Electrical Power Systems Coursework

Renewable Energy – Primary Source and Conversion Technology

Candidate Number - 181395

Abstract – This report will discuss the different types of renewable energies used in the world today, specifically how electricity is converted from solar energy from the sun using photovoltaic cells found in solar panels.

I. The Source of Renewable Energies

Renewable energy is self-explanatory, a type of energy that constantly renews which cannot deplete or run out. The increased need for renewable energy is mostly caused by the growing concern of global warming where non-renewable energies have a very significant contribution. Therefore, rather than talking about renewable and non-renewable energies, it is important to talk about sustainable energies which can be defined as "an energy source that is not substantially depleted by continued use, does not entail significant pollutant emissions or other environmental problems and does not involve the perpetuation of substantial health hazards or social injustices".[1]

Solar energy is a sustainable form of energy, it is the light or heat from the radiation emitted by the sun. This energy received from the sun is by far the largest and most abundant source of renewable energy on Earth but a lot of the energy that we receive, we cannot use at Earth's surface due to a large amount being reflected from either the surface or the atmosphere back into space or being absorbed by clouds or the ocean. Thermal energy from the sun heats up the air, land and water which leaves less solar energy to be converted into electrical energy. Despite these factors, it is still the largest source of renewable energy on Earth. In fact, most renewable energy sources originate from solar radiation from the sun. For example, wind is created by the difference in pressure of air caused by the sun heating different surfaces at different rates. Air will move from the high-pressure areas to the low-pressure areas and the wind created by this pressure difference can turn a wind turbine which in turn converts electrical energy. Just like wind turbines convert the kinetic energy to electrical energy from the wind turning the blades, photovoltaic cells in solar panels convert energy from the sun.

II. Photovoltaic Cells

A. A History

The first photovoltaic cell was discovered by a French scientist Edmund Becquerel when he noticed a rise in voltage while exposing the silver plates of an electrolytic cell to sunlight. Multiple scientists tried to test this phenomenon and while successful photovoltaic (PV) cells were made, none were efficient until Einstein released his Nobel Prize winning paper on the photoelectric effect in 1905. This inspired others to research the subject and William J. Bailey invented his copper collector in 1908, a more efficient photovoltaic cell.[2]

There was not much progress made until the 1950s, where research into global warming took place and people were becoming more aware of fossil fuel depletion. This created a need for a more reliable and sustainable energy. PV cells had their first practical use for satellites where solar power became an accepted energy source for space application and remains so today.

Through the commercialization of solar technology, there has been more development and demand for PV cells since producers were aware that they could not depend on the depleting fossil fuels. This has led to solar panel implementation for not only large producers with solar farms but also for domestic use with solar panel roof tops. Solar panels are now seen as an efficient way to save money and energy usage in the long term.

B. How They Work

PV cells are made from semiconductor materials. These materials do not usually conduct electricity well, however they can be used for conductive applications. Usually, PV cells are made using silicon as the semiconductor material and this cell is sandwiched between two conductive layers. The silicon is then split into layers, much like a diode with the p-n junction. The top layer of silicon is negatively doped, usually with phosphorus so that this layer is negatively charged and has excess electrons to freely move. The bottom layer is positively doped so that it has a positive charge and has excess 'holes' for the electrons from the negatively charged layer to move into. There is a depletion region in between these two with neutral atoms, this is the P-N junction. The top layer is usually very thin compared to the other two.

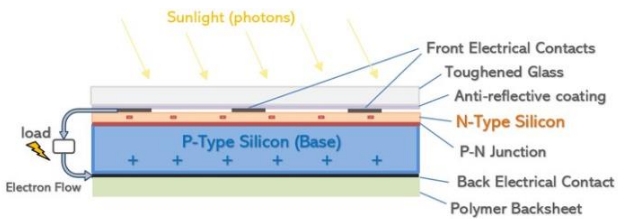

Figure 1: Cross-Sectional Structure of PV Cell[3]

Solar radiation is the flow of elementary particles called photons. These photons are massless and, in a vacuum, they travel at the speed of light. Semiconductors have a unique ability when a photon strikes it which is why silicon is used as the cell material. When a photon strikes the P-N junction with enough energy, it can knock electrons from their atomic bonds (crystal structure), leaving an electron and a hole, both free to move. The electron will be attracted towards the N layer while the hole will be attracted towards the positive layer. As more photons strike the P-N region, more electron hole pairs will be free to move. The positive layer will increase in positive charge while the negative layer will increase in negative charge, increasing the potential difference between the two layers. Since the potential difference is so high, if a wire is connected to the two conductive layers, electrons will flow from the negative layer to the positive layer creating a current.

