finite and the voltage across the semiconductor switch changes while the current is flowing, the multiplication in this period is converted to heat. The heat is the cause of the loss and bigger the power, higher the switching frequency the problem becomes more serious.

Improvement of switching characteristics of the semiconductors is one of the solutions, but the improvement of switching characteristics induces the usage at higher frequency, this cannot provide fundamental solution.

For the fundamental solution for the semiconductor power switching, either voltage or current or both should be zero at the time of switching.

In this respect, there is a technique that utilizes the resonance of inductor and capacitor. Interesting feature of resonant circuit is that even the energy applied from outside are pulses, it generates sinusoid[9]. Suppose pulses are applied to the resonant circuit as shown in Fig 4.19. By the application of pulses, the oscillation starts and after some time, stable oscillation occurs.

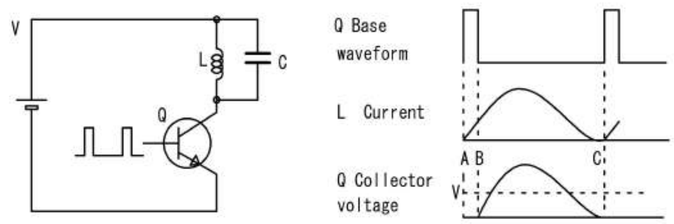

Figure 4.19: Steady state operation of parallel LC resonant circuit

From A to B, the transistor turns ON, but at A, collector current is zero. At B, current in L turns it's direction from Q to C. At this instant, collector voltage increases from zero to V, but the current is switched from L to C and no collector current flows. (Current increases linearly during AB, and then changes to sinusoidal increase, but after B, it may be said that the capacitor forcibly sinks the current. In other word, the turned OFF transistor is just an impedance, but the capacitor looks like a negative impedance.)

Eventually, switching occurs when the current is zero and the loss of the transistor does not exists in principle.

4.5.4 Driving of series LC resonant circuit

When driving a series resonant circuit by a voltage source, connect S1 so that it is serially connected to the resonant circuit and connect S2 to provide closed path when S1 is turned OFF as shown in Fig 4.20.

For driving the series resonant circuit , S1 and S2 are turned on/off alternately to always

[9]There is a limit of the duration in a period which is called conduction angle.

keep closed path but in practice, this is not easy. In case of parallel resonant circuit, there is a possibility that pulsive peak current can be supplied, but for the series resonant circuit, closed loop might be opened.

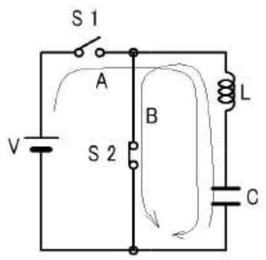

Figure 4.20: Driving a series LC resonant circuit

But in case of the ideal condition that both S1 and S2 switches without delay or gap, then no instantaneous energy supply to either inductance or capacitance will occur. This is not only applied to the voltage source, but to the current source as well.

4.5.5 Analysis of resonant converter

Resonant converters are generally divided into two types, one produces sinusoid and utilizes magnitude vs. frequency characteristics of the resonant point for regulation. The other one utilizes resonance for the soft switching of semiconductor. Here we discuss the former type.

The biggest difference between resonant converter (regulator) from resonant circuit is that the former feedbacks the output voltage and regulate the output voltage.

The resonance is also used for the zero cross switching, it is not possible to control the duty ratio with a constant frequency like PWM.

The voltage of the resonant circuit decreases at the both side of resonant point. If the Q is very high, the resonant point looks like a δ function and it will be very difficult to use the slopes on both side, but in case of power application, resistance (load) is connected in parallel with the resonant circuit which damps the resonance.

Therefore, either low or high frequency side may be used to regulate the output voltage. Sensing the output voltage and modify the driving frequency of the resonant circuit will realize a regulator.

Fig 4.21 shows a basic circuit of current resonant type converter. The configuration of this circuit is identical with Fig 4.20, except the power output circuit is equipped.

Q1 and Q2 are the main switching devices and generally, the former is called "high side", the latter is called "low side" switch. The high side switch supplies power (current A) to a series resonant circuit formed by inductor Lr [10] and capacitor Cr.

The low side switch closes the resonant path of Lr and Cr, and keeps the resonance going (current B). That is, Q1 and Q2 operates complimentary and the operating frequency is modified according to the sensed voltage at the output. FB shows a feed back circuit which

[10] A gap is provided for T1, and intentionally causes leakage inductance.

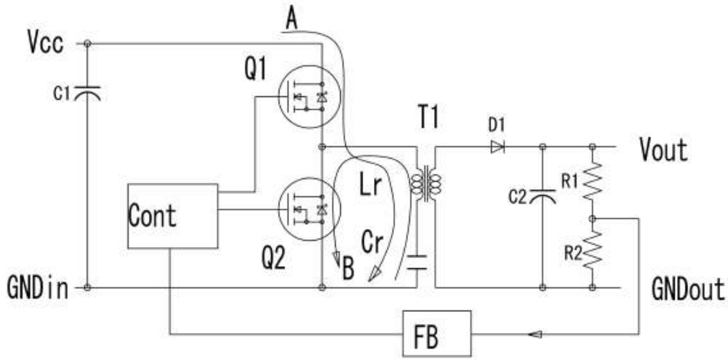

Figure 4.21: Resonant converter

often uses optical coupler to insulate primary and secondary side. Controller generates the gate drive signals for Q1, Q2 and the frequency is controlled by the feedback signal.

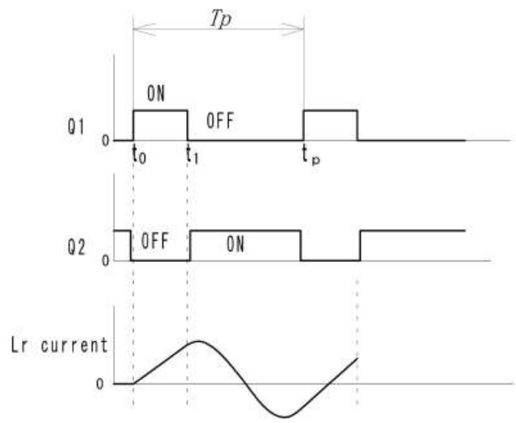

Figure 4.22: Gate drive waveform

It is obvious by the principle, that the region of operation must be in the single side of the resonant point. In practical circuit, the region is set to the higher frequency side to the resonant point which will be described below.

As shown in Fig 4.22, Q1 operates in switching mode and it stores energy when turned ON and the other period, Q2 is turned ON to make the resonant circuit. Because of this operation, the maximum ON time for Q1 must be smaller than 1/4 of one period. This ON time approaches to this value when the output voltage increases. If the lower frequency side is selected for operating region, the increase of output power shifts the operating point to higher frequency side. Then T_p become short, whereas ON period of Q1 ($t_0 - t_1$) gets longer reducing the margin.

Summing up the features of resonant converters, many problems are resolved simultaneously with very clever ideas.

(1) Switching the resonant circuit by (near) resonant frequency, high frequency sinusoid is generated, using soft switching. This is the solution for high frequency generation with minimal loss.

(2) Utilize the magnitude characteristics of resonant circuit for voltage regulation.
(3) Voltage conversion is carried out by a transformer, but provide a gap intentionally for leakage inductance, the loose coupling of primary and secondary windings, and use primary winding as the inductor for resonance.

Since, high frequency sinusoid is used, transformer can be made small in size and EMI is expected to be small. The demerit is the smaller control range for input and output voltage range and this is the penalty to pay for using the resonance.

4.5.6 Partial resonant converter

Resonant converters resolve many problems simultaneously, but there are schemes to apply a part of the resonance. One of the biggest problems is the switching loss of the main switch, and if there is an idea to solve this problem alone, it still would offer big advantage. And it is natural to apply the character of resonance to the main switches of the converters.

Fig 4.23 shows an example that is applied to an up converter. Main part of the up converter comprises inductance L, main switch Tr1, diode D and capacitor C. The idea in this example is try to turn Tr1 ON by zero cross switching. For this purpose, provide Tr2 that covers ON timing of Tr1 and resonant circuit by Cr and Lr (leakage inductance of T) so that the half period of the resonant frequency becomes equal to ON time. When Tr2 turns ON, the current Ir that flows through the resonant circuit increases and decreases as shown in the figure.

At the peak of Ir, VD1 of Tr1 becomes zero and turn Tr1 at this point. Then no power loss is expected by turning Tr1 ON. Of course, we want to do the same at the timing at Tr1 OFF, but since Tr1 is PWM controlled and it would be difficult to know the OFF timing. Secondary voltage of T caused by the resonance current by Cr and Lr is converted to DC and utilized as a part of the load power. This also works as a reset operation for primary side.

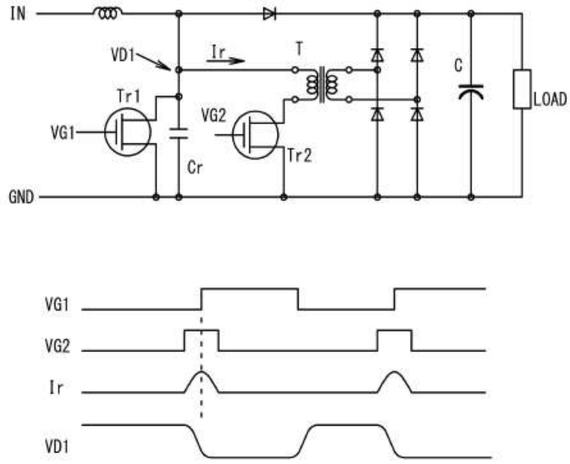

Figure 4.23: Partial resonant up converter

4.5.7 Partial resonant flyback converter

Fig 4.24 shows the most basic partial resonant converter, and by removing Cr yields a simple flyback converter. The idea of this scheme is to utilize the timing when the current D1 is decreased and turned OFF. At this timing, resonance occurs by the inductance Lr of the primary winding of the transformer and Cr. When the drain voltage Q gets smaller by this resonance, turn the Q ON. Then the loss at ON time is reduced and increases efficiency.

When the load gets smaller, the timing that the Q and D1 turns OFF simultaneously occurs, but the resonance caused by Lr and stray capacitance is not used.

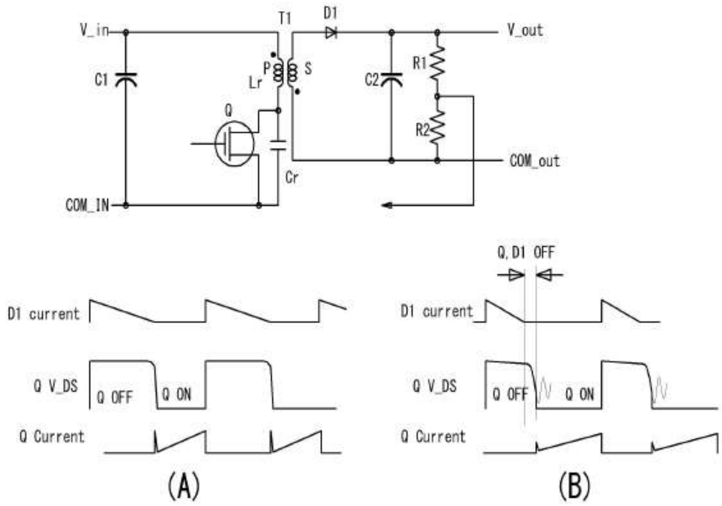

Figure 4.24: Partial resonant flyback converter

4.5.8 Active clamp forward converter

Inherent big problems caused by the energy stored in leakage inductance in simple forward converters are all resolved by this ingenious configuration. Here are the problems resolved simultaneously.

(1) Suppress surge voltage to approx. twice of input DC voltage.
(2) Low voltage rating transistor can be used.
(3) Reuse of energy stored in leakage inductance and efficiency is improved.
(4) Main transistor (and additional transistor as well) are soft switched. Efficiency is improved.
(5) L (leakage inductance) component of the transformer uses first and third quadrant of hysteresis curve, and this works as the reset of the transformer.

Fig 4.25 shows the principle circuit of the active clamp forward converter. The differences from forward converter are addition of Q2, C1 and C2 for the reuse of surge energy caused by L. In Fig4.25, the inductive component of T1 is specified by L. In the following discussion, we care only this component L. Fig 4.26 roughly shows how switches Q1, Q2 and capacitors C1, C2 operate.

