

Ground-operated Energy Recovery System for Landing Aircraft

Qing-Chang Zhong, *Senior Member, IEEE*

Abstract—In this paper, an innovative concept to convert the huge kinetic energy stored in landing aircraft into electricity is identified and presented. An appropriate technical route involving linear machines to implement this concept is proposed. Some challenges and possible applications are discussed. Simulation results on feeding the electricity generated back to the power grid are given.

Index Terms—Distributed generation, renewable energy, aircraft kinetic energy recovery, DC-AC converters, linear machine, assisted takeoff

I. INTRODUCTION

Energy is fundamental to our daily life, from heating and lighting to transport, from industry to communication. Because of reduced gas, oil and coal production, governments have set various strategies to explore renewable energy sources, such as wind power, solar power, wave and tidal power etc, and to improve energy efficiency, e.g. via the use of combined heat and power (CHP) plants. For example, the UK government has introduced the Energy White Paper [1] in 2003 and the Strategy for Combined Heat and Power [2] in 2004. The EU has set a 22% target for the share of renewable energy sources and an 18% target for the share of CHP in electricity generation by 2010. As a result, the electrical power system is currently undergoing a dramatic change from centralised generation to distributed generation.

Another main driving force behind this change is the need to address the issue of climate change, mainly due to increased greenhouse gas emissions. Levels of carbon dioxide (CO₂) in the atmosphere have risen by more than a third since the industrial revolution and are now rising faster than ever before. This has led to rising temperatures: over the 20th century, the earth warmed up by about 0.6°C largely due to increased greenhouse gas emissions from human activities [1]. The 1990s were the warmest decade since records began. How to reduce human activities to lead to a low carbon economy is crucial to this. Increasing the share of renewable energy and improving the energy efficiency are important means to reduce carbon emissions.

In this paper, an important power source is identified and an concept to utilise this energy source is presented.

Q.-C. Zhong is with the Department of Electrical Engineering & Electronics, The University of Liverpool, Brownlow Hill, Liverpool L69 3GJ, United Kingdom, E-mail: Q.Zhong@liv.ac.uk, Tel: 0044-151-79 44501.

A fast travelling aircraft contains significant kinetic energy. When an aircraft lands, the kinetic energy is dissipated as waste heat. For example, the average power dissipated during the landing period, say 30sec, of a 40-ton aircraft¹ with a touching speed of 150mph is 3MW. At Heathrow Airport, a landing happens every two minutes. This gives a constant (average) power source of 750kW. For big aircraft, e.g. A380, the landing weight can be up to 386 tonnes, which gives an almost 10 times higher power. The concept is to convert this huge kinetic energy source into an electrical power source. The electricity generated can be fed to the power grid and then electricity can be drawn from the grid to assist taking-off, which brings huge impact on carbon reduction and energy cost saving. It also improves air quality at the airport because of improved tear and wear on the tyres and brakes. This also enables engineless taxiing and pushing-back, which saves considerable amount of energy, reduces the noise level and improves air quality. Another benefit is that the fuel carried by the aircraft for taxing/takeoff can be considerably reduced, which adds more benefit. The electricity generated can be diverted to the aircraft as well if needed. The implementation of this concept will have great impact on improving energy efficiency, reducing the energy cost and the impact on environment.

The rest of this paper is organised as follows. The motivation and benefits are described in Section II, followed by technical route discussed in Section III. Some challenges and possible military applications are discussed in Section IV. A test rig is being built and some simulation results on feeding the electricity generated back to the grid is given in Section V. Conclusions are made in Section VI.

II. MOTIVATION AND BENEFITS

For an aircraft, weighing $m = 40 \text{ ton} = 4 \times 10^4 \text{ kg}$ and moving at a speed of $v_0 = 150 \text{ mph} = 0.44704 \times 150 = 67 \text{ m/s}$, the kinetic energy stored in the aircraft is

$$E = \frac{1}{2}mv_0^2 = 2 \times 10^4 \times 67^2 = 8.98 \times 10^7 \text{ Joule,}$$

which is equivalent to

$$E = \frac{8.98 \times 10^7}{1000 \times 3600} = 25 \text{ kWh.}$$

¹In the civilian aviation industry, the most commonly used aircraft are Airbus A319/A320/A321 and Boeing 737, with a maximum landing weight of around 65 tonnes.

