Energy Recovery From Landing Aircraft

by

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Abstract

Currently, renewable energy sources are the main driver for future electricity generation. This trend is growing faster in the developed countries in order to reduce the greenhouse effect and also in response to the limited supply of oil, gas and coal which are currently the major sources for electric generation. For example, the main renewable energy sources are from wind energy and solar energy but these energies are only available to those countries that are exposed to these resources. In this thesis an alternative energy source is investigated where it can be generated from the moving objects or in form of kinetic energy. The idea is to convert the kinetic energy during landing aircraft into electrical energy which it can also be stored and transferred to the existing electrical network. To convert this kinetic energy to electrical energy, the linear generator (LG) and uncontrolled rectifier have been used for energy conversion. The LG have been modelled in 3-phase model or in $dq$ model and combined with the diode rectifier that is used to generate the dc signal outputs. Due to the uncontrolled rectifier the electrical outputs will have decaying amplitude along the landing time. This condition also happen to the LG outputs such as the force and the power output. In order to control these outputs the cascaded buck-boost converter has been used. This converter is responsible to control the output current at the rectifier and also the LG output power during landing to more controllable power output. Here, the $H^\infty$ current control strategy has been used as it offers a very good performance for current tracking and to increase the robustness of the controller. During landing huge power is produced at the beginning and when the landing time is increased, the generated input power from LG is reduced to zero. Due to this, the energy storage that consists of ultracapacitor, bidirectional converter and boost converter are used in order to store and to release the energy depends on the input power source and load grid power. The voltage proportional-integral (PI) control strategy has been used for both the converters. The last part is to transfer the energy from the source and at the ultracapacitor to the load by using the inverter as the processing device. The power controller and current controller are used at the inverter in order to control the power flow between the inverter and the grid. This is when the reference power is determined from the load power in order to generate the reference current by using the voltage oriented controller (VOC), while the $H^\infty$ current controller is used to regulate the inverter current in order to inject the suitable amount of current that refer to the load power. Finally, a complete energy recovery system for landing aircraft with the grid connection have been put together to make the whole system to be as a new renewable energy source for the future electricity generation.
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List of Abbreviations

ac    alternating current
CB    Circuit breaker
CBB   Cascaded buck-boost
dc    direct current
dq    direct-quadrature
ERLA  Energy Recovery From Landing Aircraft
FIT   Feed In Tariff
G     plant
K     compensator
LG    Linear generator

PI    proportional-integral
PLL   Phase locked loop
PWM   Pulse width modulation
RHI   Renewable Heat Incentive
VOC   voltage oriented control
Chapter 1

Introduction

1.1 Motivation

Electrical energy is the fundamental and main energy source which makes the world move forward. This energy can be generated from heat, transportation and natural resources such as coal, oil, gas, wind, solar and etc. Most electrical energy that generates today is from coal, oil and gas sources where it has been used for over a century ago. Currently these sources are reducing faster than before and it has triggered a new electrical energy exploration that generates from the renewable energy sources, where it needs to be done quickly and continuously in order to meet the increasing energy demands. Most of the developed countries have explored these renewable energy sources such as wind power, solar power, tidal power and have put this task in their mainstream growth, and also included it in the annual budget to encourage people to exploit these free resources.

For example, the UK government has developed the energy policies to meet, to reduce and to promote the energy consumption in 2007 and than in 2009 to increase the usage of the renewable sources as a electrical energy source. It suggests that the electricity generation from renewable energy sources needs to increase to 30% by 2020 compared to 6.7% [1] of the generation today which includes both centralised and small-scale generation. In doing so, the government will spend around 660 million pounds [1] to achieve this target. On the other hand, the UK government has also agreed to create a system that is called the Renewable Heat Incentive (RHI) and the Feed In Tariff (FIT) for electricity generation less than 5MW, which is suitable for organisations, businesses, communities and individuals that are not involved in the electricity market in order to supply electricity to the main power grid [1]. These initiatives mean that the power system configuration is undergoing tremendous changes in order to be able to accept power generation from renewable energy resources. The other reason why the government has put these initiatives into practise is to reduce the levels of carbon dioxide
(CO₂) released to the atmosphere that causes the global warming. This situation has caused the Earth to become warmed by about 0.8 degrees per decade compared to the last 30 years which about 0.2 per decade [2]. As a result of this, the UK in 2007 has seen the warmest year compared to the previous decade. This issue needs to be solved and it has driven more renewable energy technology into action.

Alternative energy resources are also part of the renewable energy sources, and include the sources from waste energy such as kinetic energy which have no undesired consequences after generation. From the energy law, energy cannot be eliminated but it can be changed to another form of energy. Due to this concept regenerative braking has been introduced into vehicles. This is where the kinetic energy can be changed to electrical energy when the vehicle is slowing down. The energy produced here is small due to the low inertia and is only suitable for use in the vehicle operations such as initial start or small mechanical works. From this concept, huge amounts of energy can be produced and changed if high inertia can be stored in the vehicle. This has lead to using aircraft during landing as a source which stores huge kinetic energy which currently has been wasted as heat.

As a result, this research is undertaken in order to recognise, understand and process this alternative energy source that is generated from the landing aircraft and is changed to electrical energy in order to increase the power generation target set for the renewable energy sources and at the same time reduce the greenhouse effect on the environment.