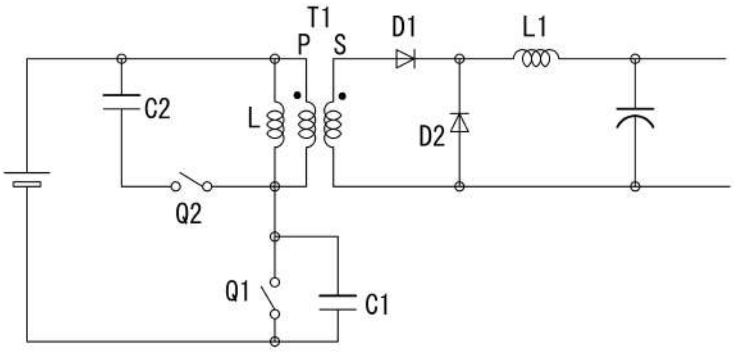

Figure 4.25: Active clamp forward converter

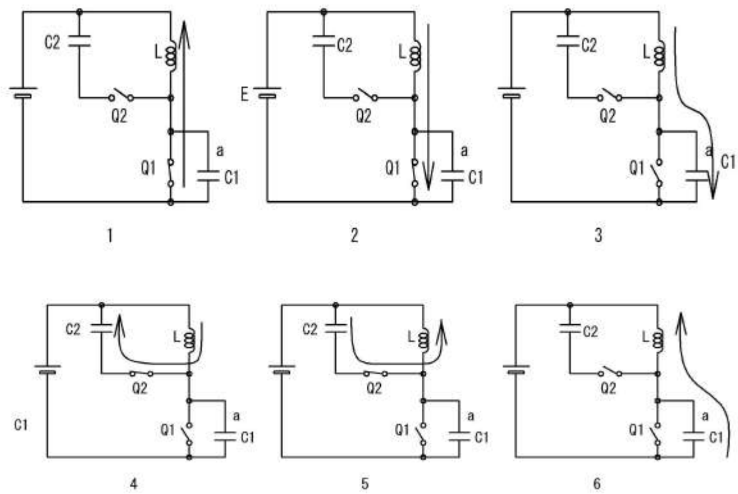

Figure 4.26: Operation of active clamp forward converter

In periods 1 and 2, main transistor Q1 turns ON and supplying current to secondary side and simultaneously stores energy in L as current. In 1, the direction of current in L looks like the inverse of the supply from power source E, but in this period L is depriving the secondary output current and the overall current of the primary winding of the T1 is not inversed. That is if we observe L only, the direction looks as shown. Also, periods 1 and 2 is the timing that supplies energy to the resonant circuit by L, C1 and C2, and can be discarded when we focus the resonant operation.

Then, the resonant operation moves on $3 \to 4 \to 5 \to 6 \to 3...$ in Fig 4.26. This means that the current switching is happening between two pairs of resonant circuit (L is the common device).

Therefore, there is a timing in each cycle that the voltage over Q2, Q1 becomes zero at which time the soft switching is performed.

Regenerated energy is transfered by the resonance of L, C1 and L, C2. The energy source of this operation was originally the wasted energy, and now it may be not be quite enough. So, sometimes, to increase this energy, provide gaps to the transformer.

Because the operation is very clever and sophisticated, the adjustment of components

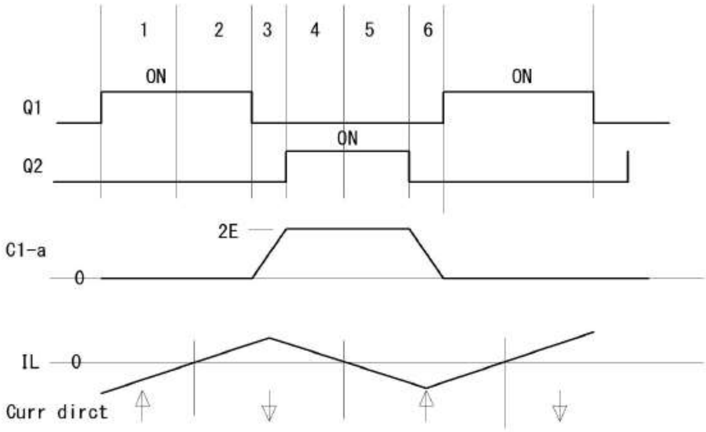

Figure 4.27: Wave form of active clamp forward converter

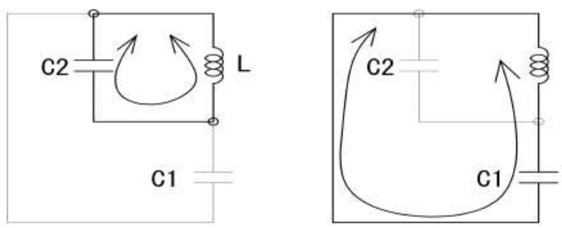

Figure 4.28: 2 pair resonant circuit

and timings tend to get difficult.

The original reason of the trouble is caused by the unidirectional switching of the transformer, maybe it's better try bidirectional drive of the transformer.

4.5.9 Classic resonant circuit power application

Driving the power resonant circuit has long history before utilized to the switching regulators.

In the final driving circuit for the antenna in wireless application as shown in Fig 4.29, the grid of the vacuum tube is driven by a carrier signal by switching mode (class C operation) .

The LC resonant circuit (tank circuit) is connected to the plate of the vacuum tube and the energy is extracted from the coil which is loosely coupled to the tank circuit. The primary and secondary windings are coupled by air (no iron core) to cause loose coupling.

High frequency sinusoid flows through the tank circuit, and the antenna feeder is impedance matched to the secondary winding. The antenna feeder cable is connected to the antenna, by matching the impedance, and looking to the secondary winding from tank circuit, it looks the parallel circuit of inductance and resistance. The vacuum tube supplies power to this low Q resonant circuit. In this case, the vacuum tube operates in switching mode and loss is minimized [11]. The energy loss of inductance is zero and all output power is applied to equivalent resistance [12] resulting that the all energy is applied to the antenna. And this resistance is the space itself and no explicit heat is produced.

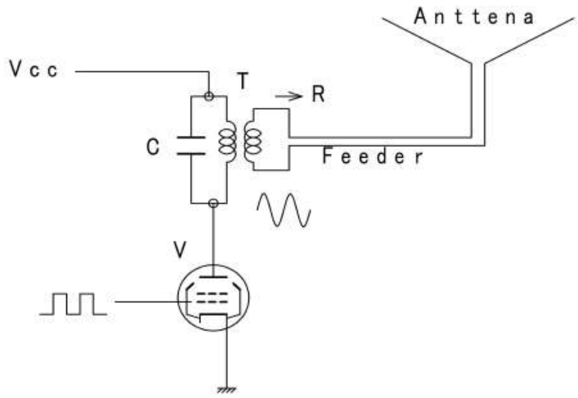

Figure 4.29: Final stage of wireless transmitter

4.5.10 Transformer, reactor, loose coupled transformer

Symbol of the transformer used in resonant converter is identical with that of AC commercial frequency transformer, but both the structure and principle differ.

The AC transformer for commercial frequency does not store energy as is discussed in Sec 4.1. The energy in primary side is transferred to secondary side instantaneously and the transformer looks like an resistance looked from primary side. The transformers used for forward converters share the same characteristics.

On the other hand, the coil used in flyback converters [13] stores and empties the energy as discussed in Sec 4.2.1. Similarly, transformers used in on/off converters, the primary and secondary side alternately stores and empties energy. Therefore, looked from primary side, it works as an inductor (and resistance in parallel) rather than a transformer (or a resistance).

The reactors and transformers designed for energy storage devices, the amount of energy is important and provide gap in the core. By the gap, inductance is reduced, but the current increases. The idea is that the energy is better stored by current than inductance.

That is, even if the symbol is identical with a transformer, it must be understood as a reactor. It must be distinguished if it has the energy storage function or not.

To understand the transformer for the resonant converters, it may be helpful to think about a device in between - partially energy storage transformer.

Let us call this device as a loose coupled transformer to clarify the difference from AC

[11] However, in case of vacuum tubes, the ON voltage of V_{pk} is not so small and still lossy.
[12] In reality, there is reactive component, but here assume this resistance as real load.
[13] Power inductor, reactor

commercial frequency transformers. Loose coupled transformers have gaps in the core [14], and even when the rated load is connected to the secondary side, it is designed to have inductance looked from primary side. That is, the energy from primary side is stored in this inductance (this energy is not transferred to the load but returns to the resonant capacitor) as well as supplied to secondary side via transformer component.

The inductance is not coupled to the secondary side (this is the reason why it still looks as an inductance) and considered as a leakage inductance. In AC commercial frequency transformers, the smaller leakage inductance, the better, but for loose coupled transformer, this term is exploited.

From other aspects, capacitive and inductive components are necessary to form a resonant circuit. If close coupled transformer is used, the virtual primary inductance becomes just a resistance when rated load is connected to the secondary side and will not form a resonant circuit. Therefore, keep inductive component by making a loose coupled transformer, and form a resonant circuit with a capacitance as well as transfer energy to secondary side.

Designing the transformer for resonant converters, the loose coupled transformer is explicitly specified (which was inexplicit in tank circuit). The loose coupled transformer design requires specifications that is different from both AC commercial frequency transformers and reactors.

Ideal resonant converters supply energy to primary side as consumed by the secondary side, high efficiency is expected. Also, the system is designed so that the current in the resonant circuit becomes sinusoid [15].

[14] In early resonant converters, gapless transformer was used with explicit series inductance.

[15] In general practical circuits, both parallel resonance and series resonance circuit is driven by voltage.

Chap5 Transformer design

5.1 Abstract

The rough process of transformer design is stated in Sec 4.1. The process is a routine work for the transformer manufacturers where the formulas and tables are used. Practically, there is no need to think about the underlying physics. On the other hand, in the textbooks of electromagnetic theory, the physics is stated but how it is applied to real design and manufacturing is not explained (this is also out of the scope).

Worse still, textbooks on electric devices/machines deals with this problem from theoretical analysis and synthesis is generally weak. In a nutshell, seamless understanding of the transformer design starting by the Maxwell's equation to the real calculation of number of windings etc. has been almost hopeless.

Transformer is one of the key devices for the DC/DC converter application, and it will be helpful to understand the idea of transformer design in general.

In this chapter, we discuss the design of AC commercial frequency transformers.

5.2 Analysis of electromagnetic field

5.2.1 Maxwell's equation

First of all, historical problem in expressing the Maxwell's equation is pointed out here. In the following expressions, $\boldsymbol{B}$ is magnetic flux density. But there is a custom to call this term just a magnetic field [1], whereas $\boldsymbol{E}$ is an intrinsic electric field. For the application in engineering, magnetic field and magnetic flux density must be clearly divided to prevent errors. And $\boldsymbol{B}$ should be called as magnetic flux density, but by doing this, the explanation of Maxwell's equation sounds very much unnatural.

In order to cope with tis situation (a sort of compromise), $\boldsymbol{B}$ shall be stated magnetic flux density only wehn necessary. By the way, $\boldsymbol{J}$ is current density.

There is a school to express Maxwell's equation by electric field $\boldsymbol{E}$, electric flux density $\boldsymbol{D}$, magnetic field $\boldsymbol{H}$, and magnetic flux density $\boldsymbol{B}$, but this makes the fundamental fact of the Maxwell's equation blurred - the three dimensional space vector differential of electric and magnetic field.

The Maxwell's equation is expressed by a pair of differential equations[2] of the electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{B}$.

[1] for instance, Feinman's Lectures on Physics.

[2] One is for the electric field and the other for the magnetic field. And one 3 dimensional vector differential equation yields vector part and scaler part. Hence, it looks that Maxwell's equation is made up by four formulas.

The basic equations of electromagnetic theory is expressed by the Maxwell's equation, and it is written by using three dimensional vectors; electric field $\boldsymbol{E}$ and magnetic filed $\boldsymbol{B}$,

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{B} = \epsilon_0 \mu_0 \frac{\partial \boldsymbol{E}}{\partial t} + \mu_0 \boldsymbol{J}$$

ϵ_0, μ_0 are permittivity and permeability in vacuum space respectively.

$$\epsilon_0 = 8.854 \times 10^{-12}$$

$$[\frac{C^2}{N \cdot m^2} = s^4 \cdot A^2 \cdot kg^{-1} \cdot m^{-3}]$$

$$\mu_0 = 4\pi \times 10^{-7}$$

$$[N/A^2 = kg \cdot m \cdot s^{-2} \cdot A^{-2}]$$

and

$$\frac{1}{c^2} = \epsilon_0 \cdot \mu_0$$

5.2.2 Maxwell's equation in real world

Maxwell's equation shows the relationship between space differential of electric field, magnetic field ($\nabla\cdot$,$\nabla\times$) and time differential ($\partial \boldsymbol{E}/\partial t$, $\partial \boldsymbol{B}/\partial t$) and constant current $\mu_0 \boldsymbol{J}$. This is the most general expression defining the pattern of time varying distribution of $\boldsymbol{E}$ and $\boldsymbol{B}$ in all possible space - not only vacuum space, but within some materials like soil, wood, human body etc..