Assume that the landing process takes about 30sec, then the kinetic energy has to be converted into other energy, e.g. waste heat nowadays. The average rate of energy transfer is about

$$P = \frac{E}{t} = \frac{8.98 \times 10^7}{30} \approx 3 \text{ MW.}$$

If there is a landing every two minutes, e.g. at Heathrow Airport, then the average power is 750 kW. In the near future, it is expected that big aircraft, such as Airbus A380, will be the main carriers at major international airports. This will give an average power of about 7.5 MW, which is equivalent to the capacity of three to four wind turbines widely used nowadays.

Since the drag coefficient of aircraft is very small (when the flaps are retracted) and the mass is very big, the recovering efficiency could be made relatively high. For similar applications in railway, currently see 31.3% efficiency²; for cars, the efficiency is lower because of the higher drag coefficient (e.g. the drag coefficient of a Toyota Prius is 0.26), lighter weight and lower efficiency in processing the electricity recovered. It is almost useless to apply this concept to electric bicycles because the drag coefficient is around 0.9 and the mass is small. An efficiency around that for railways, if not higher, is expected to achieve for landing aircraft.

The benefits of converting this energy into electricity are much more than just recovering the energy and saving the energy cost. The potential benefits include:

- Using the facility established for assisted take-off, which will considerably reduce the impact of carbon emission and improve air quality as well. This may also mean that increased payload can be carried.
- Extending the facility to taxiway so that engineless taxiing and pushing back can be implemented, which will considerably improve the energy efficiency involved as the engine are designed to run at high speeds and the efficiency of the engine is very low at low speeds. The running of the engine also causes environmental issues such as increased emissions, noise, bad air quality etc.
- Reducing the amount of fuel to be carried for takeoff and landing/taxiing, which considerably reduces the energy consumption when travelling in the air.

III. TECHNICAL ROUTES

Technically, the kinetic energy can be converted into electricity using electric machines. One way is to mount a rotating machine on the undercarriage and then feed the electricity generated to the aircraft, as normally done for regenerative braking of vehicles. By doing this, no work needs to be done to the runway and there is no need to involve the airport. The problem with this route is that there is a need to store the recovered energy in the aircraft, as storing energy efficiently is still an open technical problem. In particular, for aircraft,

²http://engineering.wikia.com/wiki/Regenerative_braking

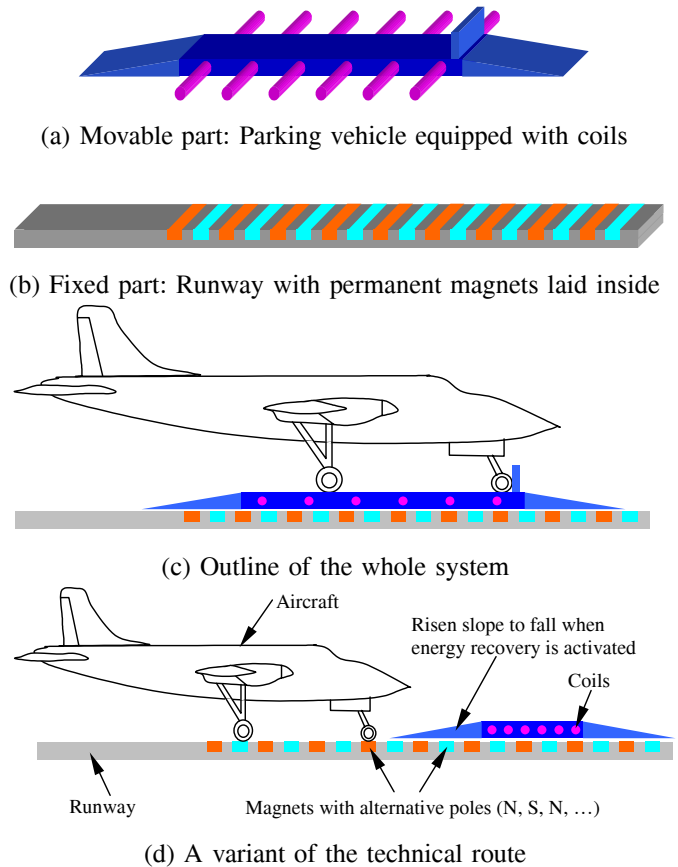


Figure 1. Sketch of an energy conversion system to recover the kinetic energy of landing aircraft