1.2 Aim and Objectives

The aim of this research are to evaluate the feasibility of converting the kinetic energy to electrical energy, and to supply this energy back to the electrical network by using the landing aircraft as an alternative energy source. In order to achieve this aim, four objectives are defined:

1. To study the components that can be used for converting, storing and transferring kinetic energy to electrical energy;

2. To change the generated power during landing by controlling the LG current in order to minimise the uncomfortable condition to the passenger by maintaining the force generated from the LG;

3. To develop the control strategies that can be used to control the generated power, to allow the power flow between the energy components and to transfer the generated power to the load;
For objective 1, it can be done by determine a suitable generator, the storage element and the power processing devices that can be used in order to change the kinetic energy to electrical energy. The arrangement of each devices is based on the distribution generation connection which is suitable to transfer the energy from the renewable energy sources to the existing electrical network. The second objective can be achieved by finding the relationship between the generated power and the output current of the LG which is determined by the landing speed. This relationship will minimise the operation cost because no speed sensor will be used in order to control the generated power during landing. At the same time it can also control the braking force generated by the LG which determines the comfort of the passengers in the aircraft.

Finally, the selection of the control strategy needs to be conducted based on objective 1 and 2 in order to have the power flow from the source to the load. The chosen controller also needs to respond to the variable magnitude inputs, disturbances and gives robust conditions.

1.3 Outline of the thesis

The concept of converting kinetic energy to electrical energy involves several parts, such as the energy conversion part, the energy storage part and the energy transfer part. The energy conversion part is described in The modelling of the linear generator for energy conversion chapter and The $H^\infty$ current control design for the energy conversion chapter. There is one chapter for the energy storage and one chapter for the energy transfer. All of these are organised as follows.

Chapter 2 is about the literature review where it explains the functions of the components and the control strategies that will be used to develop the ERLA configuration. As an addition, the $H^\infty$ control theory has been summarised in order to help to build the control application for the dc-dc converters, and the inverter that will be used in this work.

Chapter 3 is about the energy conversion process that is related to the energy conversion from kinetic energy to electrical energy by using the LG and the rectifier. This linear generator will be modelled in a 3-phase model and in a $dq$ transformation model to behave as the LG machine to see the electrical and the mechanical outputs response for the LG where uses the landing speed as the input parameter. The LG models have been modelled in the MATLAB simulink software where both models show the same results. This indicates that both models can be used as the LG model in the ERLA system network.

Chapter 4 covers the control part of the energy conversion, and at the same time will control the LG outputs. The main function for this part is to control the deceleration,
force and the shape of the generated power by only controlling the input current at the converter side. These parameters have been given more attention in order to determine the success of the control strategy. The cascaded buck-boost converter with the current control topologies is designed by using the $H^\infty$ control theory. This is where the converter can respond to the wide input range of voltage that is coming from the LG outputs.

The energy storage section that consists of the energy storage element and the dc-dc converters are explained in Chapter 5. In this chapter, the amount of energy that needs to be stored in the storage elements has been calculated and it depends on the maximum generated power. The bidirectional and boost converters have been selected in order to achieve the target for these converters with the proportional-integral control as the control strategy.

In order to transfer the energy from the source and with the energy from the storage element to the electrical grid network, a 3-phase inverter has been used which is explained in Chapter 6. This chapter also includes the design steps for the LCL filter calculation. The $H^\infty$ current control has been used to deal with the current control and the voltage oriented control-proportional-integral (VOC-PI) for energy transfer process. Attention is paid at the power output transfer in response to the power changing at the load in order to determine the effectiveness of the control strategy that has been proposed.

Finally, the main conclusions of the thesis are summarised and possible future works are proposed in Chapter 7.

1.4 Contribution of the research

In this research, the contribution to knowledge is based on the control strategies applied to the ERLA system in order to transfer the kinetic energy from the landing aircraft to the electrical energy at the grid.

1.4.1 Energy conversion

Here, the main contribution of the ERLA is to change the instantaneous power which has exponential decay graph where it is normally generated during the landing, to a more useful information/graph that can be used to determine the average power with a linearly decreasing graph. To obtain this condition, the generated force from the linear generator must be constant, which will create the linear decreasing power graph [3]. This force also relates to the braking force which is applied to the passenger. During normal landing, the aircraft generates its own force while the braking force is applied
in the opposite direction to the landing force. By maintaining this braking force the passengers will not feel any discomfort during landing. In order to control this force, the deceleration control needs to be used. For the ERLA system, no control action will be used at the LG in order to reduce the number of the controllers applied to the system. This action is taken by the dc-dc converter, which is one of the power processing devices in the energy conversion part. The current control strategy has been used as the controller, due to the relationship between the input current, the force, the power and the deceleration. This is when the input current is controlled at the dc-dc converter, and at the same time it is capable of controlling the force and deceleration at the linear generator. For the current controller design, the $H^\infty$ control theory has been used as the current control strategy. This is because, it is capable of giving small tracking the error between the feedback input current at the dc converter with the reference current and it is also able to respond to the wide output voltage generated from the LG.