And when we think about the application for the electric engineering, we have to specify the space for which Maxwell's equation is to be applied. For the electric engineering, this space or field of application is, roughly speaking, within conductive materials and insulators. The former is roughly equal to wires, the latter the air.

Then Maxwell's equation is only applied inside of the wire, inside of the air and boundaries between wire and air. Application in the air is mostly identical to that of vacuum space and we discard here.

Application to the in between field of wire and air is found in antenna theory. This is the most straight forward field of Maxwell's equation, but we will not go any further.

The last field of application [3] is within the wire, but slightly minding the interaction of the surrounding air. And this is the field we are going to analyze further.

First, within conductors, there is no electric field and we discard the term $\partial \boldsymbol{E}/\partial t$ at lease inside the wire.

However, $\partial \boldsymbol{E}/\partial t$ may affect metals that form open circuit like capacitors. But this type of capacitors should have space between both electrodes (like air variable condensers

[3]There are another field. For instance, within human body which is neither completely conductive nor an insulator.

which has only small capacitance) and this is not very common. And also, the air variable capacitors are not designed to collect electric field and maybe shielded under some strong electric field (this field is generally noise).

The capacitor with high value (this is generally what engineers want) necessarily becomes small in relative sense and the external electric field will affect less.

Summing up, we ca discard the term $\partial \boldsymbol{E}/\partial t$ in electric engineering.
Now we think about the interaction of magnetic field and wound coils. The interaction was found out by Farady and we know this is the basics of the electric magnet and related technologies. Hence $\partial \boldsymbol{B}/\partial t$ is necessary, particularly in conjunction with inductors.

The term $\mu_0 \boldsymbol{J}$ is most likely to be found inside conductive materials like wire, and it should be difficult to analyze in open space[4].

Also, there seems to be little devices that utilizes isolated charge[5]. This renders us to eliminate $\frac{\rho}{\epsilon_0}$.

5.2.3 Maxwell's equation in electric engineering

Under the conditions stated so far, the Maxwell's equation is written[6] by removing $\partial \boldsymbol{E}/\partial t$ and ρ/ϵ_0 yielding,

$$\nabla \cdot \boldsymbol{E} = 0$$
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$
$$\nabla \cdot \boldsymbol{B} = 0$$
$$\nabla \times \boldsymbol{B} = \boldsymbol{J}$$

Here we assume only dynamic magnetic field and mass of current exists (when the current is flowing, they are dynamic electrons, but become mass as an average).

We start with this assumption and analyze the magnetic field produced by constant current through solenoid.
Then replacing the constant current by time varying current as,

$$\boldsymbol{J} = \boldsymbol{J}(t)$$

and , in particular, the sinusoidal current will be considered. This eventually explains the AC electric magnets and transformers.

5.2.4 Magnetic field by constant current

When current J is flowing through the wire as shown in Fig 5.1, coaxial magnet field B is produced. Since the current is flowing, there is the power source to which the wire is

[4]But not rare. Think about lightning.
[5]Maybe an electret condenser microphone is an example.
[6]Sounds like to simplify the complete Maxwell's equation by our convenience, but the theory that ignored the displacement current is the so called AC electric theory.

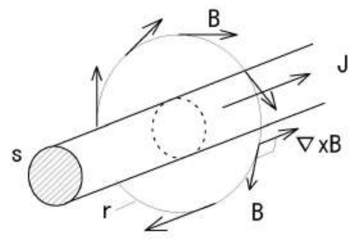

Figure 5.1: Magnetic field by constant current

connected forming a closed circuit. By electromagnetic theory, $\nabla \cdot (\nabla \times \boldsymbol{B}) \equiv 0$ always holds. The relation between current and magnetic field

$$\nabla \times \boldsymbol{B} = \boldsymbol{J}$$

becomes

$$\nabla \cdot (\nabla \times \boldsymbol{B}) = \nabla \cdot \boldsymbol{J} = 0$$

and the current does not diverge (as the magnetic field makes a closed loop) but flows a closed path.

For the quantitative relation between current and magnetic field,

$$\oint_r \boldsymbol{B} \cdot d\boldsymbol{s} = \mu_0 \int \boldsymbol{J} \cdot \boldsymbol{n} dS$$

holds. (Ampere's law)

The above equation states that the line integral of the magnetic field vector $\boldsymbol{B}$ along the coaxial path surrounding the wire (which is a scaler like integral of tangential unit vector $d\boldsymbol{s}$ and is identical with circumference integral of $\boldsymbol{B}$) becomes the total current of the wire (current density $\boldsymbol{J}$, over area S).

The magnetic flux at the distance r (radius) from the center of wire, with current I, becomes,

$$\oint_r \boldsymbol{B} \cdot d\boldsymbol{s} = B \cdot 2\pi r$$
$$= \mu_0 I$$

Therefore, the relation between magnetic flux density and current is,

$$B = \frac{\mu_0}{4\pi} \frac{2I}{r}$$

By MKS unit,

$$\frac{\mu_0}{4\pi} = 10^{-7}$$

By Fig 5.1, the magnetic field $\boldsymbol{B}$ can be generalized to arbitrary 3 dimensional vector field, and the circumference to arbitrarily closed curved surface (not necessarily be a plane) [7] and when integrated along this closed curved surface, it gives Stokes' theorem.

[7]General treatment is the inverse of here. The Stokes' theorem is applied and formularize the current of wire and magnetic field around the wire. But this is unnecessarily difficult to understand by engineers sense. We give an explanation that is self evident in engineering but special case in physics.

$$\oint_r \boldsymbol{B} \cdot d\boldsymbol{s} = \int_S (\nabla \times \boldsymbol{B}) \cdot \boldsymbol{n} dS$$

Where $\boldsymbol{n}$ is the unit normal vector. $\nabla \times \boldsymbol{B}$ and $\boldsymbol{n}$ are both 3 dimensional vectors, but the integration is carried out after taking the scaler product and the result is a scaler.

5.2.5 Solenoid

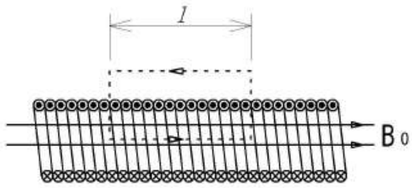

Figure 5.2: Solenoid

Suppose a coil wound by N turns, occupying length l and current I is flowing, the magnetic flux with the density B_0 is uniformly produced inside the coil.

$$B_0 L = \mu_0 N I$$

Substituting B_0 by magnetic field,

$$H = \frac{NI}{l}$$

The magnetic field at the both end of coil will make a closed loop connected by the outside of it as shown in Fig 5.3. And this means,

$$div\boldsymbol{B} = 0$$

$$(\nabla \cdot \boldsymbol{B} = 0)$$

The loop needs to be only closed and the shape does not matter.

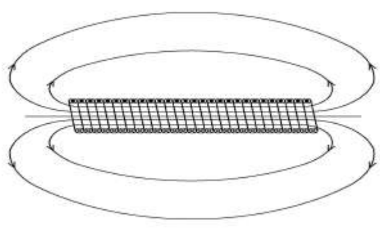

Figure 5.3: At the end of solenoid

The "long enough solenoid" in physics can be realized in engineering by a doughnut solenoid (toroid) minding the application for transformer. In this case all the magnetic field $\boldsymbol{B}$ is constrained inside the solenoid with no leakage to outside. Therefore, if the current changes as time, the magnetic field will not leak to outside as $\partial \boldsymbol{B}/\partial t$.

The constant current produces static magnetic field in space, inside the solenoid inclusive, as below.

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$$

Now we make the current time varying, by partially differentiating $\boldsymbol{J}$, (see Sec 5.2.6). Then

$$\nabla \times \frac{\partial \boldsymbol{B}}{\partial t} = \mu_0 \frac{\partial \boldsymbol{J}}{\partial t}$$

And the varying magnetic field produces voltage $\nabla \times \boldsymbol{E}$ by secondary winding of the transformer as shown below.

$$-\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \boldsymbol{E}$$

It will be clearly understood that providing the secondary winding to the toroidal solenoid forms a transformer. And time varying flux is used by secondary side and converted to current (voltage). As a toroidal transformer is expensive and many other shapes like EI cores can be used, at the cost of some leakage of magnetic field, but the effect is identical.

5.2.6 $\partial \boldsymbol{J}/\partial t$ and $\boldsymbol{J}(t)$

It may not be amiss to discuss the philosophy of $\partial \boldsymbol{J}/\partial t$ and $\boldsymbol{J}(t)$. Assuming the current in wire, the direction of current is constrained and the vector $\boldsymbol{J}$ will no longer be a vector in free space. On the other hand, the original notation $\boldsymbol{J}$ in Maxwell's equation does not restrict the current path. This may vary as time goes by as well as the strength of the current.

Therefore, if we think about the time variation of the current in space, we have to focus on the time variant aspect of $\boldsymbol{J}$ which is expressed by $\partial \boldsymbol{J}/\partial t$.
This is the reason why the following expression is derived.

$$\nabla \times \frac{\partial \boldsymbol{B}}{\partial t} = \mu_0 \frac{\partial \boldsymbol{J}}{\partial t}$$

Then if we think about the inside of wire, $\boldsymbol{J}$ is replaced by J (no longer a vector), and spacial variation of the path is neglected, yielding J(t) which becomes equal to $\partial \boldsymbol{J}/\partial t$ (interpreted as scaler).

And J(t) may well change as sinusoid, resulting $\sin(\omega t)$.

5.2.7 Magnetic field and magnetic flux density

The relationship of magnetic field and magnetic flux density in vacuum or air is,

$$\boldsymbol{B} = \mu_0 \boldsymbol{H}$$

and simply proportional. But for the vacuum/air space, μ_0 becomes a very small value and the resultant magnetic flux density becomes very small. Transformer involves the conversion of current - magnetic flux - current, reduction of the magnetic resistance of the magnetic flux path is necessary.

Fortunately, there are materials that have much lower magnetic resistance than vacuum or air. These include metals like iron, nickel and ceramics like ferrite, and called magnetic substance. The usage of these materials as a core , the transformer becomes much more efficient.

However, in these magnetic substances, magnetic field and magnetic flux density is no longer proportional, and has hysteresis characteristic as shown in Fig 4.7 and expressed by,

$$\boldsymbol{B} = \mu \boldsymbol{H}$$

Here, the coefficient μ is non linear.

$\boldsymbol{B}$ is flux density and the unit is Tesla $[Wb \cdot m^{-2}]$ having dimension in SI derived unit,

$$[kg \cdot s^{-2} \cdot A^{-1}]$$

The $\boldsymbol{H}$ expresses magnetic field and has a dimension $[A \cdot m^{-2}]$.

In case of transformer applications, smaller the area covered by the hysteresis curve, the better. Also, to get large flux density with small magnetic field, steeper the inclination, the better. And a material that has big maximum magnetic flux density B_s is desirable. Easiness of magnetization of the magnetic substance is called relative permeability μ_s [8]and is,

$$\mu_s = \frac{\mu}{\mu_0}$$

Relative permeability μ_s is not a constant value because of hysteresis characteristic and greatly depends on the materials, but roughly 7000 by silicon steel plate and 10,000 by permalloy.

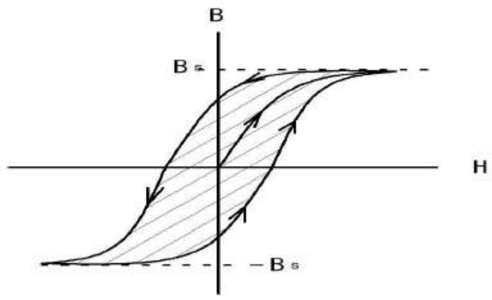

Figure 5.4: Hysteresis characteristic

5.2.8 Magnetic flux to voltage

Once the current produces magnetic field and the relation to magnetic flux density is made clear, the final part is to produce voltage from magnetic flux.