this means considerable increase of weight in limited space. Another way is to change aircraft/runway into a linear machine [3] and the interaction between the aircraft and the runway generates electricity, which is then fed into the power grid. As the electricity generated is fed into the power grid, there is no need to store energy. Even if there is a need to store energy temporarily, there is no limitation on space/weight on ground.

A. Energy conversion

One technical route taken to implement the concept is to make the aircraft as the movable part (rotor) of a linear electric machine and to make the runway as the fixed part (stator) of the machine. Permanent magnets are laid onto or into the runway, as shown in Figure 1(b). Once the aircraft is landed, it moves onto the parking vehicle shown in Figure 1(a), which is equipped with coils underneath. Because of the inertia of the landing aircraft, the parking vehicle keeps moving forward. This generates electricity in the coils, which can then be processed by a power conditioning and control system on the ground. The generated electricity can be stored locally or fed back to the grid. A sketch of the whole system is shown in

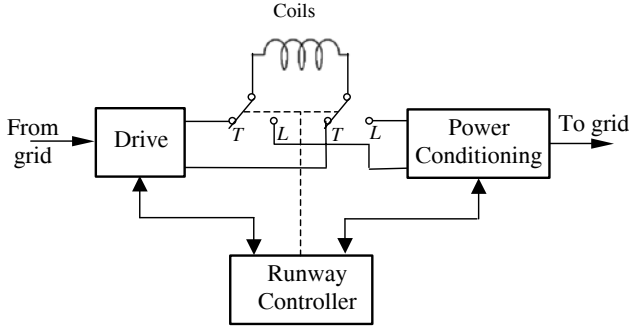


Figure 2. Power conditioning and control of the energy conversion system

Figure 1(c). If the coils on the parking vehicle are energised, the vehicle/aircraft can be taxied.

A variant of this technical route is sketched in Figure 1(d), where the aircraft does not move onto the vehicle but just pushes the vehicle/platform to move forward. If there is a fault, the slope can be maintained and the aircraft can run over the vehicle or simply the vehicle can be removed from the runway. For this variant, it is possible to install rotary electric machines on the wheels of the vehicle. This does not need changes to be made to the runway and is likely to be the easiest route to implement the concept.

Safety measures taken to minimise the impact when the aircraft touches the vehicle is the determining factor for success and special attention should be paid to this aspect. One possible way is to drive the vehicle to an appropriate speed before the aircraft touches the vehicle. As there is no need to make changes to aircraft, there is no added weight to cause fuel penalty. It can be installed, managed and operated by airports only.

B. Power conditioning and control

The power conditioning and control system is shown in Figure 2. There are two operation modes: Landing (L) and taxiing/takeoff (T). When the system works in the landing mode, the coils are connected to the power conditioning device so that the generated electricity can be processed and fed back to the grid or stored locally; when the system works in the assisted takeoff or taxiing mode, the coils are connected to a power supply via a drive. The change of the operation mode, as well as the drive for taxiing/takeoff and the power conditioning, are controlled by the runway controller. A mechanism to indicate the mode of the runway should be visible from the aircraft to ensure safety.