1.4.2 Energy storage

Energy storage is used to temporarily store the energy when the source energy is higher than the load, and to discharge the energy when the load required more energy than the main source can supply. For the ERLA, the energy conversion target is to deal with the input current but not the output voltage at the dc-link. If there is no voltage control applied at the dc-link, the energy storage can only store the energy without having the ability to discharge the energy back to the load when it is required. Due to this, the voltage control at the dc-link connection between the energy conversion and the energy storage can be applied at the bidirectional converter. In the meantime, this controller will give freedom to the storage element to store how much power regarding to the rated energy. In doing so, the proportional-integral control has been used due to the maturity of the controller.

1.4.3 Energy transfer

It is used to transfer the generated energy from the landing aircraft and the storage element to the grid. The voltage oriented control has been used for the power control strategy and it is combined with the $H^\infty$ control theory for the current controller in order to have the energy flow between them. The reason why the $H^\infty$ control theory has been selected is because the compensator value that has been designed is included the LCL filter components in the compensator calculation. By including these components, the controller that has been designed is more robust where it has a large bandwidth, and is capable of responding to the wide range of LG outputs. At the same time, it can also minimise the tracking error. Finally, all the parts are combined together to
model the complete ERLA system and it shows that the kinetic energy from the landing aircraft can be converted, stored and transferred by using the proposed controller given in this work.

1.5 Concluding remarks

The main motivation that triggers this work is to increase the capacity of the renewable energy sources in order for them to be the main sources of electricity generation in the future. By using more and more renewable energy sources the dependency on oil and gas sources can be reduced dramatically and at the same time this can reduce the CO$_2$ emission to the air and make the environment more healthy. The alternative energy which is the kinetic energy that has been left behind can be the new energy source for renewable energy source. This is because more heavier and more high speed systems have been built for vehicles today, which is the main source for kinetic energy. Normally this energy has been wasted as heat without any action to recover it. This has lead to the aim of this research is to convert the kinetic energy from high speed vehicles such as aircraft when they start to landing to electrical energy. To achieve this aim, several objectives have been listed in order to capture, to store and to transfer the energy to the existing electric network. While conducting this research several contributions have been found but the main contribution of this research is the relationship between the input current at the dc converter with the force and the power output for the LG which can reduce the number of controllers that will be used in ERLA system. This is achieved by using only one controller at the converter side which is capable of controlling the LG outputs.
Chapter 2

Literature Review

2.1 Alternative energy sources as renewable energy sources

Alternative energy sources can be divided into six categories which are chemical energy, thermal energy, kinetic energy, nuclear energy, rotational energy and solar energy. Chemical and nuclear energy are created due to chemical reactions and require a combustion to generate the electricity. These energies create air pollution and require a control environment to operate. However, these energy sources can generate high amounts of electric power with continuous supply. Thermal, rotational and solar energy are natural sources of energy that can be found in the environment and are free sources. The limitation for these energies is due to the location of the source. For example, wind turbines are most likely to be used in north European countries such as Denmark, the UK and Norway which are exposed to strong windy conditions in order to generate the electricity, while countries that are exposed to high solar radiation such as Mexico, Australia and the United States use more solar energy sources to supply electricity to the electric network. The electricity production from these sources is not constant and needs a power tracking function to maximise the electricity production. Regarding [4, 5] the other type of alternative energy comes from waste energy. This waste energy can be obtained from food waste or biomass waste. Kinetic energy can also be categorised as a waste energy. This kinetic energy can be found when there is a movement from one point to another point. This energy can be found in small amounts from water drops or in large amounts as in high speed vehicle.

According to the Defense Advanced Research Projects Agency (DARPA), humans can generate around 1 to 2 watts of energy when they walk. This indicates that humans can also generate electricity. Research has been conducted by [6], which converts walking energy to electric energy using the microgenerators made for military purposes. As is known, a normal soldier in service at the war zone will carry around 7.5kg to 13kg of
battery to power up military equipment such as night vision goggles, radio communication and other electric equipment [6]. By replacing the battery with a microgenerator the weight carried by the soldier is reduced dramatically. Electrical energy is produced due to the inertial body mass and the walking speed of the soldier. Imagine when huge amounts of mass found in high speed objects it will create huge amount of kinetic energy.

Here, this concept has been expanded to regenerative braking for vehicles. For vehicle purposes, it converts kinetic energy to electrical energy when the vehicle starts to slow down [7, 8]. In this mechanism, the motoring operation is changing to generator operation in order to store the energy inside the battery and will be used for the next acceleration cycle of the vehicle. This application has been applied in the hybrid car concept such as in the Toyota Prius and other new generations of car in order to reduce the CO\textsubscript{2} emission to the environment.

Looking at the bigger picture, for huge energy production, this concept can be applied to the airline industries. This is where the kinetic energy created during the aircraft landing is converted to electrical energy [9, 10]. In the mean time, this electrical energy can also be stored and used for the taxiing or takeoff process where it will reduce the pollution at the airport, such as noise pollution. It also will reduce the fuel cost since the amount of fuel burning during takeoff can be minimised and the aircraft can carry less fuel for long distances. In order to harvest this potential energy from the landing aircraft, the configuration of the distributed generation structure can be used to change, store and transfer this kinetic energy to electrical energy for usage at the load side.

