IEEJ TRANSACTIONS ON ELECTRICAL AND ELECTRONIC ENGINEERING
IEEJ Trans 2021
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI:10.1002/tee.23528

Invited Review Paper

Cars and Energy in the Future 'Paradigm Shift to Motor/Capacitor/Wireless'

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What will cars look like in 100 years' later? They must run by 'electric motor' and will receive energy directly from electric power infrastructure like electric trains. The key technologies here are 'supercapacitors' to excel in power input and output rather than batteries, and 'wireless power transfer' to connect cars to power infrastructure. Furthermore, energy efficiency and safety will be dramatically improved by the technology of 'motion control' to make use of the excellent torque control characteristics of electric motor, also together with automatic driving technology. © 2021 Institute of Electrical Engineers of Japan. Published by Wiley Periodicals LLC.

Keywords: electric vehicle; electric motor; supercapacitor; motion control; wireless power transfer; energy system

Received 21 July 2021; Revised 28 September 2021

1. Preface

I was the eldest professor of the Electrical Engineering Departments of the University of Tokyo, which spans Hongo, Kashiwa, Komaba campuses, and so on, and retired in March 2021, and moved to the present university. The main job was in the Department of Advanced Energy in Kashiwa Campus, which was made about 20 years ago based on the Electrical, Aerospace, and Nuclear Departments.

My specialty is in power electronics, motor control, mechatronics, and motion control of electric vehicles. As a former president of World Electric Vehicle Association (WEVA), I conducted the international conference Electric Vehicle Symposium (EVS) 31 in October 2018 in Kobe successfully. I am the Vice President of the Society of Automotive Engineers of Japan (JSAE), the past president of Industry Applications Society of the Institute of Electrical Engineers of Japan (IEE-J), the director of the Japan Automobile Research Institute (JARI), and the chairmen of Motor Technology Symposium of the Japan Management Association (JMA), the Capacitor Forum, and so on.

Prof. Satoru Sone, who specializes in railways, gave me a doctorate degree in 1983, and jointly operated the laboratory with Prof. Yoichi Kaya at the University of Tokyo until his retirement.

Recently, I served as the sub- Program Director (sub-PD) of Cross-ministerial Strategic Innovation Promotion Program (SIP) of the Cabinet Office (first phase) 'Next-generation Power Electronics'. PD was Dr. Omori at Mitsubishi Electric. In this framework, Wireless Power Transfer (WPT) in motion to Electric Vehicles (EVs) is the important topic to be realized soon. It is a crucial milestone for Japanese professionals to show a good model in advance of suspicious attempts in foreign countries. New Energy and Industrial Technology Development Organization (NEDO) is also supporting WPT in a larger scale.

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Based on these experiences, this paper presents my personal views on the future of cars and energy. I hope you will kindly accept my bias, as this paper is my personal view.

2. Gasoline and Electricity

If you look at the current trend toward electrification of cars, it seems that the engine is gradually replaced with electric motor, and after 100 years, most cars are running with electric motor.

However, the means of supplying energy to EVs is still a major problem. Do you know that the equivalent power of our daily gasoline refueling is about 20 000 [kW]? This corresponds to Shinkansen 16-car trains' full power acceleration. This power is completely different from 50 kW for rapid charging to EV.

Everyone knows that the battery EV's range is insufficient, so everyone has said that quick charging and high-performance batteries are key technologies. But, is it right?

Even though gasoline and electricity have completely different forms of energy, it is strange to try to put energy into an EV while 'stopping', 'in a short time' and 'big' energy. It is almost impossible to spray gasoline into the town and to drive cars by gathering the gasoline mist, but electricity can do virtually the same thing [1].

The battery EV, which carries a large amount of energy, is a car that will disappear in the future, although it is a necessary technology for the time being. Battery can be a source of disasters. In addition, since cobalt required for lithium ion batteries is easily depleted, it is clear that this solution is not a solution in the long term. We have quickly to shift to other measures to leave from battery.