Concerned Maxwell's equation is,

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

Using Stokes' theorem

$$\oint_r \boldsymbol{E} \cdot d\boldsymbol{s} = \int_s (\nabla \times \boldsymbol{E}) \cdot \boldsymbol{n} da$$

[8]note, it has no dimension

and we will get,

$$\oint_r \boldsymbol{E} \cdot d\boldsymbol{s} = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} \cdot \boldsymbol{n} da$$

Considering that the r is a constant closed area S, the time partial differential is shifted to the outside of the integral, yielding

$$= -\frac{\partial}{\partial t} \int_s \boldsymbol{B} \cdot \boldsymbol{n} da$$

and $\int_s \boldsymbol{B} \cdot \boldsymbol{n} da$ is an integral of magnetic flux density $\boldsymbol{B}$ over area S. This gives the overall flux as follows.

$$\oint_r \boldsymbol{E} \cdot d\boldsymbol{s} = -\frac{\partial}{\partial t}(all\ magnetic\ flux\ over\ area\ S)$$

So far we have shown the relationship between magnetic flux and electric field derived from Maxwell's equation. Michael Faraday carried out experiments on the induced voltage to a coil by the magnetic flux change, and defined the voltage per turn caused by the coil as

$$V_{emf} = -\frac{\partial}{\partial t}(all\ magnetic\ flux\ of\ the\ coil)$$

Expressing the all magnetic flux by ϕ, and suppose an N turn coil, we get

$$V_{emf} = -N\frac{d\phi}{dt}$$

Unit for the magnetic flux density is Tesla T, and the dimension is $[kgs^{-2}A^{-1}]$, whereas the unit of magnetic flux is Weber W_b, and dimension is $[kgm^2s^{-2}A^{-1}]$. Number of turns N has no dimension, but there is the differential of magnetic flux, the unit of induced voltage is $[kgm^2s^{-3}A^{-1}]$.

5.3 Inductance

A toroidal core wound by wire makes an ideal reactor. Faraday found out heuristically that the output is,

$$V(t) = -N\frac{d\phi(t)}{dt}$$

Here, ϕ is the total magnetic flux and N the number of windings.

The Ampere's law

$$\oint_r \boldsymbol{B} \cdot d\boldsymbol{s} = \mu_0 \int \boldsymbol{J} \cdot \boldsymbol{n} dS$$

says that the total magnetic flux ϕ is proportional to the coil current. Writing the coefficient by L, for the N turn coil, the following equation holds.

$$\phi(t) = LI(t)$$

This is the definition of inductance (unit is H). The output voltage $V(t)$ will be,

$$V(t) = -NL\frac{dI(t)}{dt}$$

When the core is not air (like toroidal core), magnetic flux density is multiplied by μ_s yielding,

$$\mu = \mu_s \cdot \mu_0$$

And the inductance is increased. μ_s is called relative permeability.

5.4 Basic equations for transformer design

We now start discussion of synthesis of the transformer as compared with the analysis in Sec 5.2. It may be easy to understand that the process is the inverse of analysis.

Calculation of number of primary windings is directly derived from Maxwell's equation.

With the equation derived in Sec 5.2.8, V_{emf} is replaced by V and remove the minus sign.

$$V = N\frac{d\phi}{dt}$$

By integration, we get,

$$\phi = \frac{1}{N}\int V dt$$

Assuming sinusoidal wave form, magnetic flux density B, sectional area of core S, then by $\phi = BS$ we get,

$$\begin{aligned} B &= \frac{1}{SN}\int V dt \\ &= \frac{1}{SN}\int E\sin\omega t dt \end{aligned}$$

Maximum value B_{max} of magnetic flux density B is derived by the integration over half period,

$$\begin{aligned} B_{max} &= \frac{E}{SN}\Big[-\cos\omega t\Big]_0^{\pi} \\ &= \frac{E}{\omega SN} \\ &= \frac{E}{2\pi fSN} \end{aligned}$$

E is the peak value, then the root mean square value will be,

$$B_{max} = \frac{E_{rms}}{\sqrt{2}\pi fSN}$$

Unit of B_{max} is Tesla, and SI unit is $[kg \cdot s^{-2} \cdot A^{-1}]$.

Therefore, the winding number N will be

$$N = \frac{E_{rms}}{\sqrt{2}\pi fSB_{max}}$$

Other equation that concerns the transformer design, we have the following. Between input voltage V_i, output voltage V_o and number of primary and secondary windings n_1 and n_2,

$$\frac{V_o}{Vi} = \frac{n_2}{n_1}$$

holds.

5.5 Process of transformer design

5.5.1 Specification

Specification is necessary for transformer design, and they should at least include
(1) Input voltage
(2) Output voltage and current (if multiple outputs, each of them)
(3) Frequency

Other specifications listed below may be necessary.

(4) Output regulation(The voltage at no load and maximum load)
(5) (rough) Size, weight
(6) Style of transformer (core style, case, terminal, mounting)
(7) Destination of the transformer (or equipment) (applicable safety standard)
(8) Magnetic shield
(9) Cost
These specification may not be satisfied[9] at first and designer (user) should consult with the manufacturer in detail.

5.5.2 Selection of core

The selection of core may go back to the magnetic characteristics of the material, but for the commercial frequency applications, the frequency is either 50 or $60Hz$ and sinusoid, choose common silicon steel unless the efficiency is the top priority [10]. Depending on the shape of the core, there can be orient silicon steel (effective to cut cores) or normal silicon steel (EI core and others) , and these are the items that greatly depends on size and cost.

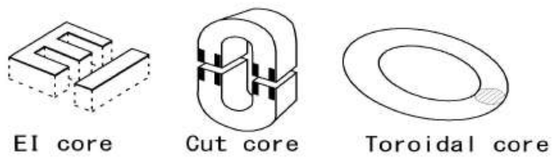

Figure 5.5: Core shape

In practice, core selection is based on the required power capacity of the transformer. The overall power capacity is calculated by adding required output power, resistance loss of the primary and secondary windings (copper loss), and core loss (iron loss). For small transformers (ie., less than 200VA), it will be reasonable to expect 1.2 times more power input than total output. By selection of core, consider the power output, cost, availability, size and manufacturing ease and select from EI core, cut core and toroidal core. For the

[9]Customers generally do not know about the detail and some specification may not be precise, even contradictory.
[10]Power transformer used by AC grid for supplying final households, the increase of efficiency greatly affects the overall power loss, amorphous core is researched. See[?]

EI core, it is possible to make a prototype by hand winding, but for toroidal core, this is impossible.

The selection of core determines the final size and mounting scheme.

5.5.3 Number of windings of primary side and the wire selection

The number of primary winding is calculated by the following formula.

$$N = \frac{E_{rms}}{\sqrt{2}\pi f S B_{max}}$$

Note that the maximum magnetic flux density of the core is used for the calculation. This means that **when the transformer is used under nominal output, the operating point for the core is near to the saturation point.** The reason is the optimization of the size and cost of the transformer and not much margin is counted for.

This may result the burning [11] of transformer when used under over load or used 60Hz transformer by 50Hz[12].

B_{max} is determined by the core material (silicon steel, oriented silicon steel, permalloy and amorphous etc.) and values differ much. In practice, the material of the core should have been already selected when specifying the size or core type, and thus use the value of the selected core. Generally, all the cores are constructed by piling up thin steels to reduce the eddy current and for EI and cut cores, assembled by facing two sides. The assembly inevitably cause some error from calculation.

Since cores are selected, the sectional area for the windings is already known. The area is generally divided in two for primary and secondary windings and calculate the area for the primary windings. Or most likely, the bobbin is also determined at the time of core selection and it may specify the primary and secondary area to assure the insulation. Once the area for primary winding is known, the diameter of the wire (or overall sectional area of windings) is calculated. Of course, use thickest wire. However, full utilization of the winding area depends on the bobbin, winding style (lined up or random) and the inserted insulation paper and so on. That is, there are a lot of know how and for optimal transformer design, consultation will be necessary.

Example shown in Sec 5.6, the sectional area of windings uses the following value as it is.

$$S = \frac{\pi \phi_d^2}{4}$$

This is because the core size and bobbins are designed to satisfy the above formula.

Conductivity of the wire (called magnet wire, made by insulated copper or aluminum) is determined by the wire actually going to use, and the length is calculated by the core (or bobbin).

Specifying the power capacity of the transformer determines the wire size and length. This means that the regulation is almost decided at this time and conversely, the core manufacturers provide standard cores that can satisfy customer's requirements.

[11] Transformers for consumer equipments, the safety regulations in many countries require thermal fuse in the primary winding.

[12] Maximum magnetic flux density B_{max} is inversely proportional to the frequency.

5.5.4 Calculation of the secondary winding

Number of windings for the secondary winding is determined by the ratio of voltage automatically[13]. Then select wire (diameter of the wire) so that the winding area of the core can accommodate the whole windings. The length is calculated by a formula taking account of the bobbin. Here are know hows like primary winding design.

5.5.5 Calculation of efficiency

So far, the length and diameter of the primary and secondary wire is determined, the resistance is now known and nominal current is given by the specification. Then the loss by wire (copper loss) is calculated.
Also, size and weight of the core is already known and the iron loss is now calculated.
This yields overall loss of the transformer and efficiency is calculated (or estimated).
Small transformers up to 200VA or about, the efficiency is reasonable at 80% or more. If the calculated value is about this value, then the designed transformer will be usable.

5.5.6 Production and test

Since all the number of windings for primary and secondary side, size of wire are determined, the real manufacturing shall be carried out. (At this time how the wires are treated for external connection, necessity of varnishing etc., shall be specified.)

Then measure voltage output, at both no load and nominal load, regulation by varying the input voltage and so on. If the design is unsatisfactory, redesigning may necessary.

In general, the first design/manufacturing cannot satisfy the required specifications[14] and requires a long design/manufacturing experience to satisfy the customers.

5.5.7 Inductance of a transformer

For the commercial frequency transformer design, the windings and core are determined by the condition that the nominal load is connected to the secondary side. And when the nominal load is connected, the impedance looking from primary winding become resistive and no inductive components exists. This is the reason why there ins no consideration of inductance in the design process.

But when the load at the secondary side is smaller, or open, inductance components appear looking from primary winding.

The primary inductance is determined by the number of windings and magnetic flux density of the core and can be measured when the secondary is open. In this case, transformer is working as an inductor, and there will be phase difference between primary voltage and current, and the power consumption is caused only by the magnetizing power.

When the secondary load increases, the secondary power consumption is added to the magnetizing power. At the nominal load, this magnetizing power must be much smaller

[13]Taking the voltage drop in account and set slightly higher than calculation. This is also a know how.
[14]It is likely that the user recognizes the defect or new requirement of specification only after first sample.

compared to the total output power.

If the primary winding is not enough, the following equation holds only when the B_{max} increases and compensates.

$$N = \frac{E_{rms}}{\sqrt{2}\pi f S B_{max}}$$

But of course, for the same core, B_{max} is a constant and the saturation occurs. And eventually, transformer will burn. This is the reason that even the ratio of the primary vs secondary is kept constant, the number of primary windings cannot be reduced. For instance, if there is a transformer that converts 100V to 10V, by the primary winding of 1000 turns, it cannot be made by 100 turns for primary and 10 turns for secondary.

Commercial frequency transformers for both 50 and 60Hz, are designed by 50Hz. Because designing the number of turns at 50Hz, the application in 60Hz provide more margin for the B_{max} [15].

5.6 Example of transformer design

Here is an example of small single phase transformer design. This is almost a verbatim explanation of the web page by a real transformer manufacturer Tokyo-seiden company. The example uses core TES1-A series, and the original page is found at,

$http://www.tokyo-seiden.co.jp/gijyutu/report/tr/trans.htm$

5.6.1 Specification

Specification shall be as follows.

Power capacity 20VA
Frequency 50Hz
Primary voltage 100V
secondary voltage 20V
secondary current 1A
Insulation : class A
Maximum operating temperature: 105°C
temperature increase : less than 55°C

5.6.2 Selection of core

Size of the core and thickness is determined by the power capacity. Common silicon steel (not oriented) core is used.
Since capacity is 20VA the appropriate core is found by Fig 5.6 as below.

core EI-60
thickness 25mm
material 50A600A

[15] In case of output transformers for vacuum tube audio amplifiers, to have large power at lower frequency, the turn of windings must be increased, but this increases capacitance between windings and the high frequency response gets worse. Here is a dilemma.