2.2 Introduction to distributed generation (DG) for renewable energy sources

DG is an electric power generation which is located near to the load/ electrical grid in order to reduce the losses along the transmission line that happen in power generation by the synchronous generator, or to improve the voltage or current at the distribution network. This configuration is suitable for renewable energy production where the power generated can be connected directly to the load without having transmission losses. To convert the renewable energy to electrical energy, a power conditioning process is needed. It uses several power converters as shown in Figure 2.1. It often consists of an ac-dc converter, a dc-dc converter and a dc-ac converter. The advantages of using these converters are: they are easy to develop, and the control methods are easy to model with regards to the objective of the converters. The generator is used to change
the mechanical inputs to electrical outputs. Figure 2.1 shows an example of renewable energy sources that use the DG structure. The energy storage system is used next to the converters, and the generator, in order to provide a place to store the excess energy and also to supply the power when the load demand is higher than the amount of power that can be provided by the source. The filter and transformer in Figure 2.1 are used to connect the DG to the grid without affecting the voltage and current at the grid. The filter, such as inductor (L), or inductor-capacitor (LC), or inductor-capacitor-inductor (LCL), can be applied to reduce the injected harmonic current to the grid by the inverter.

![Diagram of renewable energy source in DG connection](image)

Figure 2.1: Example of the renewable energy source in DG connection

Examples of renewable energy sources that can be applied to the DG are wind energy, solar energy, fuel cell energy and alternative energy sources. These sources can be separated into two types of electrical output generation: the ac output source or the dc output source. Figure 2.1 shows these two kinds of electrical output. The only difference between them is that the generator block is used for ac output generation and not for dc output generation. In order to harvest the energy from renewable sources, power tracking control is needed, and it is a challenging task for the researcher because different sources need different methods of control. For example, wind and solar energy require maximum point power tracking in order to generate the maximum electrical output power, while for the wave energy this is determined by the motion of the point absorber [11].
As is known, the power generated from renewable sources is currently lower than the power generated from the synchronous generator. Because of this, the DG cannot be operated alone. By connecting several of them to the existing distribution network, a micro-grid can be formed as shown in Figure 2.2. This micro-grid will give a continuous and level amount of power supply from other renewable energy sources placed in the electrical network. The circuit breaker (CB) is used to disconnect or to connect other power sources to the existing electrical network. In the mean time, a single DG configuration is more suitable for use at the remote area where the electricity network is not available or difficult to reach by the transmission network.

Other than grid connection, the DG can also be connected directly to the load or can be the main power source to the load. This kind of DG connection is known as the islanded mode. The islanded mode is basically used for small scale power supply while at the same time it is able to reduce the amount of carbon emission to the environment [12]. To understand the DG’s operation under the renewable energy source configuration more clearly, the DG system can be separated into three parts. The first part is the energy conversion, the second part is known as the energy storage, followed by the energy transfer part.

![Diagram of DGs in micro-grid connection](image)

Figure 2.2: DGs in micro-grid connection

### 2.3 Energy conversion

The idea behind the energy conversion is to convert/harvest the maximum generated power from the renewable energy sources. For example, wind is used for wind turbine generation and solar radiation for solar energy production. Both of the sources come from the environment and cannot be controlled, which will affect the output power. To help to control this power, a power conditioning configuration can be used as shown
in Figure 2.3; this uses wind as a source and consists of a synchronous generator, a diode rectifier and a dc-dc converter. For the wind turbine generator, it is most likely that the wind energy can be converted to electrical energy by using the Doubly Fed Induction Generator (DFIG), the synchronous generator and the permanent magnet synchronous generator that have been applied in [13, 14, 15]. The voltages generated from the generator are connected to the diode rectifier and the dc-dc converter in order to control the maximum power generated by the wind source as has been discussed in [13, 16, 17, 18, 19, 20].

This process described is known as Maximum Point Power Tracking (MPPT) and has been discussed widely. For solar and fuel cell renewable energy sources, the outputs are in dc signal and they are not constant due to the varying input source. To obtain the MPPT from this variable dc input power, the dc-dc converter can be used without using the rectifier [20, 21, 22]. As has been stated, the MPPT is related to the input source of the energy but it can be controlled when the control strategy is applied to the power conditioning side. For wind turbine applications, the current at the dc-dc converter can been controlled according to the speed of the generator and it will determine the power generated from the source. This concept, which has been applied to wind energy, can also been implemented in the ERLA configuration. Controlling the output current at the diode rectifier will at the same time control the generated output power from the generator.

![Figure 2.3: Topology of energy conversion in renewable energy source](image-url)

**2.3.1 Linear synchronous machine in energy conversion**

For an aircraft landing application, the linear synchronous machine has gained interest due to the structure, the speed and the precision that can be achieved from it. Linear machines can be separated into two operations: motor operation or generator operation. In motor operation, the linear machine is used for the high precision location that
is needed for the machine tool industry. For high speed systems, it is used in transport
ation such as the Maglev train application [23]. Linear generators are linear motion
electromagnetic devices that transform an oscillatory motion of mechanical energy into
 electrical energy. In synchronous generator operation, the idea of regenerative braking
that converts the energy from vehicle braking into electrical energy has been discussed
[7, 24, 25, 26]. For linear generator machines, regenerative braking is used mostly in
 ocean wave harvesting technology [27, 28, 29, 30, 11, 31] by converting the ocean wave
energy into electrical energy. It is used in wave energy because the linear machine is
capable of directly utilising the linear piston force without the need for an additional
mechanical component, compared to a rotary device that needs a crankshaft mechanism
to change the linear force to rotary torque and then transmit it to the generator.