Semiconductors are naturally reflective, therefore an anti-reflection layer is placed on the top layer to optimize efficiency and avoid photons reflecting from the surface of the material and not being used. The photons must be absorbed in the P-N region. Solar radiation is made up of photons of varying energy. In the electromagnetic spectrum these are wavelengths known as visible light, ultraviolet and infrared. Of these wavelengths, only visible light can be absorbed, therefore photovoltaic cells cannot harness the maximum amount of energy from the sun. This is because only certain energies can remove an electron from its crystal structure. This is known as the "bandgap" energy. Any photon with an energy below that bandgap energy cannot remove the electron from its structure and a photon with energy above the band-gap energy will be converted to heat and is considered wasted energy. This bandgap of the semiconductor material greatly effects the efficiency of the PV cell.

C. *Optimizing Efficiency*

A problem with photovoltaic cells is the efficiency of them. While these cells have a large history and the technology has been known for over a century, the development of this technology is relatively new and has progressed mostly in just the last 20 years. This development is usually tasked with increasing the efficiency of the cells which depends on a number of things. Firstly, the bandgap of the semiconductor effects the range of photon energies that knocks electrons from their structure. Secondly, not all electrons that are free to move will be accelerated sufficiently to reach the conductive layers. This can be prevented depending on the purity of the semiconductor used.

Silicon is the most widely used semiconductor for PV cells due to its abundance and relatively low price compared to other semiconductors like gallium which has been used for more efficient solar panels. The most efficient PV cell ever made is currently at 47.1%, a six-junction solar cell developed by the National Renewable Energy Laboratory (NREL)[4]. However, most commercial PV cells range from 15 to 20 percent[]. The cells in that range are made from silicon and are either polycrystalline or monocrystalline structured. Polycrystalline structured cells are blended from multiple silicon sources whereas monocrystalline cells are from a single source. This makes monocrystalline cells more efficient as it is purer and have less imperfections than polycrystalline. There are more technologies being developed like thin film PV cells which are much cheaper than other silicon cells but are also less efficient. They are used for large scale projects with a cost-effective option.

Another factor that effects efficiency is the angle the panel is at compared to the sun. The photons from the sun need to strike the cell perpendicularly to energize more electrons. Producers are experimenting with sun tracking solar panels so that the panels are perpendicular to the sun and more energy is converted. Large producers are competing each year to increase efficiency in their solar panels which means we should see higher efficiencies in both commercial and experimental sectors, leading to more sustainable energy in the future.

III. Other Forms of Energy

Due to more competition and awareness of global warming, the total power from solar energy is increasing each year. According to the International Energy Agency (IEA) the average annual growth rate of solar power supply from 1990 to 2018 is 37% [5]. It is the fastest growing renewable energy source, adding an average 125 GW of energy capacity per year.[] Despite this, there are many troubles with the future of solar power.

As previously mentioned, the efficiency of solar power is low. Another thing that makes this worse is that solar power is extremely dependent on the environment around it. A glaring feature of solar power is how it can only be generated when the sun is out so it does not generate anything at night. Furthermore, if sunlight is blocked by clouds then that also limits the power generated by the solar panels. This may not be a huge issue for commercial use when used on rooftops for a household, solar battery banks can be used to store electricity for future use. However, without serious development and investment, solar power would not generate the sufficient energy needed to power an entire grid in place of current energy sources like coal or nuclear.