3. Motor/Capacitor/Wireless

So, what should we do? Actually, there is a completely different way. If you supply energy directly to the EV from the power infrastructure like a train, the one-charge 'range' loses meaning. With the 'choko-choko (frequent) charging' while parking and 'dara-dara (slow) charging' while running, a car needs not to carry a large amount of energy and we can depict a future car society completely different from one based on the battery EV. The key technology here is 'wireless power transfer', which takes responsibility for the last few meters connecting the car to the power grid.

If the car in the future moves by electricity and is connected to the power infrastructure, the cruising distance is not the distance that can be traveled by one battery charge, but it has only the meaning of 'the distance that can be relieved from the infrastructure'. A car like a train will be normal. Here, 'battery to capacitor' transition and 'wireless power transfer' are realized, and people are freed from the work of charging. At the same time, 'motion control' that makes use of the excellent controllability of the electric motor will become commonplace, and the fuel efficiency of the car will be greatly improved. Here, 'wireless power transfer' will be more realistic.

Let us discuss these three points a little more.

3.1. Motor The advantage of EV is the advantage itself of the electric motor. That is, there are three points: (i) the torque response is 100 times faster than the engine, (ii) the motors can be distributed in the wheels, and (iii) the generated torque can be accurately grasped. The adhesion control to make torque down quickly in millisecond order against small tire slippage makes the tireless slippery. If the same adhesion performance is acceptable, the fuel consumption will be several times smaller by using narrower and harder tires.

Generally speaking, a fast feedback control can change mechanical plant dynamics. Fast response of the actuator can realize such controls, which is firstly available in EV.

Figure 1 shows the basic block diagram of slip prevention control for EV based on Model Following Control. $F_m{}^*$ is the driver acceleration command roughly proportional to acceleration pedal angle. Vehicle dynamics $P(s)$ including tire and road surface characteristics are very complicated, but the vehicle body can be seen as a simple one inertia system. When a vehicle starts skidding during acceleration, its wheel velocity increases rapidly, and during deceleration, it decreases rapidly due to the wheel lock. Such rapid change of wheel velocity is caused by a sudden drop of equivalent wheel inertia moment expressed by $P_{\mathrm{skid}}(s)$.

Based on this viewpoint, taking the wheel speed difference between the real and model speed of the nominal model $P_{\mathrm{adh}}(s)$, the feedback loop to reduce the driver's torque command is

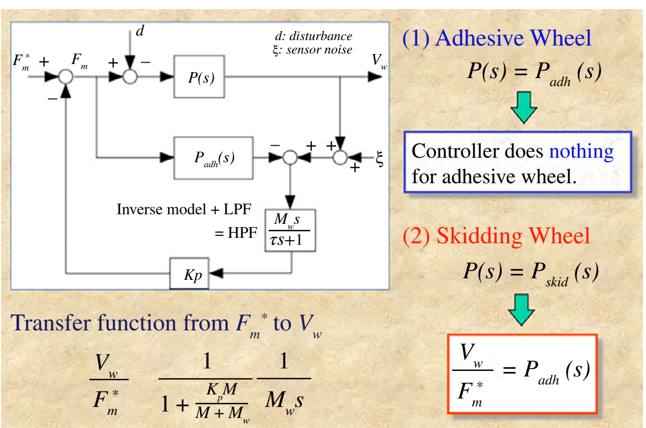

Fig. 1. Model following control to prevent tire slip

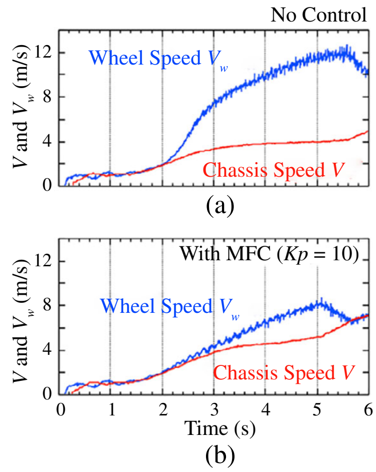

Fig. 2. Experimental result of tire slip prevention

applied. The principle is similar to Anti-lock Braking System, but its behavior is much quicker, i.e. in 1 ms order.