The linear machine is one where the stator and the rotor of the rotating machine
have been cut and put flat on the surface, but the working principle remains the same
as the synchronous generator. Figure 2.4 shows an example of a linear machine [32].
The advantages of the linear machine are that it drives the linear motion load without
gears, screws or crankshafts, and it can also overcome the problems of stiffness, mass
friction and backlash. It can also create a levitation force between the stator and the
rotor due to a magnetic field which is used in high speed train application.

Figure 2.4: Example of a linear generator

The operation of the linear generator is based on mechanical motion; it generates
a travelling magnetic field flowing in a horizontal direction which creates the induced
voltage at the stator output. It also shows that the travelling magnetic field is equivalent
to the velocity [33] of the speed of the rotor as given in equation 2.1:

\[ v = f_e \beta, \]  

(2.1)

where \( v \) is the velocity of the rotor, \( f_e \) is the exciting frequency in hertz and \( \beta \) is the
winding wavelength. By expanding equation 2.1 between the synchronous generator
with a linear generator, the relationship of them can be given as:
\[ \theta^0 = \frac{2\pi vt}{\beta} = \frac{2\pi z}{\beta}, \]

where \( \theta^0 \) is the rotating mode in the synchronous generator while \( z \) is the displacement for the linear generator. It can be summarised that for the linear generator, \( z \) is the same as \( \theta \) while the force \( (F) \) is the same as the torque \( (T) \) in the synchronous generator.

The concept of the linear generator is based on the travelling magnetic field [33, 34] which has gained interest for high speed applications. This travelling magnetic field is proportional along the landing speed, and it gives an indication that the linear generator is suitable for harvesting the energy during aircraft landing. For the ERLA structure that uses the linear generator structure, two techniques can be applied to the landing process as shown in Figures 2.5 and 2.6. Both figures illustrate the arrangement of the stator and the rotor during landing. For the first technique, the rotor is used as a park platform for the aircraft when it lands as shown in Figure 2.5. Here, the aircraft will move on the platform and it will move together with the rotor during landing. In the meantime the stator can be placed underneath the runway to capture this kinetic energy and change it to electrical energy.

![Figure 2.5: First technique of LG configuration in the ERLA application](image)

The second technique is by pushing the rotor along the runway which is shown in Figure 2.6. This technique gives more advantage compared to the first technique in terms of safety. This is because the landing speed can be controlled by the pilot.
For example when the condition of the runway is slippery or wet the pilot can release more breaking force in order to control the vehicle. For both techniques the slot-less permanent magnet is used as a stator while the rotor consists of coil [9].

Figure 2.6: Second technique of LG configuration in the ERLA application

Many controllers can be applied to the linear generator depending on the function of the machine. The linear generator control in wave energy technology has been discussed here where it has the same function as the ERLA system. Currently, the control topologies for LG in wave technology are by using the power or force control. The power can be controlled if the current at the generator can be controlled [29]. This is done by ensuring that the current is the same as the electromagnetic force in magnitude and phase inside the LG. This will cause the power generated from the LG to be isolated. Other than the power control technique, the LG can also use the force control which is explained in [27, 35, 36, 37]. This force is proportional to the velocity and displacement of the damping spring in wave energy applications. At the same time, this force is proportional to the current generated at the output of the LG. Because of this, by controlling the current, the force will be controlled, and the maximum power from the wave can be extracted [27]. This is where the current controller can be used at the power conditioning converter to extract the maximum power from the input. In [11], the LG is connected to the diode rectifier which will generate variable voltage and frequency at the outputs. Due to these output variables, the dc-dc converters are needed in order to give constant voltage and frequency outputs that can be used as a power source.

This power and force control can also be achieved by using the back to back converter, the rectifier, or the dc-dc converter in [35, 38]. By using these converters, the
control strategy can be made sensor-less to the speed. This is where the controller does not use the information from the speed, but at the same time is able to control the force. This will allow the control strategy to be applied at the power conditioning devices, rather than on the LG. In this case, it is capable of reducing the cost and number of controllers that will be used in the ERLA system application.

2.3.2 DC-DC converter as power conditioning in energy conversion

Wind, solar and fuel cell energy generate fluctuating output power at all times. Due to this, a converter is needed in order to control the output power flow to the storage element or to transmit it to the electrical grid network. In this case, the dc-dc converter can be used to control the power generated from the source and at the same time enable the maximum power point tracking [16, 17, 18, 39, 40]. For wind energy source, the output voltage from the generator contains variable magnitude current, voltage and frequency. This also happens in the ERLA system, where the voltage and current outputs from the LG are reduced to zero which result from the reducing landing speed. This means that at the beginning, the power generated from the LG is at a maximum because this is the time when the maximum landing speed is applied to the LG. After that it will start to reduce to zero. In this case, it will cause the outputs of the LG to be generated with a wide range of input voltages and currents that need to be controlled by the dc-dc converter. Some common dc-dc converters that can be used in wide range input are the boost, buck-boost, SEPIC or Cuk [41] converters. Apart from these, several other topologies can be used which are listed below:

- the single switch or buck-boost converter shown in Figure 2.7a,
- the two switch, as shown in Figure 2.7b,
- the three level boost converter as in [42],
- the cascaded, interleaved and superimposed connection of the converter [43].