At the landing mode, the electricity generated from the coils has a variable voltage and a variable frequency because the speed of the aircraft (parking vehicle) decreases when time goes. Also the speed, mass and braking force of one aircraft are different from those of others. Hence, there is a need to process the electrical power recovered from the landing

aircraft. This device normally consists of a rectifier, a DC-DC converter, a temporary energy storage, and a DC-AC converter that interfaces with the power grid; see Figure 3. Some of the technologies involved are matured. However, how to integrate everything together so that it functions well is still a great challenge. Moreover, this power conditioning device needs to be able to cope with a much higher transient power than the average power and hence it needs to be designed carefully. At the taxiing mode, the coils are energised so that the parking vehicle can be moved forward or backward. This involves running the machine as a motor and is implemented via the drive device. The whole system is controlled by the runway controller, which receives commands from the control tower.

C. Power profile

Assume that the braking force f is constant, which gives a constant deceleration $a \text{ m/s}^2$, then the braking power is

$$p = f \cdot v = f \cdot (v_0 - at),$$

which decreases as the speed decreases. For the data given in Section II, the deceleration is

$$a = \frac{67}{30} = 2.23 \text{ m/s}^2$$

and the braking force is

$$f = ma = 4 \times 10^4 \times 2.23 = 8.93 \times 10^4 \text{ N.}$$

As a result, the instantaneous braking power is

$$p = 8.93 \times 10^4 (67 - 2.23t) \text{ W,}$$

as shown in Figure 4(a). The transient power is much higher than the average power.

Assume that the braking force applied increases with time, i.e., $f = ma_0t$. This gives a linearly increasing deceleration $a = a_0t$. The velocity is

$$v = v_0 - \frac{1}{2}a_0t^2$$

and the instantaneous braking power is

$$p = ma_0t(v_0 - \frac{1}{2}a_0t^2).$$

For the data given in Section II, $a_0 = 0.1489 \text{ m/s}^3$ with a maximum deceleration of 4.667 m/s^2 at $t = 30$ second. In this case, the profile of the braking power is shown in Figure 4(b). The above shows that the profile of the instantaneous power can be changed by changing the acceleration/deceleration profile. Of course, the passenger's comfort should not be compromised; see [4] for details about human responses to acceleration.

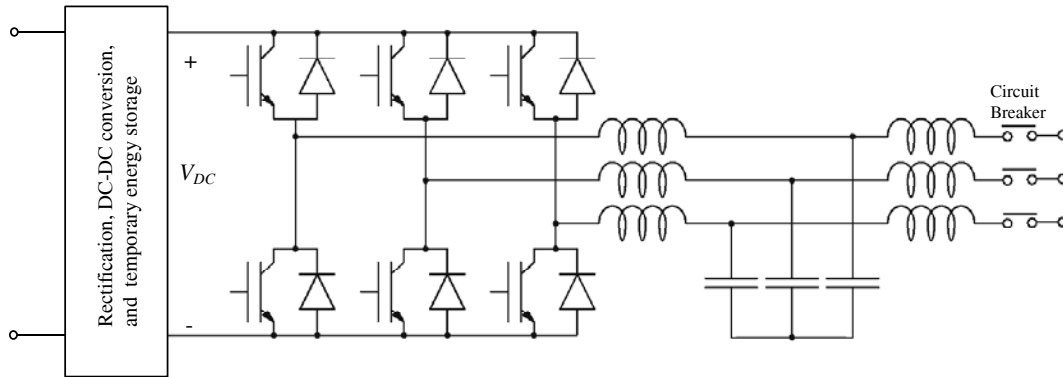


Figure 3. Sketch of the power conditioning device

IV. CHALLENGES AND POTENTIAL MILITARY APPLICATIONS

Although the technology about linear electrical machines and power electronics has arrived at a great level of maturity, there are still a lot of challenges in putting this concept into reality. Some of them are:

- How to obtain a satisfactory recovery efficiency ;
- How to cope with the high transient power;
- How to minimise/cope with the mechanical impact of the energy conversion to the aircraft/parking vehicle/undercarriage;
- How to minimise/cope with the mechanical impact of the force to the runway;
- How to minimise the EMI effect of the magnetic field;
- How to integrate all the parties involved together.

Because of the huge environmental and economic impact, this concept is expected to be eventually implemented. A test rig is to be built to investigate various issues of the system.