Series TES1-	Cap VA	Type	Thickness mm	Area m2	Weight kg	W mm	D mm	I mm
		-----------Core-----------			------- Bobbin----------			
0.5	0.5	EI-28	11	0.088×10-3	0.042	10.0	13.4	4.2
1	1	EI-35	10	0.096×10-3	0.056	12.3	12.3	6.0
2	2	EI-38	13	0.14×10-3	0.091	13.8	15.4	5.6
5	5	EI-41	13	0.17×10-3	0.10	15.5	15.4	6.4
10	10	EI-48	20	0.32×10-3	0.24	18.9	22.7	6.0
15	15	EI-57	23	0.44×10-3	0.38	21.5	25.7	7.6
20	20	EI-60	25	0.50×10-3	0.46	22.5	26.6	8.4
25	25	EI-60	30	0.60×10-3	0.55	22.5	31.6	8.4
30	30	EI-66	25	0.55×10-3	0.56	24.5	27.2	8.4
35	35	EI-66	30	0.66×10-3	0.67	25.6	32.0	8.4
40	40	EI-66	35	0.77×10-3	0.78	25.6	38.0	8.8
50	50	EI-66	40	0.88×10-3	0.89	24.8	42.8	8.8
60	60	EI-76.2	35	0.89×10-3	1.0	28.6	38.0	10.4
75	75	EI-76.2	40	1.02×10-3	1.2	28.6	43.0	10.4

Figure 5.6: Core list

5.6.3 Turns of primary winding

The number of turns for primary winding is calculated by the following formula.

$$N1 = \frac{E_1}{\sqrt{2}\pi f A_e B_m} \qquad (1)$$

where,

N1 : Turns of primary winding
E1 : Primary voltage(V)
f : Frequency(Hz)
Ae : core section area(m^2)(by Fig 5.6)
Bm : Maximum magnetic flux density(T)

The maximum magnetic flux density is 1.4T[16], and putting this value into formula (1),

$$N1 = \frac{100}{\sqrt{2}\pi \times 50 \times 0.5 \times 10^{-3} \times 1.4} = 643$$

And round N1 to 650.

5.6.4 Turns of secondary winding

Calculate by the following formula.

$$N2 = \frac{E2 + V_e}{E1} \times N1 \qquad turns$$

N2 : secondary winding
E2 : secondary voltage(V)
V_e : internal voltage drop(V)

Secondary voltage is 20V, and primary winding is 650, then by formula (2)

$$N2 = \frac{20 + 2}{100} \times 650 = 143$$

V_e is assumed to 2V expecting 10% drop of the secondary output; 20V.

[16]This is the value of the manufacturer's standard core

5.6.5 Primary and secondary current calculation

Calculate by the following formula.

$$I1 = \frac{P}{E1} \tag{3}$$

where

I1 : primary current(A)

P : power capacity(VA)

E1 : primary voltage(V)

P is 20VA and input voltage is 100v, then by formula (3),

$$I1 = \frac{20}{100} = 0.2 \quad (A)$$

Similarly, the secondary voltage is,

$$I2 = \frac{20}{20} = 1 \qquad (A)$$

5.6.6 Selection of primary wire

The calculation of wire diameter is carried out as below.

$$S = \frac{\pi\phi_d^2}{4} \tag{4}$$

Current density is,

$$\delta = \frac{I}{S} \tag{5}$$

By (4) and (5)

$$\delta = \frac{4I}{\pi\phi_d^2} \tag{6}$$

Therefore

$$\phi_d = 2\sqrt{\frac{I}{\pi\delta}} \tag{7}$$

where

ϕ_d : wire diameter (mm)

S : sectional area of wire (mm^2)

I : current (A)

δ : current density (A/mm^2)

Assuming the current density of the wire $3A/mm^2$, the diameter of the primary windings is calculated by formula (7),

$$\begin{aligned}\phi_{d1} &= 2\sqrt{\frac{0.2}{\pi \times 3}}\\ &= 0.2913\end{aligned}$$

Round the value to 0.29ϕ. Similarly, for the secondary wire, diameter is 0.65ϕ.

5.6.7 Calculation of wire resistance

Wire resistance r is calculated as below.

$$r = \rho \frac{L}{S} \quad (\Omega) \tag{8}$$

$$L = \Big((W + D) \times 2 + T \times 8\Big) \times N \times 10^{-3} \ (m) \tag{9}$$

where

ρ : resistivity of copper $(\Omega \cdot mm^2/m)$ [0.01724 at 20]

L : wire length (m)

W,D,T : bobbin size(mm) see fig 5.7

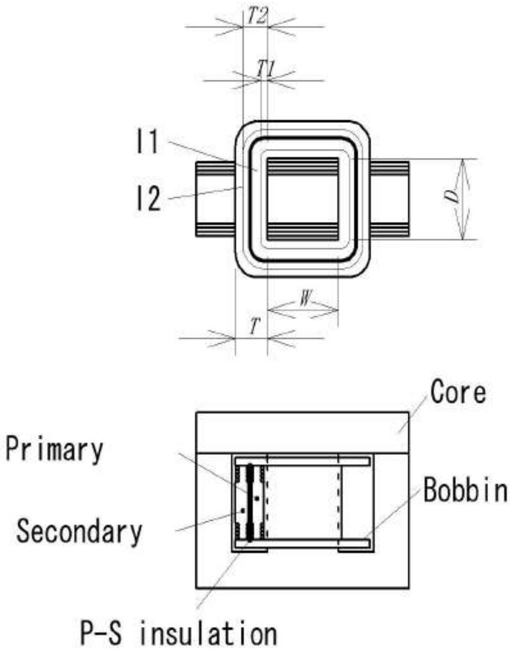

Figure 5.7: Structure of transformer

We set T for primary winding $T/4$ and for secondary winding $3T/4$.
By the formula (8) and (9), the length of primary winding and resistance are,

$$L1 = ((22.5 + 26.6) \times 2 + 2.1 \times 8) \times 650 \times 10^{-3} = 74.8 \quad (m)$$

$$r1 = 0.01724 \times \frac{74.8}{0.066} = 19.5 \quad (\Omega)$$

Similarly, wire length and resistance for the secondary winding are,

$$L2 = ((22.5 + 26.6) \times 2 + 6.3 \times 8) \times 143 \times 10^{-3} = 21.2 \quad (m)$$

$$r1 = 0.01724 \times \frac{21.2}{0.332} = 1.1 \quad (\Omega)$$

5.6.8 Calculation of copper loss

Calculate copper loss P_c(W) by wire.

$$P_c = r1 \times I1^2 + r2 \times I2^2(W) \qquad (10)$$

By replacing with actual value,

$$P_c = 19.5 \times 0.2^2 + 1.1 \times 1^2 = 2 \quad (W)$$

5.6.9 Calculation of iron loss

Iron loss P_f is,

$$P_f = P_a \times P_b(W) \qquad (11)$$

where
P_f : iron loss(W)
P_a : iron loss per 1kg (W/kg)
P_b : weight of core(kg)
Weight of core is given by list 1, and assuming maximum magnetic flux density 1.4T , iron loss per 1kg is 4.8W/kg. Then by formula (11),

$$P_f = 4.8 \times 0.46 = 2.2 \quad (W)$$

5.6.10 Calculation of voltage regulation

$$\epsilon = \frac{P_c}{P} \times 100(\%) \qquad (12)$$

The above value is reflected to the internal voltage drop $V_e(V)$ when the secondary winding count is determined. By formula (12),

$$\epsilon = \frac{2}{20} \times 100 = 10 \quad (\%)$$

5.6.11 Calculation of efficiency

Efficiency η is,

$$\eta = \frac{P}{P + P_c + P_f} \times 100 \quad (\%) \qquad (13)$$

By formula (13),

$$\eta = \frac{20}{20 + 2 + 2.2} \times 100 = 82.6 \quad (\%)$$

This is the finish of all process.

Chap6 Analysis of switching transformer and reactor

Transformers for commercial frequency applications operate under low and constant frequency, the design is relatively simple. However, the designer rarely construct transformer by themselves and generally place an order to a manufacturer.

In case of switching transformers, there are following differences from commercial frequency transformers, thus design method and points differ.

(1) Analysis of characteristics is done by differential equations. (AC theory that deals with single frequency sinusoid is not applicable.)

(2) There is a freedom of switching frequency and duty ratio.

(3) Wider variety for selection of cores (physical characteristics and shape).

(5) There are different designs in which the cores store, or not to store magnetic energy.

Because of the reasons stated above, there is no standard pre-designed switching transformers, and they must be designed specifically to meet the each power converters. Hence, the switching transformers - and sometimes reactors - are basically designed and constructed by power converter designer at prototype.

6.1 Core material

First problem is the magnetic characteristics of the materials to be used. In case of AC transformer, frequency characteristics were hardly the problem, but for switching transformers we discuss about this point first.

Silicon steels used for AC transformers, the frequency characteristics is improved even up to $20KHz$ when thinned and reduced the eddy current loss. One of the example is the thin silicon steel band manufactured by Nikkin Denji Kohgyo. The non-oriented thin silicon steel band $ST-050$ has flat frequency response between $50-20kHz$. These materials are used for choke coils that operates more than 10kHz frequency. Choke coils for even higher frequencies, dust cores (molybdenum based) that have good DC superposition characteristic, ferrite cores with gap and amorphous cores are used.

When thinking about the power switching applications, $20kHz$ is too low frequency and more than $100kHz$ switching frequency is preferred. That is, core materials used for AC transformers are no longer usable, and cores with higher frequency characteristics are necessary. Currently, ferrite materials are most suitable for this application even they have smaller saturation magnetic flux density. Ferrite cores inherently have small eddy current loss, it is not necessary to make thin materials and laminate like (conductive) steel cores. Therefore, they are sintered into some specific shapes and combined by small numbers of windings, the prototyping is much easier than AC transformers.

6.2 Ferrite

Ferrite is a ceramic that is mainly based by iron oxide, and there are hard ferrite that is most suitable for permanent magnets and soft ferrite that are used for cores of transformers and choke coils.

We discuss only the characteristics of the soft ferrite targeting the transformer application.

Ferrite is non-conductive material with small eddy current loss and has wide BH frequency characteristics, it is most widely appreciated for switching power supplies. On the other hand the maximum magnetic flux density is smaller (PC90 by TDK, 0.54T) than silicon steel (approx. 1.8T) and mainly used for smaller power switching applications.

Power conditioners (a device that is used to interconnect power from PV cells to grid) that deals with 3kW or about, the operating frequency of reactors inside is about 16-18kHz, and this has been managed by silicon steel or sen-dust cores with good margin of maximum saturation magnetic flux density. But the frequency more than above, the loss becomes impractical and for these applications, ferrite cores like PE90 (TDK) is available now. The trend of increasing the switching frequency for transformers and inductors shall be accelerated by these materials.

Frequency response of the initial permeability[1] for MC2 manufactured by JFE Ferrite, goes up to 3MHz (slight peak at 3MHz). General material like PC40 manufactured by TDK has frequency response up to 1MHz. Therefore, the possible switching frequency is up to approx. 200kHz, but the precise maximum usable frequency cannot be decided by theory alone and requires cut and try at the design.

Another characteristic of the core is the core loss. Core loss is produced by local eddy current that flows inside small crystal grains that forms the sintered ferrite core. For PC44 by TDK, the loss is approx. $300kW/m^3$ between 90°C and 110°C. Interesting thing for the PC44 is that the core loss become minimum at the temperature 90°C -110°C, and this implies that the switching supplies with this core may be used in relatively high temperature environment.

6.3 Ferrite core material

6.3.1 Summary

Ferrite cores are supplied as pre-fabricated standard cores from manufacturers like the cores for AC transformers. The shapes include EI type and their derivatives (EE, center of EI made circular), ring (toroidal), and pot type which covers the coil inside to reduce leakage flux. These variation is possible because the cores are made by sintering the powdered material and has more freedom in shape compared with the silicon steel cores. Also, bobbins that match the cores are provided. Since the number of windings are

[1] Permeability is not linear, this is the starting point of gradient. Defined by $\mu_i = \frac{1}{\mu_0} \lim_{\mu \to 0} \frac{B}{H}$.

generally small, it is easy to wind and make a transformer by the designer for parameter adjusting. There is no need to firmly bind the cores by screws (EI core) or fasten by steel belt (cut core) like AC transformers to suppress sound associated with the AC. The ferrite transformers can readily operate just binding the cores by the adhesive tape [2].