The single switch or boost converter is a conventional dc-dc converter that is used in power tracking for wind power or fuel cell power applications [17, 18, 44, 45, 46, 47]. In order to achieve the MPPT, the controller for this converter needs an algorithm to calculate the maximum power which responds to the suitable duty cycle for the converter. In this case, the power function, which consists of wind speed and the previous power, needs to be developed. This converter creates a high stress value on the inductor and the capacitor and it will increase the cost of the converter [43, 48].

The two switches application is more appropriate because the stress of the inductor can be dissipated by reducing the size of the inductor and capacitor, compared to the
Figure 2.7: Example of dc-dc converters that can be applied in energy conversion

single switch dc-dc converter [43, 41]. The cascaded buck-boost converter with two switches, known as the non-inverting buck-boost converter, has been used to regulate the variable input voltage and have non polarity inversion at the output with regards to the input voltage [42, 49, 50, 51, 52, 53, 54, 55, 56]. This structure generates the direct path for the power flow from the input to the converter, and the losses at the inductor are at a minimum [43, 49]. The cascaded converter is shown in Figure 2.8 where it will be focused to the ERLA system.

For the cascaded buck-boost converter, two control strategies can be applied which are the current and voltage control. For the current control, several types can be used such as the sliding mode control with proportional-integral (PI) [52], the two independent controls applied in [48], the unified controller suggested in [57] and the back stepping control with PI control proposed in [58]. All of these use input feedback current. The voltage control can be achieved by separating the operation mode of the cascaded buck-boost converter, so that for half of the time it operates as a buck converter and for the other half of the time as a boost converter by using logic sequences [53, 52]. More complex controllers can be applied to improve the performance of the cascaded
Figure 2.8: Circuit diagram of a cascaded buck-boost converter in energy conversion

buck-boost converter by using the robust control technique in the average mode model explained in [58, 59, 60].

Different structures of the buck-boost converter with more than two switches have been discussed in [43, 42, 50, 61]. For example, the three level boost converter gives less stress to the inductors compared to other converters. It is easy to model the controller that is based on the boost control structure, but the disadvantages are that it uses more inductors and switches. Due to the increasing number of switches, additional control loops need to be applied at the main controller.

In [43, 61], a more complex arrangement of the buck-boost converter has been used in order to minimise the stress of the inductor. First, the structure can be connected in an interleaved or superimposed connection, where these connections improve the stress and the conduction losses of the inductor compared to the others. These configurations will behave like a filter for the converter, and the controller needs to use a more complex controller which includes the three mode duty cycle. These converters create problems such as a higher harmonic current at the output [41, 48, 50].

As a solution, a cascaded buck-boost converter has been used in the ERLA application which is capable of giving a constant output with a wide range of input voltages and currents. It is also capable of changing the variable dc inputs to constant dc outputs in the continuous conduction mode at the inductor. By using the current controller combined with the logic sequence, the cascaded buck-boost converter is able to control the LG outputs in order to change the power output profile.

2.4 Energy storage

After the power from the energy conversion has been controlled, this huge amount of power at the beginning needs to be stored. Because of this, the energy storage part is essential. At the same time, the function of energy storage is to release the energy to the load when the load requires more power than the source power which is coming from
energy conversion. It is also to ensure that a continuous power supply can be supplied to the load.

Most of the renewable energy sources, generate low voltage output compared to the input voltage which needs to be used in the energy transfer process. Because of this, the boost converter is used to increase the input voltage. The energy storage element is combined with the bidirectional converter in order to have the function of absorbing and releasing the energy from the storage elements. Figure 2.9 shows the topology of the energy storage part in renewable energy source applications.

![Diagram of energy storage part](image)

**Figure 2.9: Topology of energy storage in renewable energy source applications**

### 2.4.1 Energy storage elements

Generally, the functions of the energy storage elements in renewable energy, hybrid vehicles or uninterrupted power supplies are to provide power during transient, inject the power when the main source has a low power output such as in renewable energy sources, and to absorb the energy during braking [62, 63, 64]. Another function is as a temporary storage (short term) [65] or a transit place before it can be transferred to the load. For example, energy storage elements such as the ultracapacitor, battery, flywheel etc can be used as storage devices by connecting them to the dc-link [66, 44, 67, 68]. For renewable energy source applications, the battery and the ultracapacitor can be used as storage elements to improve the reliability and the stability of the grid connection [62, 44, 69, 63, 70, 71, 72].

Due to its fast power regulation, the ultracapacitor is more suitable for use in landing aircraft. This is because it can respond to high power density, has a high charging
speed, a longer life time and a high energy density output [64, 70, 73, 74, 75, 76]. The ultracapacitor stores the energy by separating the positive and negative charge, and it has a fast discharging rate due to the high rated current [75]. By placing the dc converter between the ultracapacitor and the dc-link, the direction of the current can be obtained and at the same time it can control the voltage at the dc-link. The ultracapacitor can be modelled by the internal capacitance \((C)\) and with the series resistor \((R_{esr})\). This combination will give a more accurate expression for the ultracapacitor as given by [70, 77]:

\[
Z(s) = R_{esr} + \frac{1}{C(s)}.
\]  

2.4.2 Energy storage with bidirectional converter

A bidirectional converter has the ability to allow two directions of power flow, either flowing from the energy storage elements to the dc-link voltage or vice versa. More of these converters have been applied at the energy storage element in renewable energy applications and in uninterrupted power supplies [57, 63, 66, 78]. The bidirectional converter structure resembles the half bridge circuit which consists of only one inductor in order to reduce the current stress and also to give high efficiency. The bidirectional converter with the energy storage element is parallel connected to the dc-link voltage in order to regulate the dc-link voltage, and to discharge the stored energy [76].