Experiments were carried out with UOT (University of Tokyo) March-I, which is our first laboratory-made EV made in 1997. Figure 2 shows the time responses. The vehicle was accelerated on the slippery test road, while the motor torque was increased linearly. Without control, the slip occurred at $t = 2$ [s]. On the contrary, the increase of slip is suppressed when the proposed controller is applied.

Such 'EV motion control' that makes use of the excellent controllability of the motor drastically reduces the energy consumption used by the car and reduces the need for loading a large number of batteries. In addition to the prevention of skidding, attitude control such as active suspension, yaw, pitch, and roll controls using in-wheel motor will become a common technology, and the safety and the ride quality will be greatly improved.

The details including much more sophisticated controls are described in Ref. [1]. Readers who are interested in this technique should read them. This is the most important advantage of EV, and it is also the motivation that I myself started EV research.

3.2. Capacitor There is no need for high-performance batteries to run over 500 km. The reason why many expensive batteries are loaded is to try to achieve the same range as conventional gasoline vehicles. However, it is best to use electricity as soon as it is generated, and it is not clever to save and use it. For this reason, past engineers have made great efforts and built long-distance high-voltage power transmission networks. Because I do not deny the convenience of the small battery, please do not misunderstand.

Figure 3 shows our small vehicles driven only by supercapacitors. In Shanghai, there are stable bus routes running only with capacitors. The Shanghai World Expo operated about 60 lithium-ion battery buses and about 30 capacitor buses. It was also found that the battery bus needs a huge battery exchange station, and its daily practical operations is questionable. On the other hand, capacitor buses continue to run forever with charging for about 30 s to 1 min at the bus stops (Fig. 4).

Supercapacitors (EDLCs: Electric Double Layer Capacitors), occasionally referred to as physical batteries, have the following remarkable advantages as compared to conventional batteries: (i)

Fig. 3. C-COMS 1 and C-COMS 2 running only with capacitors

Fig. 4. A capacitor bus at the Shanghai World Expo (2010)

long operating life (a supercapacitor can be charged and discharged for an average of 1 million times); (ii) extremely high power density; (iii) use of environmentally friendly materials; and (iv) energy level estimation from terminal voltages.

Several years ago, ATENZA, AXCELA (Mazda), and FIT (Honda) appeared as mass-production hybrid vehicles using Nippon Chemi-Con capacitors. It was proved that capacitor is extremely effective for absorption of regenerative energy and acceleration assist.

3.3. Wireless Even in Japan, there are outlets of about 100 V and 10 to 15 A all around, and 'choko-choko (frequent) charging' is already possible. Moreover, wireless power transfer (WPT) technology that is actively researched and developed is showing signs of explosive development (Fig. 5). The current technical level of WPT is about 50 cm to 1 m of power transmission distance, and about 95% of transmission efficiency between transmitting and receiving coils. The distance can be extended to several meters using simple relay coils [3].

The concept of the capacitor EV is 'Auto-charge Super Urban Intelligent Card: electronic train ticket in Japan (SUICA)', and the WPT is 'Energy version Electronic Toll Collection (ETC System)' (Fig. 6). In the past, SUICA was only able to be charged at large stations, but as the range that can be used gradually expanded, carrying amounts of money became smaller. The same thing can be said. Even if all the infrastructure is not prepared, it can be introduced from the place where it is possible.

The inside of the car is completely computerized and connected to the infrastructure. So many people cannot drive without navigation system. This trend is further accelerated with the progress of autonomous driving. There is no reason to carry energy alone. It is a concept that is appropriate to the car in future 'IoE (Internet of Energy) society' being aimed by SIP (second phase).

One hundred years later, the battery EV that made the present world noisy for a long time, will be seen only in the museum along with gasoline cars and fuel cell cars.

4. Laying Wireless Power onto the Road

In the practical scene of WPT while traveling with a view to laying on a road as shown in Fig. 7, the distance is several meters and the power should be 10 kW. At my laboratory, in collaboration with Toa Road, a major road making company, we are researching a practical laying method.

There are many who are worried that it will need a huge amount of money to build a WPT infrastructure while driving. Then, let us show off the following story.