One of the characters of ferrite core is fragility just like ceramics. This character requires careful handling over the whole production processes. Although, it is non-conductive, the resistance of the core is not that high and cannot be treated as an insulator. Therefor, in case of high voltage application, it will be necessary to insulate the core.

Ferrite cores are sold in various shapes by many manufactures, but each core has different characteristics about leakage flux, maximum magnetic flux density and so on, which are different from the value of original materials.

The manufacturers of ferrite cores are not many in Japan - TDK, NEC Tokin, JFE ferrite, Nihon ceramic and Hitachi Kinzoku are the major suppliers.

6.3.2 Magnetic flux density of core

Magnetic flux density B of ferrite is defined as follows.

$$B = \mu_s \mu_0 H$$

Where, magnetic field strength H, permeability of vacuum space μ_0, relative permeability μ_s[3].

Since, ferrite cores have many variations, the relative magnetic flux density of the materials is defined as stated below.

Making a toroidal core by the target material[4] and wind a coil, then measure the inductance. The inductance L is calculated by the sectional area of the core A_e, number of windings N and the effective core length l_e.

$$L = \frac{\mu_s \mu_0 A_e N^2}{l_e}$$

Therefore,

$$\mu_s = \frac{L l_e}{\mu_0 A_e N^2}$$

Since $\mu_0 = 4\pi \times 10^7 [H/m]$, we get

$$\mu_s = \frac{L l_e}{4\pi A_e N^2} \times 10^{-7} \qquad [No\ \ dimension]$$

Then the effective relative permeability is defined for specific cores by using the value obtained above. Also, related variable of the specific cores are defined and for actual transformer design, these parameters are used for calculation.

[2]At design and development phase. There is bigger core that is bound by steel fastener.

[3]Here, μ_s is just a coefficient and has no dimension. It is misleading, but this is the custom of the industry.

[4]For the coils wound on toroidal core, the magnetic flux is constrained inside the core, and define relative permeability under this condition.

6.3.3 Magnetic characteristics of ferrite

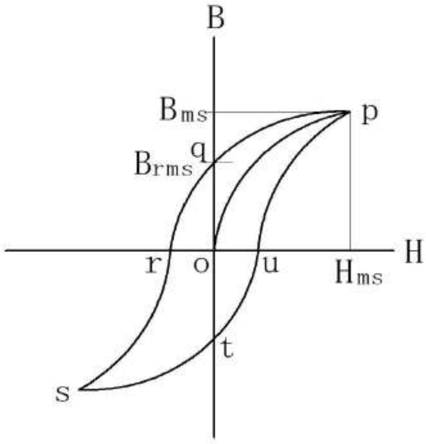

Figure 6.1: BH curve

Fig 6.1 shows so called BH curve of a magnetic material. When magnetic field is applied, the magnetic flux density curve starts at point o and moves as $o \to p$. When the magnetic field is inversed, it then moves $p \to q \to r \to s$. The magnetic flux density B_{ms} that corresponds point p is called "effective saturation magnetic flux density". The magnetic flux density B_{rms} which is the residual density when the magnetic field is removed, is called "effective residual magnetic flux density". Applications that use the transformer as a magnetic energy storage device like flyback converters, the magnetic flux between B_{ms} and B_{rms} is used. Fig6.1 shows schematic BH curve and a real example (NEC Tokin FEI12.5, BH2) is shown in fig6.1. In this figure, $B_{rms} = 510mT$ and $B_{ms} = 100mT$.

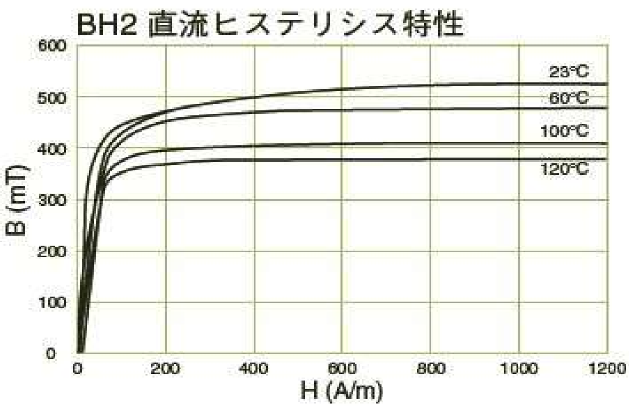

Figure 6.2: Hysteresis curve ; NEC Tokin BH2

6.4 Operation mode of transformer and reactor

6.4.1 Effect of gap

Considering that the maximum magnetic density of ferrite is small, it is vital to use the core without causing saturation. Most common way is to provide a gap to the core.

The gaps are made by inserting a plastic sheet etc., with appropriate thickness to reduce the permeability of the core, so that bigger magnetic field can be applied to the core. In Fig 6.3, the dotted line shows the hysteresis curve without a gap. When a gap is provided, the tangent of the hysteresis curve becomes smaller as shown by the solid line. That is, the saturating point of permeability shifts from point p to q when a gap is provided.

This meas that the gap increases the current×turn (AT) product making the energy capacity of the core bigger.

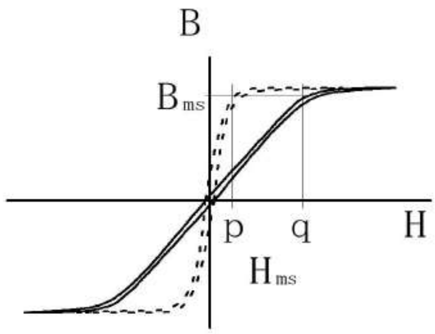

Figure 6.3: Gap and BH curve

Since the gap increases AT value, there are two ways to exploit this effect - current or/and turn of windings. In case of flyback mode transformer[5] design, the calculated inductance without the gap becomes too big and decreases the inductance by inserting a gap. This results the reduction of number of windings and eventually the current through the winding increases.

Cores with pre-fabricated gap are also available. In these cores, the gap is made by slightly cutting off the center pole of EI core and cannot be observable after transformer assembly.

The choke coils used for the ripple filter generally are superimposed with DC, the benefit by the gap may be used for either current value or inductance or both. In latter example, the inductance of the choke coil is increased with the same core. However, the winding space is identical and the diameter of the wire must be decreased causing the increase of DC resistance. Thus maximum DC current is decreased.

In order to clarify the relationship between the gap and resultant inductance, we introduce magnetic resistance that is analogous to electric resistance. Assuming a toroidal core[6] that has effective magnetic length l_e, sectional area A_e, and N turn coil was wound

[5]Flyback transformer referred to a transformer used in CRT television until quite recently. In order to avoid confusion, we call flyback mode transformer.

[6]Closed cores are treated in the same way, but for simplicity toroidal core is chosen here.

with current I, overall magnetic flux ϕ will be,

$$\phi = BA_e = \mu_s \mu_0 H A_e$$

And (see Sec 5.2.5),

$$H = NI/l_e$$

Then,

$$\begin{aligned}\phi &= \mu_s \mu_0 \frac{NI}{l_e} A_e \\ &= NI / \frac{l_e}{\mu_s \mu_0 A_e}\end{aligned}$$

Here, the NI is a potential to generate magnetic force, $l_e/\mu_s\mu_0 A_e$ is magnetic resistance (proportional to magnetic length and inversely proportional to the sectional area), the equivalent Ohm's law in magnetic circuit is derived. Namely, putting $R_m = l_e/\mu_s\mu_0 A_e \mathrm{A} NI = V_m$, we get

$$\phi = \frac{V_m}{R_m}$$

The ϕ is equivalent magnetic current.
By Sec 6.3.2,

$$\begin{aligned}L &= \frac{\mu_s \mu_0 A_e N^2}{l_e} \\ &= \frac{1}{R_m} N^2\end{aligned}$$

Or,

$$N^2 = R_m L$$

Then the inductance with a gap is calculated as below. The toroidal core is not completely closed, but has cut out of length l_g, that works as "the gap". The magnetic resistance R_{mc} of the toroidal core is, by ignoring the length og the gap,

$$R_{mc} = \frac{l_e}{\mu_s \mu_0 A_e}$$

For the gap, the permeability is that of the space,

$$R_{mg} = \frac{l_g}{\mu_0 A_e}$$

Then,

$$\begin{aligned}N^2 &= (R_{mc} + R_{mg})L \\ &= (\frac{l_e}{\mu_s \mu_0 A_e} + \frac{l_g}{\mu_0 A_e})L\end{aligned}$$

Solving the above equation for l_g,

$$l_g = \frac{\mu_0 A_e}{L} N^2 - \frac{l_e}{\mu_s}$$

Here, the real core length l_e is generally 100mm maximum, μ_s is more than 500, the second term is omitted ($\mu_0 = 4\pi \times 10^{-7}[H/m], A_e[m^2], L[H]$)

$$l_g = \frac{\mu_0 A_e}{L} N^2 \qquad [m]$$

This shall be written into

$$\frac{A_e}{l_g} = \frac{1}{\mu_0} \frac{L}{N^2}$$

clearly showing how the inductance is affected when gap is provided for the core with sectional area A_e. The value is called inductance coefficient or A_L value [7].

6.4.2 A_L value FInductance coefficient

The gap is an important factor for designing flyback mode transformers and reactors. In the design sheets by ferrite core manufacturers, the parameter A_L is used for this purpose.

Fig 6.4 shows an example of A_L value for specific core. It shows the relationship between inductance and number of turns. The horizontal axis shows the product of turn of the windings and current AT, whereas vertical axis shows A_L value. The unit of Al value is generally nH/N^2. The graphs show for the various gap length as a parameter.

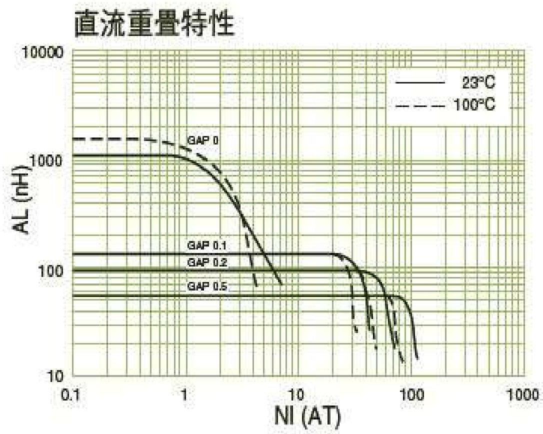

Figure 6.4: NEC Tokin FEI12.5 (BH2) A_l value

6.4.3 Through Energy mode

This mode is utilized for the conventional AC transformers and forward converter transformers. The input energy in primary side is transferred to secondary winding instantaneously and the transformer does not store energy as magnetic flux. The magnetic flux density is maximally used and no gaps are provided. In particular, from the point of efficient usage of BH curve of the core, exploiting all the four quadrant is most efficient. For instance, forward converters by full bridge configuration use the switching transformer in this way. See Chap 4, Fig 4.2.

[7] Originally, it mus have been A/L value.

6.4.4 Energy store mode

This is the mode adopted by the transformer of flyback converters, reactors of up converter and inverse converters. As shown in Fig 6.5, the current flows alternately through primary and secondary windings[8].

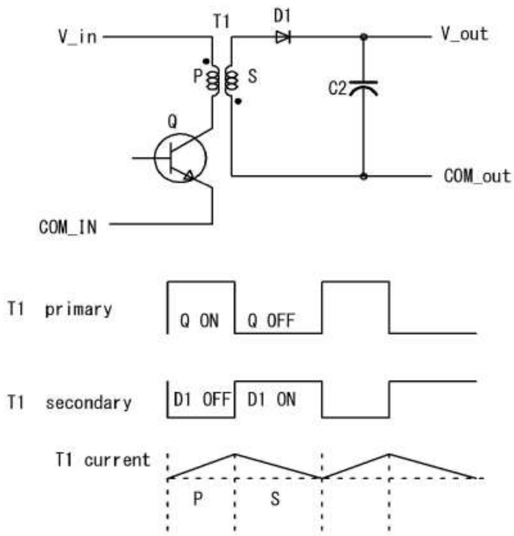

Figure 6.5: Transformer current for flyback mode converter

In this mode of operation, the 1st quadrant of BH curve is used. Flyback mode transformer and choke coils use the core as magnetic flux storage device (energy storage device). The strategy to maximize the core energy is a natural way to take.

Using the core as an energy storage device means that the transformer is always looked as an inductor regardless the existence of the secondary windings.
Assuming that a continuous current I is flowing through L, the energy E_L stored in the inductance,

$$E_L = \frac{1}{2}LI^2$$

Therefore, to increase the total energy, either L or current I may be increased.