The concept presented here has a great potential in aircraft carriers³, which brings the following significant benefits:

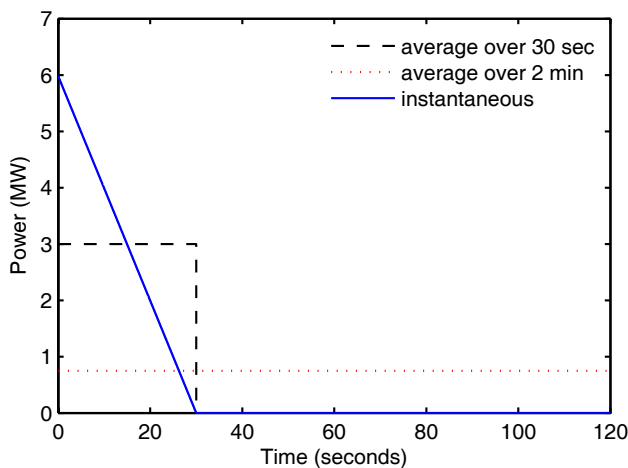
- Saving a lot of fuel usage so that the operation range can be considerably extended;
- Assisted take-off increases the amount of payload so that more weapons can be loaded;
- Reduced take-off/landing time increases the turnaround of operation.

V. PARTIAL SIMULATION RESULTS

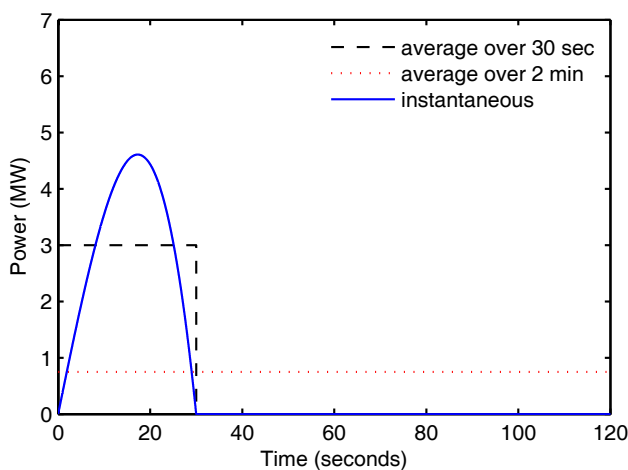
Here, only some simulation results about feeding the energy recovered back to the grid is included, assuming that the energy is stored temporarily and available as a DC power source.

The inverter is connected to the grid via a breaker and a step-up transformer. The parameters of the inverter for carrying out simulations are given in Table I.

³The reason of mentioning this potential application is simply based on academic grounds. It does not reflect the author's personal opinion on whether this should be used or not.



(a) Constant deceleration

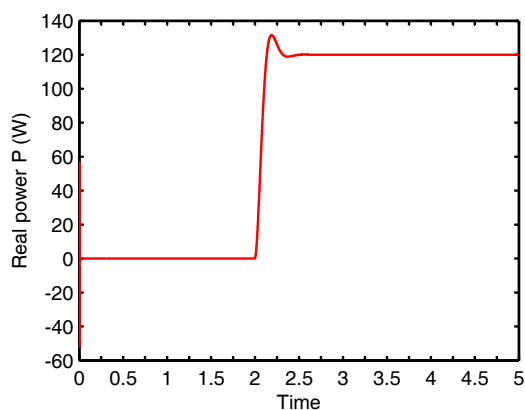


(b) Linearly increasing deceleration

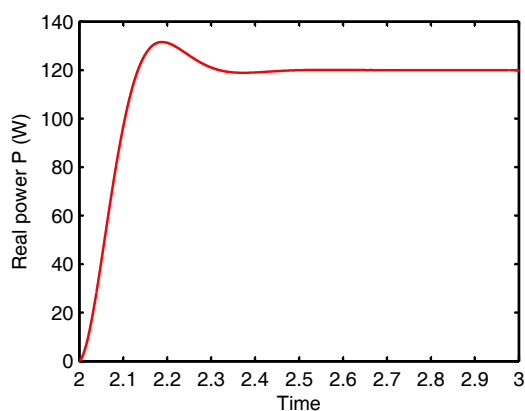
Figure 4. Profiles of the braking power

Table I
PARAMETERS OF THE INVERTER-INFINITE BUS SYSTEM

Parameters	Values	Parameters	Values
inverter side L_s	0.15 mH	grid side L_g	0.0534 mH
inverter side R_s	0.045 Ω	grid side R_g	0.06 Ω
C	22 μF	Frequency	50 Hz
R	1000 Ω	Grid voltage (line-line)	17 Vrms
Rated power	120 W	Line-line voltage	17 Vrms