The Shin-Tomei Expressway, which was partially opened 162 km in April 2012, costs 2.6 trillion yen, including all personnel expenses. When divided, it becomes 16 billion yen per 1 km, but we still have no clear feeling. Then, how about speaking of 16 million yen per meter. A house can be built if we run 3 m. The construction cost of Tokyo Bay Aqua Line and recent subway is 100 million yen per meter. Is it difficult to include WPT equipment in that?

Large-scale cost estimates have already been made. It is only 630.0 billion yen for the WPT system (about 210 000 places of the whole country) during the quasi-driving before the traffic lights, and about 100 billion yen for the WPT system on the highway from Tokyo IC to Toyonaka IC in Osaka.

On the other hand, if about 5 million new cars in Japan will be all EV, and one has 100 kWh battery (5000 ¥/kWh, which is 1/5 of the current price), the total will be 2.5 trillion yen. Surprisingly, the infrastructure for WPT is much inexpensive.

Rather, the problem is who makes it. I share my wisdom all over the world, but I cannot find clear answers. In a democratic country like Japan, we should make a common vision of the future, and the industries have to work together toward that. In countries with a remnant socialist economy, such as China, Korea, and Vietnam, it may be easier.

Table I summarizes the points to be noted in the practical application of WPT during traveling. The ground equipment will be built for several kilometers and over the years, so it will have to be quite simple. On the other hand, equipment on the upper side will be added value to the car, and its life cycle will be shorter, so it may be somewhat advanced. The situation here is completely different from the recent static charging system which has one-to-one equipment on the ground and on the vehicle, and frequently exchanges control signals. The technology of power transfer in stationary manner is not very useful for power transfer while traveling.

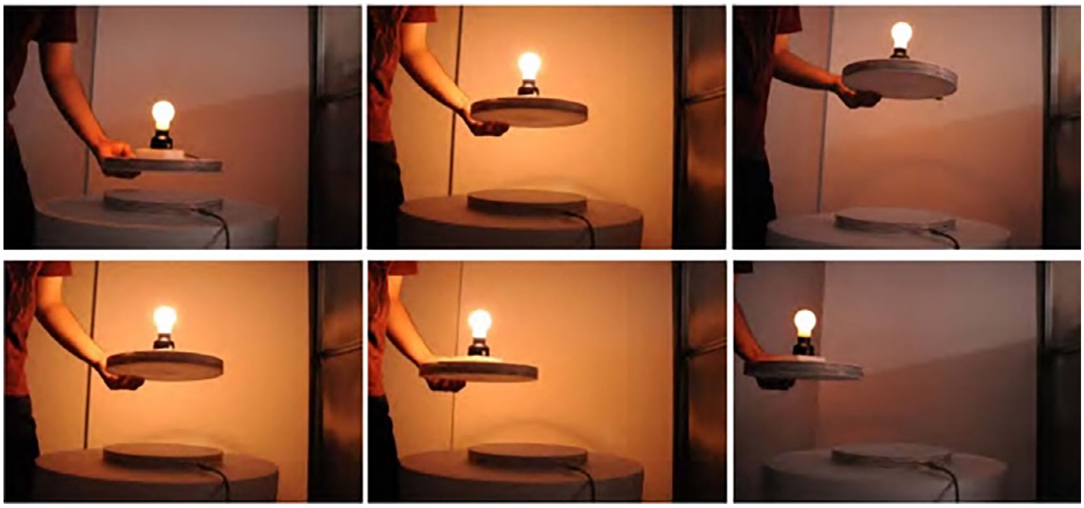

Fig. 5. Wireless power transfer by magnetic resonance coupling (robust against wide gap and lateral displacement)