Inserting a gap to the core increases the AT value with same size. This can be utilized to increase L (increase number of windings) or increase current. For the common flyback converters, the calculated value of AT becomes generally too big (and saturates the core) without a gap. Then the gap is provided to decrease inductance.

6.4.5 Choke coil

Choke coils are generally used by superimposing the DC current. Then, the only first quadrant of the BH curve is used meaning that only the half (there is no effective usage in second and forth quadrant) of the potential is utilized.

[8]Under the case of non continuous operation, there is a timing that both primary and secondary current is not flowing.

To maximize the core capacity, a gap is provided or open core (drum core) is used. For the choke coils, the manufacturers provide series product for various value, current capacity, frequency range and so on and in practical design, the designer shall choose a sample among them.

For relatively small output applications, very high switching frequency(as of 2013, around 6MHz) design is in use. These are basically all chopper regulators and do not use transformers, but use choke coils only and the materials are metal composite (NEC Tokin MPC series) with the inductance less than $1\mu H$.

Chap7 Design of switching transformer

Transformers used for switching power supplies are basically divided into three categories - energy is stored by magnetic flux, power passes through from primary to secondary without storing energy and the ones in between[1]. It will be sufficient to discuss only energy storing transformer and pass through transformer since the ones in between shall not be difficult to understand.

7.1 Flyback converter transformer design

We discuss the design of transformers that store energy as magnetic flux used for flyback converters.

The characters of the flyback converter transformers are that they are inductors in reality even though called "transformers", and a gap is inserted to the core to increase the capacity of stored energy.

Fig 7.1 shows the design process of a flyback mode transformers.

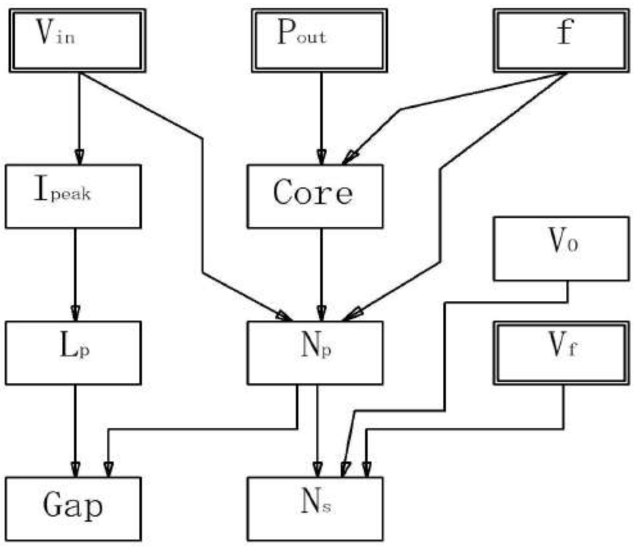

Figure 7.1: Process of flyback converter transformer design

In Fig 7.1, the items that the designers should decide at the beginning are shown by doubly circled frames. These include the input voltage (minimum value), output voltage, output power and switching frequency.

[1]Resonant converters use transformer with a gap that intentionally produce leakage inductance. The resonant circuit is formed by a capacitor and the leakage inductance.

In general, the input voltage, output voltage and output power are given as a specification. Higher the switching frequency, the transformer is made smaller in size, but this shall be limited by the frequency response of the core material, speed of switching devices and so on. In actual design, the selection of the core by the output determines the usable maximum frequency.

7.1.1 Number of primary winding

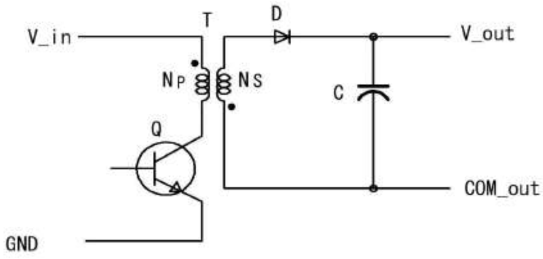

Figure 7.2: Flyback converter

Once the core is selected, the number of primary winding is calculated by the characteristic of the magnetic flux density ΔB. In practice, the structure of the wire (single wire, lits wire), thickness and materials (copper, aluminium) must be selected, but here we only discuss the fundamental items for the transformer design.

Input voltage V_{in} is expressed by number of primary winding N_p and magnetic flux ϕ as follows.

$$V_{in} = N_p \frac{d\phi}{dt}$$

By integration,

$$\phi = \frac{1}{N_p} \int V_{in} dt$$

The magnetic flux is written by usable magnetic flux range ΔB (between B_{ms} and B_{rms}) and the core sectional areaA_e as,

$$\phi = \Delta B A_e$$

Then,

$$\Delta B = \frac{1}{A_e N_p} \int V_{in} dt$$

Putting the on time t_{on} of the switch,

$$= \frac{V_{in} t_{on}}{A_e N_p}$$

The number of primary winding N_p is expressed by,

$$N_p = \frac{V_{in} t_{on}}{A_e \Delta B}$$

The unit of ΔB is Tesla, dimension by SI system $[kg \cdot s^{-2} \cdot A^{-1}]$, the unit of A_e is $[m^2]$. Number of primary winding is also affected by the duty ratio, the on time t_{on} is generally set to the half of the switching period T.

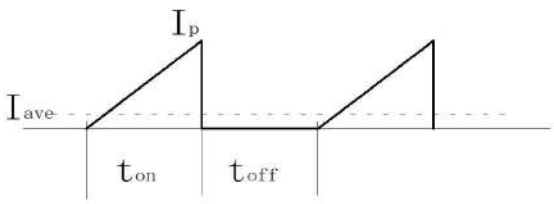

Figure 7.3: Primary current

7.1.2 Inductance calculation of the primary winding

The output power P_o is expressed by average input current I_{ave} and by the efficiency of the transformer η as,

$$P_o = \eta V_{in} I_{ave}$$

Here, note that V_{in} is the minimum input voltage.
Assuming peak current I_p and $t_{on} = T/2$, the primary current increases linearly

$$I_p = 4I_{ave} = 4\frac{P_o}{\eta V_{in}}$$

The stored energy E of the inductance L_p in time t_{on} is,

$$E = \frac{1}{2} L_p {I_p}^2 = \frac{{V_{in}}^2 \cdot {t_{on}}^2}{2L_p} @$$

Therefore,

$$\begin{aligned} L_p &= \frac{V_{in}}{I_p} t_{on} \\ &= \frac{\eta {V_{in}}^2 t_{on}}{4P_o} \qquad [H] \end{aligned}$$

7.1.3 Number of the secondary winding

Assuming the secondary current I_o, the peak current I_{2p} is,

$$I_{2p} = 4I_o$$

The inductance L_s of the secondary winding is,

$$\begin{aligned} L_s &= \frac{V_s}{I_{2p}} t_{off} \\ &= \frac{V_s}{4I_o} t_{off} \end{aligned}$$

Number of the secondary winding will be,

$$\begin{aligned} N_s &= \sqrt{\frac{L_s}{L_p}} \cdot N_p \\ &= \sqrt{\frac{P_o(V_o + V_F)}{\eta {V_{in}}^2 I_o}} \cdot N_p \end{aligned}$$

Here, V_F is the forward voltage drop of the secondary side diode.

7.1.4 Calculation of gap

The number of the primary winding is calculated in Sec 7.1.1, no gap is assumed to the core. Generally, the inductance becomes too big by the number of calculated winding (or, the core size is decided by the manufacturer to be like this).

Therefore, the gap is introduced to reduce the effective magnetic flux density and increase the total amount of energy stored in the core.

By Sec 6.4.1, the length of the gap is calculated as bellow.

$$l_g = \frac{\mu_0 A_e}{L} N^2 \qquad [m]$$

7.2 Forward converter transformer design

We discuss the design of forward converter transformer that does not store energy as magnetic flux.

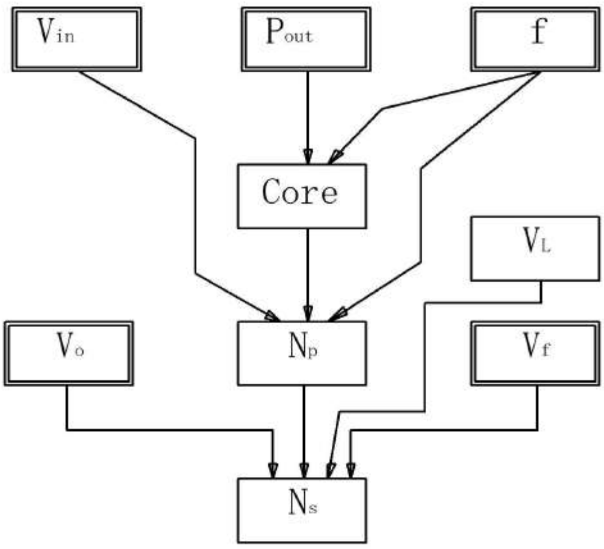

Figure 7.4: Process of forward converter transformer design

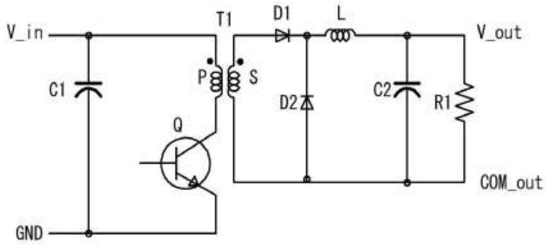

Figure 7.5: Forward converter

Since no gaps are introduced to forward converter transformers, the calculation becomes a bit simpler. On the other hand, an inductor is required to the secondary side and needs to design the inductance as well as the reset circuit for the primary winding of the transformer. However, we discuss the transformer design only.

7.2.1 Number of primary winding

The calculation of the number of primary winding is identical to that of the flyback converters. Just take care about the characteristics of the core to avoid saturation under any circumstances and assume margin to ensure.

It holds always $\Delta B < (B_{ms} - B_{rms})$ and considering the maximum time of t_{on} [2], we get

$$N_p = \frac{V_{in} t_{on}}{A_e \Delta B}$$

7.2.2 Number of secondary winding

In Fig7.5, the duty ratio D is,

$$D = \frac{t_{on}}{t_{on} + t_{off}}$$

The secondary output voltage V_s of the transformer T1 is,

$$V_s = \frac{V_{out}}{D} + V_f + V_L$$

Here, V_{out} is the output voltage, V_f is the forward voltage drop of the diode and V_L is the voltage drop through the inductance L. The ratio of the primary and secondary voltage is simply,

$$\frac{V_s}{V_{in}} = \frac{N_s}{N_p}$$

Therefore,

$$\begin{aligned} N_s &= \frac{V_s}{V_{in}} \cdot N_p \\ &= \frac{V_{out}/D + V_f + V_L}{V_{in}} \cdot N_p \end{aligned}$$

The number of the secondary winding is not decided simply by the voltage ratio of the primary and secondary voltage, but affected by the duty ratio as well. Since we assume that the output voltage is regulated by feedback, it is possible to operate by lower input voltage when duty ratio is set smaller (smaller t_{on}). In this case the output voltage is set higher (number of secondary winding increased), the output can be regulated to the lower input voltage.

However, for the forward converters, the energy is supplied to the load as well as the secondary inductor L when the switch Q is turned on. This renders us to set duty ratio at normal operation by 50%. The calculation so far assumed the minimum input voltage, the duty ratio of around 0.4 must be recommended in this instance.

Transformer T1 does not store energy as magnetic flux, there is no need to calculate primary inductance.

[2] This happens at the time of start up, other than normal operation.

We omitted the calculation of inductance of the secondary inductor L, but this shall be necessary for the practical design.

Chap8 Mathematical basics

Mathematical basics that are used in electric engineering sometimes lacks convincing treatise. In this chapter, some of the topics are picked up and tried to give explanations that fill the gaps of mathematics and engineering.

8.1 Complex notation of sinusoid

8.1.1 trigonometric function

The trigonometric function is defied by the ratio of sides in right triangle as shown in Fig 8.1.

$$\sin\theta = \frac{c}{a}$$
$$\cos\theta = \frac{b}{a}$$

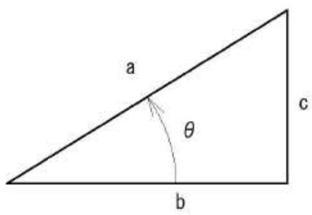

Figure 8.1: Trigonometric function

The parameter θ represents an angle, and therefore the "degree" is used for the unit, but a dimensionless quantity. When θ is varied from 0 degree to 360 degree, the magnitude of sinusoid and co-sinusoid vary as shown in Fig 8.2.