Another issue for solar power is the costs associated with it. It is the most expensive source of renewable energy and also uses far more space than other sources when not used on roof tops. While technologies like thin film and solar islands are being developed to fix that issue, solar power has the smallest power production per area. The costs associated are a problem as the geographic locations with the most sunlight and highest solar energy potential are countries around the equator, which are unfortunately less wealthy than other countries, therefore countries in Africa who experience the hottest climate produce very little to no solar power. Although, an advantage to solar power is that it can be used almost anywhere as it does not have to connect to an electrical grid, it can store energy so that if a solar farm can be built in the Sahara desert, the power obtained there can be stored. Although, solar energy storage can also be expensive.

As of 2018, according to the institute for sustainable energy policies (ISEP), hydro energy is the largest supplier of renewable energy at 8% of all energy production, compared to solar at 6.4%, wind at 0.8%, biomass at 0.7% and geothermal at 0.2%. Hydroelectricity has a long history and while it is still the largest sustainable energy supplier, solar panel expansion rates are much higher and will overtake to become the largest supplier.

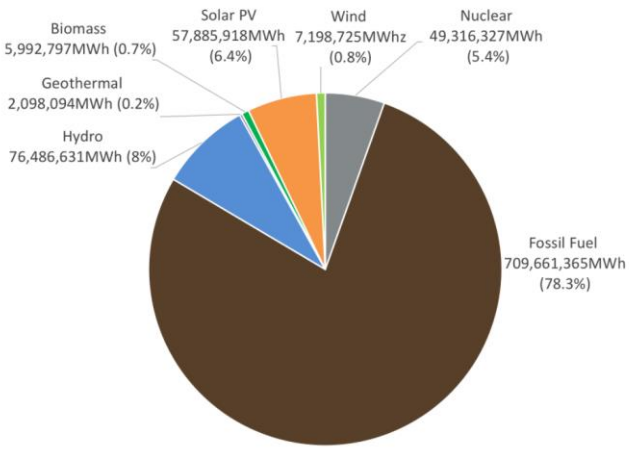

Figure 2: Chart Showing the Ratio of Renewable Energy Sources[6]

Hydroelectricity sources convert electricity using the kinetic energy from moving water. They produce large amounts of energy without depending on climate conditions like wind and solar and they can manually adjust the amount of energy produced and can turn on and off instantly to meet alterations in demand. Furthermore, sources like dams have a very long life cycle and low maintenance costs, making it cheaper and more accessible to run. However, much like other renewable energy sources, they are geographically dependent, they must be at a location for water to travel but not any oceans or seas. In addition, they are harmful to many ecosystems. While they have low maintenance costs and long life cycles, they are very expensive to build for upfront costs.

Wind energy has a large contribution to sustainable energy supply, wind turbines convert the kinetic energy from the win to generate electricity. This can be on-shore or off-shore but are usually far from populous areas. This makes wind energy a useful source for rural areas, as electricity can be distributed there from the turbines rather than through long transmission lines from power plants. The fact that wind turbines can be built offshore in the sea is a huge advantage compared to solar as there is no shortage of space in waters. Furthermore, wind energy can be harnessed day or night, it is not dependent on the time like solar panels. Like hydroelectricity sources, it generates more electricity than solar cells and are also very low maintenance after being built. On the other hand, wind is very unpredictable and unreliable as an energy source, it may produce lots one day but very little the next. While solar power is also dependent on the environment around it, weather forecasts can be used to predict the likeliness of clouds, whereas wind is a lot harder to predict. Also, the turbines could be damaged by environments surrounding it like wind, water and lightning. Like the hydroelectricity sources, wind turbines can damage ecosystems and can harm flying wildlife. Wind energy could not practically be used as the main power supply to a large population since the turbines are so remote, long transmission lines would be needed to distribute electricity.

Geothermal energy is a great source of renewable energy as is very efficient and is a reliable source of energy compared to wind and solar as it is not dependent on the environment around the plants. It uses thermal energy from sub-surface areas, usually to produce steam which turns a turbine. However, there is a possibility of depletion for geothermal sources with some locations cooling down over time. This is made worse by the large upfront costs associated with building geothermal plants.

Other sources like biomass energy are considered renewable but can be extremely dangerous for the environment as it involves the burning of 'agricultural waste' to either heat things or create steam to turn a turbine. This is dangerous as it releases greenhouse gases to the atmosphere, while it can be a good short-term solution, the reason for the development of renewable energy sources is to combat global warming.