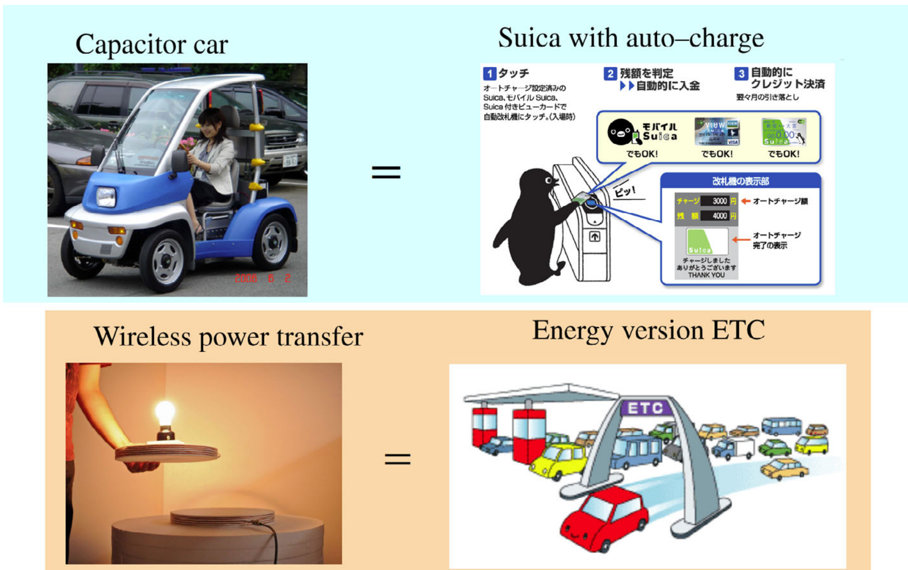

Fig. 6. Concept of motor/capacitor/wireless

Although it is omitted here due to space limitations, EMC (Electro-Magnetic Compatibility) issues from WPT and human protection are well studied, and the standards to be observed are well developed. However, it should be noted that the magnetic resonance coupling method is power transmission using much safer magnetic field, not an electromagnetic wave. These two are different from each other, but there are many people in the world who cannot distinguish the difference between these two.

5. Paradigm Shift every 100 Years

According to Mr. Ken-ichiro Seno [2], the world has experienced a paradigm shift every 100 years. The concept of the 18th century is ‘material’. The industrial revolution took place to make things, and networks such as railways and ships carrying things were built. The concept of the 19th century is ‘energy’, and the energy revolution centered on oil has taken place, and it is new to our memory that the network carrying energy has swept the world (Table II).

The 21st century is an age that embodies the concept ‘information’ born in the 20th century. If you look at the so-called winning companies such as GAFA, the user only has an inexpensive terminal that is just an interface, and the true intelligence is in the Cloud connected by the internet.

Our generation often used to say, ‘Daddy, buy a car for me’, but what was the car that the father bought for his son? engine? exterior? interior? tire? Is it an inverter now? Would you really show off to your friends saying ‘SiC (Silicon-Carbide) inverter in my car is great’?

Just as it is the music itself that buys in iTunes, and Compact Disks (CDs) are not necessary, if buying in cars is a pleasant move and enjoyment of driving, the cars which carry big energy, i.e. engine cars, battery EVs, fuel cell cars are anachronistic products. There is no necessity to own the energy to carry in the age when the car is connected to the information network.

Fig. 7. The day will come when cars run with wireless power supply from guardrails along median strip

I have stated that a car after 100 years will be run by 'motor', 'capacitor', and 'wireless' instead of 'engine', 'battery', and 'quick charge'. This follows the industrial structure theory that Seno said. It is also a necessity of history.

Cars in the future will not carry large amounts of energy, and 'wireless power transfer', which plays the last few meters connecting cars to the power grid, plays an important role. The main line of the optical network is coming up with hardware to very near to our houses, but the last few meters are carried by high-speed Wi-Fi (Wireless Fidelity). WPT is similar to such the information network.

Furthermore, in order to sell a company's car, a car company will maintain a power transfer infrastructure. On railways, both the railway infrastructure and the vehicles that run there are from the same company. This also seems to be an inevitable part of history for carmakers.

Table I. Precautions to be taken in wireless power transfer system in motion

Important Points for Dynamic Wireless Power Transfer

(1) Static and Dynamic Power Supplies are different techniques.

- Let us have this recognition and develop carefully.

(2) Ground equipment must be extremely easy.

- We need to lay the facility for several 100 km.
- Dynamic charge cannot be realized by lots of static charge sets.
- Receiving and transmission sides should not exchange control signals.