This bidirectional converter can be controlled depending on the type of energy storage element that has been used. If the battery is used, this converter is used to control the state of charge with a state control for optimum charging, while the ultracapacitor is used to regulate the dc-link voltage [40, 71, 79]. Other than these strategies it can also use the inner loop current control, the other voltage loop that been proposed in [67, 72, 76], the finite state machine in [64], or the dynamic evolution control in which the switching angle was calculated by [69]; these are able to control the power flows from the bidirectional converter. In [80] it has been suggested to use the state of charge for the ultracapacitor for the power flow process. A more advanced control strategy that includes 3 modes of operation for the bidirectional converter which are buck, boost and shutdown. It is combined with a power management application in order to have the current flow between the energy storage and the dc link [66, 81].

From the conventional to the more complex methods can be applied to control the bidirectional converter. One of the solutions is by changing the nonlinear equation that is caused by the switches to a linear equation by using the average control technique. This is done by integrating the switches cycle in order to produce a constant signal at the output [51, 82], which will be used to determine the controller structure.
2.4.3 Boost converter

The boost converter is used to increase the dc-link voltage to the desired output voltage in order to be used by the energy transfer part. This is to ensure that the input voltage at the inverter is capable of generating 3-phase voltage for the existing electrical network or for the load demand. The boost converter has been used widely in renewable energy structures [62, 83]. This converter is easier to build and control because it consists of one inductor and one switch which will respond to the output voltage.

As is known, the boost converter is a nonlinear element which creates a nonlinear equation in which only the nonlinear control can be used. This nonlinear condition can be solved by using a controller that has a wide bandwidth of response such as the PI controller [84], the proportional-integral derivative (PID) controller which uses a genetic algorithm in order to determine the duty cycle gain for the controller [85], or by using the sliding mode controller (SMC) that has been proposed in [86, 87, 88].

2.5 Energy transfer

All the power from the source and the storage element need to be transferred to the grid. This part consists of the inverter, the filter and the grid source as shown in Figure 2.10. The inverter can be driven by power electronics devices such as GTOs, MOSFETs, FETs and IGBTs. The choice of power electronics devices is based on the rated output power of the inverter. Due to the switching effect of the power electronics devices, the inverter will inject a high current harmonic to the grid, and increase the total harmonic distortion of the grid current. In order to solve this problem, a filter can be connected between the inverter and the grid. The inverter also functions as the synchronisation component between the renewable source and the grid source. Synchronisation must happen between the inverter and the grid in order to transfer the power to the grid without causing any damage to it.

2.5.1 Filter component at the energy transfer part

To improve the injected current and to transfer clean sinusoidal current to the grid, three types of filter such as L, LC or LCL can be used. The L filter consists only the inductor; here the inductor size is bigger thus reducing the dynamic of the system. It also creates a longer response time for the current [20]. To improve this, the capacitor C is introduced, and is known as the LC filter. In this case, the inductance value can be reduced by selecting a very large capacitance which will create an inrush current; this high capacitance is not suitable for current injection [89]. Due to these disadvantages with both filters, most researchers have used the LCL filter model. This is also known
as the electromagnetic interference (EMI) filter and is used at the inverter to prevent high harmonics at the switching frequency. It will give low ripple current, prevents inrush current, and leads to small values for the inductor and the capacitor which are suitable to be used for the grid connection [20, 90, 89, 91, 92, 93].

### 2.5.2 Synchronisation of the inverter with the grid source

Synchronisation of the DG structure is important in order to ensure that the power can flow from the DG to the electric grid network. For normal synchronous generator operation, the synchronisation can be established when the frequency of the rotating flux is the same as the grid frequency. When a fault happens, both frequencies are not the same, and the generator will be separated from the grid. It takes a longer time to synchronise back. The DG synchronisation is better than the generator because it is not related to the rotating phase angle, but the inverter needs the information about the amplitude, the phase angle and the frequency of the grid source which can be collected using a proper synchronisation technique.

The most common or most used synchronisation method is the phase-locked loop (PLL) applied in [94, 95, 96, 97]. The operation of the PLL is one which uses the feedback response of the voltage controller oscillator to lock the phase of the grid voltage. Another technique is the sinusoidal tracking algorithm (STA), which is able to detect the frequency changes in the grid faster then the PLL and with a high setting time [98]. This STA is also able to lock the phase and the frequency if the grid is not balanced. A new kind of synchronisation, known as the synchronverters structure which does not use the PLL, has been implemented in [99]. It makes the inverter behave like a synchronous generator with frequency droop control for synchronisation of the inverter and the grid.
2.5.3 Power flow between the inverter and the grid source

Power flow refers to the power interchange between the main source and the grid network. In the DG unit, the renewable energy is the main power source while the inverter is a drive structure to transfer the energy to the grid. This power flow can be achieved by using a proper control application on the inverter. The current or voltage control strategy can be used in order to transmit the power from the inverter to the grid. Here, most researchers have used the current control application [94, 100, 101]. By adding the power control to be the outer loop control while the current control is the inner loop, the amount of power flow that is related to the injected current can be established [17, 97, 93]. The equations that relate these two are given as:

\[ P = v_a i_a + v_b i_b + v_c i_c \]  \hspace{1cm} (2.3)

\[ Q = \sqrt{3} [(v_a - v_b) i_a + (v_b - v_c) i_b + (v_c - v_a) i_c] \]  \hspace{1cm} (2.4)

where \( P \) is the real power, \( Q \) is the reactive power, \( v_a, v_b, v_c \) are the line to live voltage and \( i_a, i_b, i_c \) are the inverter line currents.