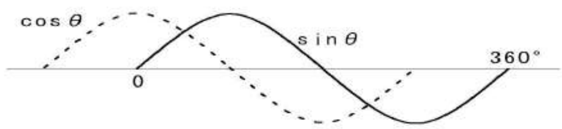

Figure 8.2: Sine, cosine

8.1.2 Sinusoid and co-sinusoid

A pendulum is one of the simplest physical phenomena. Suppose a bucket with a pin hole in the bottom is supported by a string and oscillated. When a long paper placed under the bucket is moved by a constant speed, we will get a pattern shown in Fig 8.3, and this is a sinusoid. The parameters of this sinusoid are magnitude and frequency.

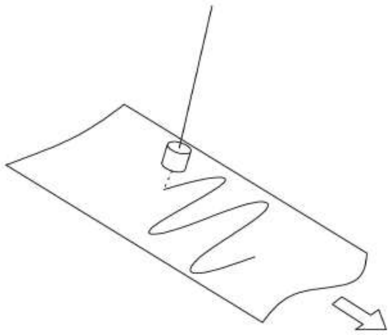

Figure 8.3: Pendulum and sinusoid

Similarly, suppose a wheel that is suspended in the air with constant speed rotation. The point A on the wheel projects a trace which again becomes sinusoid. This shows that a sinusoid is also produced by some rotation, and it will be natural that people want to investigate the relationship between rotation and sinusoid just like the case of pendulum.

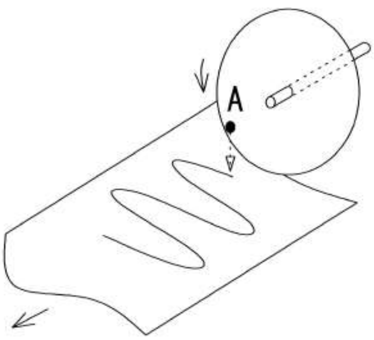

Figure 8.4: Sinusoid by a rotating object

Parameters of rotation are, diameter, velocity, direction and current position of point A. Using radian for unit of angle, angular velocity ω and frequency of sinusoid f is related by,

$$\omega = 2\pi f$$

The unit of ω is radian/sec, the dimension of ω is $1/s$, because radian is dimensionless quantity. Expressing the sinusoid as a projected image of A, simply replacing θ by ω and write

$$f(\omega) = \sin \omega$$

is inappropriate. Because, in definition of the sine, θ is a dimensionless quantity and putting a value with a dimension $1/s$ does not make sense. Therefore, the dimension $1/s$ must be canceled by multiplying with a variable t whose dimension is s.

Now supposing that the point A has a fixed length r from the center (Fig 8.4), we try to determine the position of A. One simple idea is to assuming a vertical or horizontal line crossing the axis, and define the angle ϕ for point A. In this case, parameters are magnitude 2r, angular velocity ω, position (phase) ϕ.

Another example is shown in Fig 8.5. In this case, vertical and horizontal projection is paired to express the rotation and these projected image will become sinusoid and co-sinusoid.

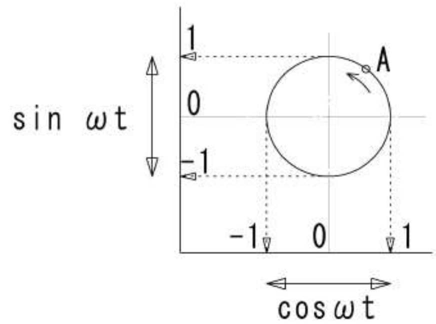

Figure 8.5: Pair of sinusoid and co-sinusoid by a rotation

Sinusoid and co-sinusoid has identical form, and if one is defined, the other is automatically known and it is not clear enough why we need two.

However, if we assume or extend that the origin of sinusoid is a rotation, the reason to have two forms - sinusoid and co-sinusoid - becomes clear. If we have either sinusoid or co-sinusoid only, we have to assume some reference to define phase. One idea is to introduce ϕ, and in this case the reference line is prepared outside of the rotating object. And by using ϕ, direction of rotation is not known even if we define negative ϕ.

But using a pair of sinusoid and co-sinusoid, we can define not only the phase but the rotation of direction as well. This is an idea by taking advantage of the already fixed phase of sinusoid and co-sinusoid ; posses the phase reference internally. In this notation, the reference is included in the rotation and is more flexible.

A wave that has an arbitrary phase difference ϕ to sinusoid is shown as,

$$\sin(\omega t + \phi) = \sin(\omega t)\cos(\phi) + \cos(\omega t)\sin(\phi)$$

Since $\cos(\phi), \sin(\phi)$ are constants, replacing by A and B it becomes,

$$\sin(\omega t + \phi) = A\sin(\omega t) + B\cos(\omega t)$$

When sinusoid and co-sinusoid is pared, any sinusoid with arbitrary phase (with same frequency) can be expressed by a simple addition. Or, the phase ϕ can be deleted.

The deleted ϕ is always reproduced by,

$$\phi = \tan^{-1} \frac{B}{A}$$

8.1.3 Complex frequency

By the formula in Sec 8.1.2,

$$\sin(\omega t + \phi) = A \sin(\omega t) + B \cos(\omega t)$$

both $\sin \omega t$ and $\cos \omega t$ are real number and by using these terms, the original rotation cannot be expressed even if the phase is expressed. The reason that the Fig 8.5 can show the rotation is that the $\sin \omega t$ and $\cos \omega t$ are laid out so that they are orthogonal.

Now we jump a bit by the above facts. That is, we introduce complex notation so that $\sin \omega t$ and $\cos \omega t$ becomes orthogonal. Assigning which one to imaginary part is not fundamental, but in general,

$$\cos(\omega t) - j \sin(\omega t) = e^{-j\omega t}$$

If we introduce magnitude r,

$$r\big(\cos(\omega t) - j \sin(\omega t)\big) = re^{-j\omega t}$$

This completes the expression for rotation. By the above expression, magnitude, frequency, phase and direction are all included. This is shown in Fig 8.6.

This expression can include many parameters within, but this is only applicable to a single frequency sinusoid [1].

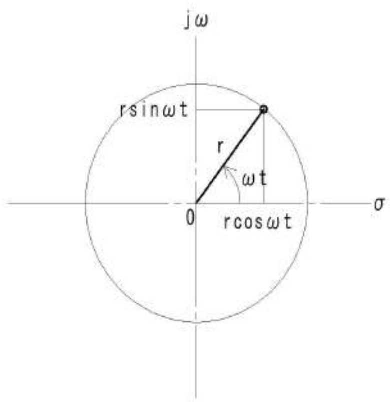

Figure 8.6: Complex frequency

Sinusoid does not change it's shape by differential or integration. Only the phase changes. In AC circuit theory, it takes full advantage of this point, and try to analyze without solving differential equations. Differential and integration correspond to the

[1] In AC circuit theory, the direction is only counter clock wise (positive frequency) and no clock wise rotation appears.

rotation of $\pi/2$ radian in complex plane. Hence, the notation goes quite well with the AC circuit theory.

The sort of toughness of the sinusoid against differential and integration is really amazing.

8.2 Linear components and circuit

8.2.1 Linear components

Linearity in mathematics is defined that the function (operator) and variable (target of operation) A,B holds the following equation.

$$f(A) + f(B) = f(A + B)$$

$$f(cA) = cf(A)$$

where c is a constant.

Therefore, an impedance (combination of resistance, capacitance and inductance) is linear, and differential and integration (operator) are also linear. On the other hand, by Fig 8.7, input square wave and differential and integration output is shown. Linearity and proportional is almost the synonym, but there is no similarity between input and output.

However, remembering that the square wave is a linear combination of sinusoid as follows,

$$f(t) = c_1 \sin \omega_1 t + c_3 f \sin \omega_3 t + ...c_n \sin \omega_n t + ...$$

it satisfies the definition of linearity.

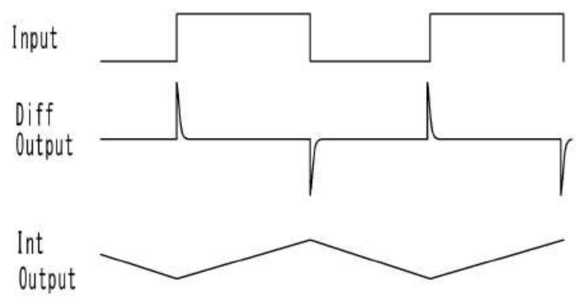

Figure 8.7: Wave form change by differential and integration

That is, for general signals, both differential and integration deforms their original shapes. The decomposed components to sinusoid will not change by either differential and integration, but the phase and magnitude has become different and re-addition cannot restore the original wave forms.

8.2.2 Linear circuit and liner component

Suppose a circuit made of two linear components, and try to connect external linear component. In order to connect to external component, there can be two ways ; one is to connect to the both points of the components (parallel) , the other is to cut open the components (series). Parallel/series is only defined when try to connect to external component. By considering the circuit as a black box, they are both linear.

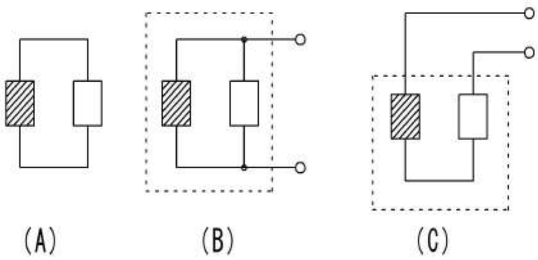

Figure 8.8: Black box by two liniar components

Connecting a linear component to this black box again makes a linear circuit. That is, in whatever ways the linear components are connected, the resultant circuit becomes linear by looking into arbitrary two points.

8.2.3 Thevenin's law

Given an electric grid as a black box, and try to connect a load to certain node of the black box. We try to estimate how much power can be drawn from the node. The first step is to calculate the internal resistance. We add known load $R_L$to the black box , and apply Thevenin's law, as shown in Fig 8.9,

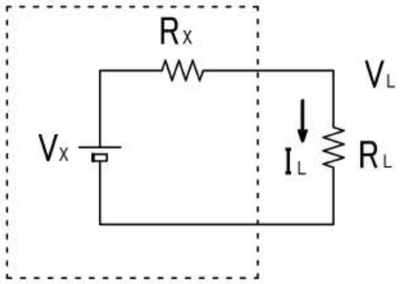

Figure 8.9: Thevinin's law

$$V_L = \frac{R_L}{R_X + R_L} V_X$$
$$I_L = \frac{1}{R_X + R_L} V_X$$

That is, when the open voltage of the black box V_X is known, the internal resistance R_X will be calculated by adding and measuring the voltage of some load resistance R_L. Somewhat self evident, but this is convenient since the black box can contain arbitrary network composed of any number of voltage sources and resistances.

The internal resistance is calculated, but we cannot know the precise ability of power supply. However, in practice, we may assume the maximum load R_L to be less than 5% of R_X. For example, the output voltage of pole transformer is 110V against the nominal voltage 100V at home. In this example, 10% voltage drops are anticipated at the maximum load.

8.2.4 Application of Thevenin's law

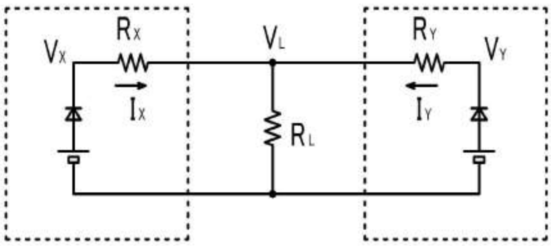

Figure 8.10: 2 power source

Every node of electric network is equipped with communication function with any other node[2]. Therefore, arbitrary load R_L connected to this network will observe two nodes as shown in Fig 8.10 [3]. Open voltage V_X, V_Y are know by communication, and the wire resistanceR_X, R_Y are known by connecting load R_L and measure load voltage V_L, and current I_X,I_Y,

$$V_X - V_L = R_X \cdot I_X$$

$$V_Y - V_L = R_Y \cdot I_Y$$

The series diode connected to the power source is to clarify the direction of current flow when supplying power. iIt does not mean that the batteries cannot be charged.)

In a nutshell, the measurement of wire resistance to the power source is a simple and direct application of Thevenin's law.

[2]This is the basic assumption of the target system in discussion in this document

[3]It is possible to connect a load to the center of Y connection of 3 nodes, but here we do not assume this.

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