(3) Cars can be intelligent and complex.

- Various systems (induction, resonance, microwave) can be adapted to.
- Frequency and voltage are also various.
- Infrastructure is made over 100 years. Cars should receive energy from ancient infrastructure.

(4) Business model holds?

- It would be OK if only highways will be electrified.
- Highway toll of Japan is high. Electricity fee may be included in it.
- Feeding lane can use automatic traveling technology (lane keeping, etc.) for cars not to run above the transmitting coil.

6. Energy after 100 Years

Even in the world after 1000 years, there is no doubt that 'electricity,' which can be finely controlled, plays an important role as a medium for various types of energy.

The massive introduction of solar power and wind power plants significantly threatens the stability of the power system. It is an illusion that it can be averaged if summarized. There are many times that the sun and the wind squeeze all at once on the scale of the wide Kanto district including Tokyo.

Five-megawatt windmill is several times larger than the Jumbo Jet B747. Battery to store approximately of the same capacity is necessary. By multiplying the operating rate 10%, 500 kW is the averagely generated power. You need 2000 wind power stations in order to replace a one million kW generator being used in normal thermal power stations. To make it in a year, you can make 40 units each a week. In order to replace 20% of TEPCO, it is all right to keep making 10 times of that, i.e. only 500 units in a week.

The photo voltaic (PV) power generation is similar. Kyogoku thermal power plant in Hokkaido has a PV power plant on the same site, and both have almost the same area. Because there are two 350 000 kW thermal power plants, a total of 700 000 kW. However, since it is for peak load, the operating rate may be 70%, so it is actually 500 000 kW. The solar power is 1 MW of installed capacity, or 1000 kW. Since the annual power generation amount was 1000 [MWh] in actuality, by being divided by 24 h a day and 365 days a year, it is converted to an hourly rate, $1000\,\mathrm{MWh}/365/24 = 0.1\,\mathrm{MW} = 100\,\mathrm{kW}$. The well-known figure of 10% is obtained as solar power generation's operating rate.

In summary, the PV power plant is of (i) facility capacity 1/700, (ii) actual ability 1/5000. PV power plant requires 5000 times the site area of thermal power. However, we still have to do PV. This is the stance of our society. I pray for good luck.

Then what will be the energy after 100 years? There is no doubt that it is the best mix of various energy sources, but hot-rock power generation (magma power generation) may not be included in it. There is an extraordinary amount of energy sleeping with geothermal power. How about looking at the infinite energy 'underground stars' in the basement without looking only at the sky?

In order to use magma energy stably, it is essential to develop unresolved technologies such as selection of appropriate sites and development of materials that withstand high temperature and high pressure. However, when considering the energy not after 20 and 30 years, but 100 years later, I think that there is enough meaning to make challenge from now on.

Table II. Paradigm shifts every 100 years

	concept	worldview	revolution	network
18th century	material	-	-	-
19th century	energy	materialist view	⇒ industrial revolution	⇒ carry things
20th century	information	space view	⇒ energy revolution	⇒ carry energy
21th century	?	information worldview	⇒ information revolution	⇒ carry information

Source: This table is made by the author inspired from a lecture by Mr. Ken-ichiro Seno.

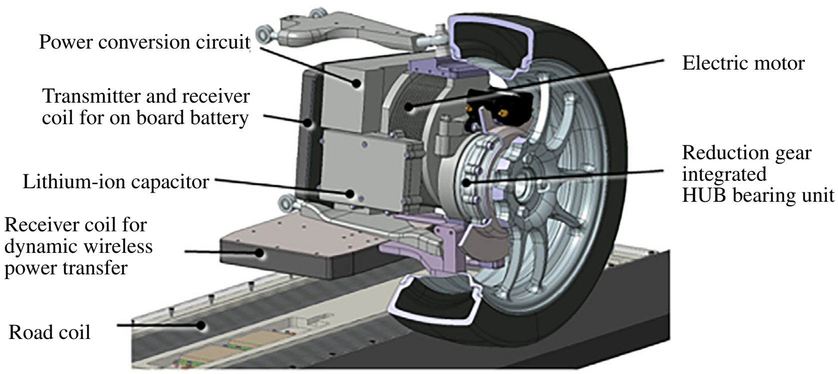

Fig. 8. Wireless in-wheel motor (second generation)

7. Wireless in-Wheel Motor

Finally, I would like to introduce 'Wireless in-wheel motor' by Prof. Fujimoto, who co-operates our laboratory [4–12].