(a) whole period



(b) after a virtual landing

Figure 5. Feeding the recovered power back to the grid

The newly-developed grid-friendly inverter proposed in [5] is adopted to control the inverter for regulation of the power fed to the grid. The inverter is connected to the grid at $t = 1$ sec and then the inverter is given instructions to feed a real power of $P = 120\text{W}$ to the grid at $t = 2$ sec when a landing takes place. The output power of the inverter is shown in Figure 5.

VI. CONCLUSIONS

A concept to convert the kinetic energy in landing aircraft has been proposed, together with an appropriate technical route to implement it. Although some of the technologies are matured, but there are still a lot of challenges to be resolved.

Simulation results on how to feed the electricity recovered back to the power grid is given.

REFERENCES

- [1] Department of Trade and Industry (DTI). *Energy White Paper: Our Energy Future - Creating a Low Carbon Economy*. The Stationery Office, UK, 2003. available at <http://www.dti.gov.uk/files/file10719.pdf>.
- [2] Department for Environment Food and Rural Affairs (defra). *The Government's Strategy for Combined Heat and Power to 2010*. Defra, UK, 2004. available at <http://www.defra.gov.uk/environment/climatechange/uk/energy/chp/pdf/chp-strategy.pdf>.
- [3] J.F. Gieras and Z.J. Piech. *Linear Synchronous Motors: Transportation and Automation Systems*. CRC Press, 1999.
- [4] R.D. Banks, J.W. Brinkley, R. Allnutt, and R. M. Harding. Human response to acceleration. In J. Stepanek J. R. Davis, R. Johnson and J.A. Fogarty, editors, *Fundamentals of Aerospace Medicine*, pages 83–109. Lippincott Williams and Wilkins, 2008.
- [5] Q.-C. Zhong and G. Weiss. Static synchronous generators for distributed generation and renewable energy. In *Proc. of the 2009 IEEE PES Power Systems Conference & Exhibition (PSCE)*, Washington, USA, March 2009.



Qing-Chang Zhong (M'04-SM'04)

received the M.Sc. degree in electrical engineering from Hunan University, China, the Ph.D. degree in control theory and engineering from Shanghai Jiao Tong University, China, and the Ph.D. degree in control and power engineering (awarded the Best Doctoral Thesis Prize) from Imperial College London, UK, in 1997,

1999, and 2004, respectively.

He started working in the area of control engineering after graduated from Hunan Institute of Engineering, China, in 1990. He was a postdoctoral research fellow at the Faculty of Mechanical Engineering, Technion-Israel Institute of Technology, Israel, from 2000 to 2001, and then a Research Associate at Imperial College London from 2001 to 2003. He took up a Senior Lectureship at the School of Electronics, University of Glamorgan, UK, in January 2004 and was subsequently promoted to Reader in May 2005. He joined the Department of Electrical Engineering and Electronics, The University of Liverpool, UK, in August 2005 as a Senior Lecturer. His current research interests cover control theory (including H-infinity control, time-delay systems and infinite-dimensional systems) and control engineering (including process control, power electronics, renewable energy, grid connection, energy recovery and storage, embedded control, rapid control prototyping and hardware-in-the-loop, engine control, hybrid vehicles and control using delay elements such as input-shaping technique and repetitive control). He is currently leading an EPSRC-funded Network for New Academics in Control Engineering (New-ACE, www.newace.org.uk), which has attracted more than 70 members from academia and industry. He is the author of the monograph *Robust Control of Time-delay Systems* published by Springer-Verlag Ltd in 2006.