Due to issues involving other renewable and sustainable energy sources, solar energy is the best option for future energy production. This is because the technology is constantly evolving, there is a much higher potential for solar power compared to others where there is little to no room for improvement. Solar energy is also good for the environment and it combats global warming, there are no greenhouse gases produced in converting solar energy to electrical energy. While there is some pollution in making PV cells and the transportation of solar panels, it is miniscule when compared to non-renewable sources as well as most renewable sources. Furthermore, it could also help consumers financially. If every household had solar panels, it would drastically reduce demand for electricity from the grid as well as significantly reduce energy bills. The capital saved through harnessing solar energy could lead to investment in increased development through quantum physics or nanotechnology to increase their efficiency or diversify applications. The same cannot be said for other sustainable energy sources.

REFERENCES

[1] G. Boyle, "Renewable Energy: Power For a Sustainable Future", 2012

[2] The Renewable Energy Hub UK, "History of Solar PV", https://www.renewableenergyhub.co.uk/main/solar-panels/the-history-of-solar-power/, 2020

[3] Jason Svarc, "Solar Panel Contruction", https://www.cleanenergyreviews.info/blog/solar-panel-components-construction, 20th March, 2020

[4] John F. Geisz, "Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration", 13th April 2020

[5] IEA, "Renewables Information: Overview", https://www.iea.org/reports/renewables-information-overview, July 2020

[6] ISEP Energy Chart, "What is the ratio of renewable energy in 2018?" https://isep-energychart.com/en/1105/#:~:text=The%20share%20of%20renewable%20energy,of%20nuclear%20power%2C%205.4%25, 2nd July, 2020

Electrical Power Systems Coursework

Smart Grids – Electric Vehicle Grid Impact

For this part of the report, I used the Siemens PSS/E software to design a smart grid and simulate what impact electric vehicle chargers at certain points had on the rest of the grid. The smart grid can be seen in figure 3.

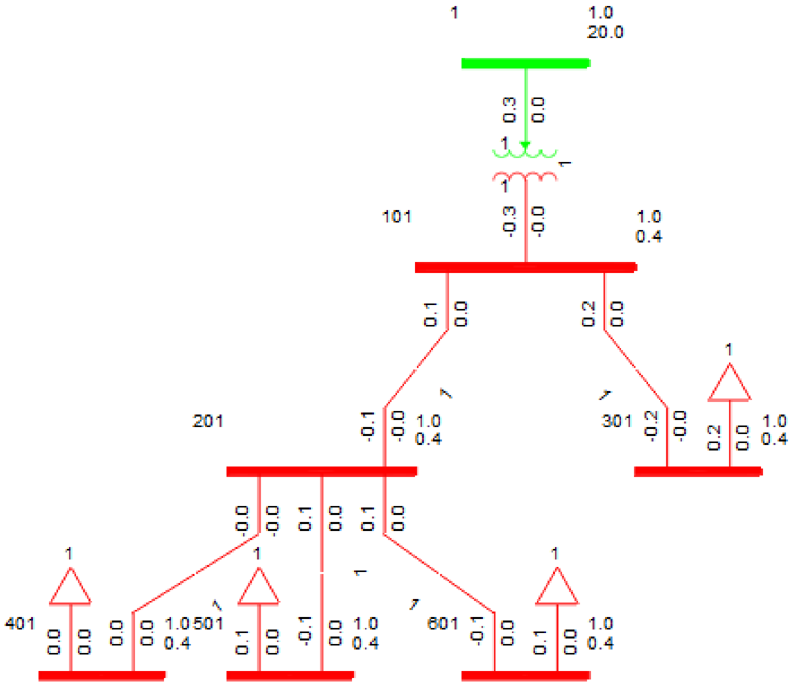

Figure 3: Diagram of smart grid designed on PSS/E to simulate power flow

As per specifications, I designed the grid to have 4 loads at particular places which act as the charging points for the electric vehicles. At each load there is a power rating of 36.8 kW (0.0368 MW). This is the power rating required to supply 10 electric vehicle chargers (230V x 16A x 10). Furthermore, each transformer, busbar and branch were designed according to their per-unit specification. Once the grid was fully designed, I could simulate it by performing a power flow. The results of which are as follows.