The in-wheel motor has various merits such as the extension of the cruising distance of the EV and the improvement of the running stability. It has been long stated that the un-sprung weight increase is harmful for ride comfort. But it is now a thing of the past. However, there is a risk that the power line that supplies electric power from the vehicle body to the motor may break, so it has not been widely used.

Fujimoto *et al.* applied the wireless power transfer technology to solve this problem and also to respond to power supply while driving. They succeeded in the world's first driving experiment (Fig. 8). A supercapacitor is mounted on the wheel side to improve the efficiency of regenerative braking, and a motor is directly driven by wireless power transfer while traveling from a power transmission facility laid on the road surface. The key technology is power control that utilizes cutting-edge power devices such as *SiC* and cutting-edge control theory that appropriately controls power from various power sources (Fig. 9).

At present, we are laying an experimental road on Kashiwa Campus, University of Tokyo, and conducting experiments vigorously (Fig. 10). According to Fujimoto, the wireless in-wheel motor is the ultimate driving method, and it can be said that it is a good example that embodies the concept of motor/capacitor/wireless in an easy-to-understand manner. The third generation has been complete and unveiled a few months ago.

This research was also included in the framework of a national project and the goal is to supply electricity at 85 kHz during higher speed traveling at 60 km/h or more, 30 kW per EV, and rated efficiency of 90% or more. It is necessary to realize advanced transient response control to feed at high speed. Coil detection compares vehicle-mounted and wheel side coil method. The key company members' aim is the compatible production of the in-station feed system at 85 kHz. The 13.5 MHz feed is now a

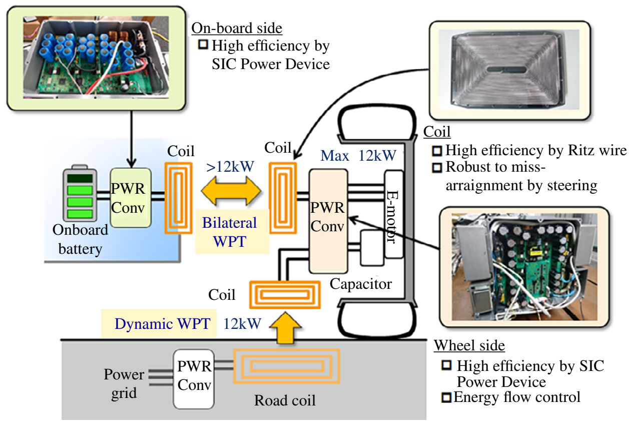

Fig. 9. Power conversion circuit configuration

Fig. 10. Experimental road for power supply in motion (Kashiwa Campus, The University of Tokyo)

fundamental development as a future target. None of this can be imitated in other countries.

8. Conclusion

All things that people are chorusing for no doubt like battery EV may be wrong.

Based on the theory that a strong power grid is essential to the introduction of wind and solar power, if we keep the grid maintenance costs as before, a strong grid remains for power company even if renewable energy fails. I think this will be of much greater benefit to the world. What do you think?

Now, the trend toward electrification of cars is not to be doubted. About 30 years ago, I did not think that cars moving with electric motors would overwhelm the world. There are some who are half-hearted, may say that the EV age has finally come to an end. But I do not think it will be so easy for the era of EVs to flourish. I want to avoid becoming euphoric.

Internet of energy (IoT), artificial intelligence (AI), virtual reality (VR), and so on are the same. There is no intention to argue against the boom, but it is now only after experiencing a long-long winter period. It is necessary to calmly identify the future without being swept into the boom any time. According to the author's poor experience, most of the technology takes 20 years from invention to production. Now WPT is in that state. On the other hand, if you notice an error, it is also important to have a spirit of 'Never hesitate to change'.

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