From equations 2.3 and 2.4, the real and reactive power are easier to control in the inverter compared to the synchronous generator, where the current at the inverter terminal is used as the feedback control and the PLL block is used for the synchronisation.

2.5.4 Control scheme for inverter-side converter

Basically, the structure of the grid side inverter is monopolised by the voltage source inverter (VSI) due to the high power rating, and the time response is faster than the current source inverter (CSI). As is known, the function of the inverter is to inject the current to the grid by using the current control, in order to have a power flow which is important for renewable energy power. It can also use voltage control in order to improve the power quality at the terminal voltage grid caused by voltage sag, voltage swell etc.

2.5.4.1 Current control for the inverter

Due to the maturity of this control structure, most researchers use this strategy for the grid connected system. Figure 2.11 shows the current control topologies to the grid connected system based on the natural frame control.

Figure 2.11 shows that, each phase has its own current control to create a more dynamic response [20] compared to using only one current controller. Here, it gives a high accuracy control for instantaneous current, a peak current protection, an overload rejection and a very good dynamic [20, 94, 102]. These advantages ensure that the
tracking error between the reference current and the inverter current can be kept to a minimum in order to inject less Total Harmonic Distortion (THD) to the grid. The P+ Resonant controller with harmonic compensation is also able to inject less THD current to the grid if it has been implemented at the inverter control. Meanwhile, the dead-beat controller, the hysteresis and the PI controllers can also be used for current control [92, 97, 103] for the current injection from the inverter.

All of these controllers are known as the classical control approach. Recently, more robust controllers have been adopted for the inverter. The $H_\infty$ control theory has been put into practice in order to control the injected current by the inverter to the grid [100, 101, 102]. This controller is able to minimise the tracking error and at the same time it can operate during the unbalanced condition, or when a nonlinear load is connected to the DG. Meanwhile, the existence of the LC filter shown in Figure 2.11 requires a more complex current control strategy in order to maintain the stability [92]. Due to this, the current controller design must include the LC filter and the grid inductance ($L_a, L_b, L_c$) parameters for the controller calculation which can be achieved by using the robust control strategy.

Figure 2.11 shows the reference currents ($I^*_q$ and $I^*_d$) coming from the outer power control technique. The $abc$ – $dq$ transformation is used in order to change the current references from $I^*_q$ and $I^*_d$ format to three phase format ($i^*_a, i^*_b$ and $i^*_c$). The error signal between the reference and feedback current will be fed into the current controller block in order to generate the required pulse width modulation (PWM) signal to the inverter for the power electronics devices.
2.5.4.2 Power control technique at the inverter

Power control is used at the inverter in order to generate the reference currents for the current control which are proportional to the required power. There are two types of power control can be used for the inverter, the first is the Direct Power Control (DPC) and the second one is the active and reactive power control.

The DPC strategy has been used in [13, 98, 104, 105]. The DPC is based on the Direct Torque Control (DTC) which has been used in controlling the motor regarding the rotating flux. For the DPC control, the switching signals that are used for the inverter switches are generated from the switching table, based on the error between the reference and the measured real and reactive power [13]. The advantage of using DPC is that the inner current loop and PWM switching model are not needed, because the switching is based on the look-up table that is based on the hysteresis control [98, 106].

For this control technique, the reference real power $P^*$ is generated from the dc voltage controller, and the reference reactive power $Q^*$ is set to zero for the unity power factor. The unity power factor means that the voltage and current at the grid terminal are in the same phase angle. The generated signal is based on three conditions which are the $P, Q$ and the flux vector position $\gamma$ of the power. The generated signal can be expressed as:

\[
S_p = \begin{cases} 
1 & P < P^* \\
0 & P > P^* 
\end{cases}
\]

\[
S_q = \begin{cases} 
1 & Q < Q^* \\
0 & Q > Q^* 
\end{cases}
\]

By addressing the $\gamma$ with the $S_p$ and $S_q$ value, the appropriate voltage vector can be selected from the look-up table. Figure 2.12 shows the conventional DPC structure.

For real and reactive power control, it is based on the $dq$–$abc$ transformation and the feed-forward of the inverter input dc voltage. This transformation guarantees the fast transient response and gives high static performance with the inner current controller for the inverter which has been applied in [38, 97, 107]. The real power control and the dc voltage control will correspond to the $I_d^*$, while the reactive power will correspond to $I_q^*$ as shown in Figure 2.13. This power control is known as voltage oriented control (VOC), where the reference currents $(I_d^*, I_q^*)$ are the output from the power and reactive power calculation in [99, 108]. Figure 2.13 shows the complete control strategies applied to the energy transfer.
References