Busbar Number	Per-Unit Voltage (V_{pu})	Angle (deg)
1	1.0000	0.00
101	0.9985	-0.34
201	0.9726	-0.80
301	0.9899	-0.49
401	0.9640	-0.95
501	0.9640	-0.95
601	0.9640	-0.95

Table 1: Values obtained from power flow for 10 chargers at each load

This data shows us the per unit voltage at each busbar after the power flow operation is performed. Per-unit values are useful as it allows easier analysis of complex power systems by simplifying calculations and reducing theoretical complexities. The general formula:

$$\text{Per unit value } = \frac{\text{Actual value in any unit}}{\textit{Base value in any unit}}$$

The base values at each level were given in the specification with the base power being 1 MVA for the entire system, the base voltage at busbar 1 being 20 kV and after being stepped down by the transformer, the base voltage for the other busbars was 0.4 kV. The per-unit values change based on the resistance and reactance of the branches which is why busbar 1 has $V_{pu} = 1$. The base voltage given is equal to the actual voltage in the system as there are no impedances yet. The other per-unit voltages were lower than 1 due to the actual voltage being slightly higher than the given base voltage. This is because of the resistance and reactance in the transformer and the branches, according to ohms law, voltage is proportional to resistance. The angles shown above represent the difference in phase of each voltage, the waveform is at a different phase at each level.

A common technique used in industry is to set statutory limits so the voltage cannot reach levels too high or low. If we used statutory limits of +10%/-6% of 1.0 pu, the voltage at each busbar would be within limits and satisfactory. If they were under 0.94 or above 1.1 then you must reassess the design and change the power ratings at each load.

Now that a power flow has been performed for this system, the maximum number of chargers for each busbar could be calculated. This number would change depending on what charger is specified as different chargers have different power ratings. For this exercise, electric vehicle chargers selected were:

- Type 2, 16A
- Type 2, 32A,
- CHAdeMO, 62.5 kW

Firstly, the power ratings needed to be calculated. The type 2 charger receives a single-phase voltage of 230 V[7] and a current of 16 A gives a power rating of 3.68 kW. This is the same charger used in the first exercise. The same type 2 charger but with a current of 32 A gives a power rating of 7.36 kW, double the power of the previous charger. The CHAdeMO charger has a power rating of 62.5 kW as stated in specification.

Busbar Number	Number of Chargers	Power (MV)	Voltage (V_{pu})	Angle (deg)
1	N/A	N/A	1	0
101	N/A	N/A	0.9955	-0.94
201	N/A	N/A	0.9541	-1.67
301	60	0.2208	0.9404	-1.92
401	15	0.0552	0.9404	-1.92
501	15	0.0552	0.9404	-1.92
601	15	0.0552	0.9404	-1.92

Table 2: Outputs from power flow operation for type 2, 16 A chargers

Busbar Number	Number of Chargers	Power (MV)	Voltage (V_{pu})	Angle (deg)
1	N/A	N/A	1	0
101	N/A	N/A	0.9956	-0.91
201	N/A	N/A	0.9572	-1.59
301	30	0.2208	0.9405	-1.9
401	7	0.05152	0.9444	-1.83
501	7	0.05152	0.9444	-1.83
601	7	0.05152	0.9444	-1.83

Table 3: Outputs from power flow operation for type 2, 32 A chargers

Busbar Number	Number of Chargers	Power (MV)	Voltage (V_{pu})	Angle (deg)
1	N/A	N/A	1	0
101	N/A	N/A	0.9964	-0.75
201	N/A	N/A	0.9656	-1.29
301	3	0.1875	0.9502	-1.58
401	0	0	0.9656	-1.29
501	1	0.0625	0.9502	-1.58
601	1	0.0625	0.9502	-1.58

Table 4: Outputs from power flow operation for CHAdeMO, 62.5 kW chargers

From these results, we can see that for every charger, the voltage at each busbar is within statutory limitations with no value reaching above 1.1 or below 0.94 V_{pu}. In order to find the maximum number of chargers, hence the maximum power rating at each load, a trial and error solution was used. The process was as follows:

1. In network tab, reset all V_{pu} values to 1 and angles to 0.
2. Set loads on busbars 401, 501 and 601 to 0 MV so that only the load on busbar 301 is tested.
3. Set load on busbar 301 to power rating equal to a certain number of chargers.
4. Perform power flow operation multiple times until values stabilize and do not change
5. Observe V_{pu} value, if $V_{pu} > 0.94$ then increase power rating on load by multiples of the charger rating (e.g. one charger = 36.8 kW, increase by multiples of 0.00368 MW) and repeat steps 1 and 4 until V_{pu} reaches 0.94 without going below that value.
6. If $V_{pu} < 0.94$, decrease power rating on load by multiples of the charger rating. Repeat steps 1 and 4 until V_{pu} goes above 0.94.
7. This is the maximum number of chargers at that load for busbar 301. The maximum number of chargers for the other 3 loads should be the same at each busbar, therefore set a power rating at each load. Perform a power flow operation multiple times and apply the same trial and error technique in steps 5 and 6 to find the max number of chargers for loads at busbars 401, 501 and 601.
8. The chargers can be set in any configuration as long as the max number of chargers are found for the entire system, therefore if any values are below 0.94, adjust power ratings for one of the four loads to observe effect on the other loads.

System Analysis

Using this trial and error technique allowed the calculations for the maximum number of chargers in the system. We can see from tables 2-4 the max number of type 2, 16 A chargers was 105 for the entire grid. The max number of type 2, 32 A chargers was 51 and the max number of CHAdeMO chargers was just 5. For this exercise, a particular trial and error solution was used however there are a variety of methods to obtain this metric.

A study like this is extremely important as it allows the simulation of smart grids so the effects that different components have on the rest of the system can be observed. In the process of working out how many chargers the grid could handle without going over statutory limits, it was difficult to change one component as it had a large effect on other components in the system. This is an issue with power flow systems and is a reason why this study is so important. For the smart grid simulated in this exercise, it is relatively easy to calculate the maximum power rating available to each load by calculating the per-unit voltage at each busbar from per-unit impedance values in the branches and transformer. However, for more complex and realistic power flow systems where there may be 1000s of loads connected different ways, an approach like this could be a fast and useful approach.

Whatever way results are obtained, it is important to produce these studies because smart grids are used for large populations including households and businesses. As stated before, a load in one place can greatly affect other loads, therefore a fault in the system at one location will impact other points in the system. In a practical scenario, a fault in the system at one location could impact consumers miles away. Therefore, before building or changing design to a smart grid, it is vital to simulate the power flow like this report has demonstrated.

In regard to the exercise in this report where the smart grid is designed to supply power to EV chargers so that consumers can charge their cars, we need to find the maximum number of chargers to stay within statutory limits (+10%/-6%). These statutory limits ensure the voltage is stable throughout a system. A per-unit voltage close to 1 towards the power source of the grid, means there is more voltage power available lower down further away from the power source since the electricity must travel through transmission lines with impedances. For example, reducing the power rating for the load on busbar 301 means the power ratings for the other 3 loads can be higher, they are further from the power source than the load at busbar 301. “For a smooth functioning of any generic smart grid type system, correct behaviour of all these independent entities must be preserved when one or more of these entities are subjected to various loading levels. Correct behaviour of all the entities (sub-systems) will ensure correct behaviour of the overall system (smart grid)”[8]. Statutory limits in industry are set by regulatory authorities, in Europe the standard EN 50160 allows a tolerance of ±10% of the nominal voltage.

The consequence of using loads drawing more power than the max power found in the exercise, is that it could cause not enough power being supplied to another point in the grid, which could be extremely dangerous depending on the source drawing its power, e.g. a hospital. Therefore, when designing smart grids, it is extremely important to complete a study as has been done in this report, otherwise power supply may be insufficient at any location on the grid or the voltage could be unstable.

References

[7] Spirit Energy, “Understanding Electric Car Charging”, https://www.spiritenergy.co.uk/kb-ev-understanding-electric-car-charging

[8] Tamal Paul, Harsha Ravindra, Michael Steurer, Jonathon W. Kimball, “Voltage stability preserving invariants for smart grids”, https://ieeexplore.ieee.org/document/7064878, February 2020