

October 8, 2015

Press Release

Toyohashi University of Technology

Anritsu Corporation

## **Toyohashi University of Technology and Anritsu Jointly Develop kQ Measurement System for Wireless Power Transfer**

### **Supporting construction of highly efficient transfer links through real time display of kQ**

Toyohashi University of Technology (President: Takashi Onishi, 1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi) and Anritsu Corporation (President: Hirokazu Hashimoto, 5-1-1 Onna, Atsugi-shi, Kanagawa) have jointly developed a “kQ measurement system for wireless power transfer.”

This measurement system was produced by Anritsu developing software for a method of evaluating the  $kQ^{*1}$  product, which is an essential design criterion of wireless power transfer systems<sup>\*2</sup> developed by Professor Takashi Ohira, Director of Research Center for Future Vehicle City at Toyohashi University of Technology. This software is installed in the ShockLine series Vector Network Analyzers MS461xxA, MS463xxA, and MS465xxB.

The ShockLine series sweep the frequency and display the kQ product in real time.

This contributes to the construction of highly efficient wireless power transfer system by enabling the followings:

- Finding the maximum transmission efficiency by changing (scanning) the power transmission and reception positions.
- Improving development speed through quick discovery of structures and dimensions.
- Rapid discovering dependency of the optimum transmission frequency on structural parameters.

Wireless power transfer has many promising applications such as contactless powering of home appliances and electric vehicles as well as energy harvesting<sup>\*3</sup>.

Through joint development of the measurement system for real time evaluation of kQ product,

Toyohashi University of Technology and Anritsu contribute to the worldwide spread of wireless power transfer systems.

Note that part of this measurement system is an achievement of SCOPE (Strategic Information and Communications R&D Promotion Programme) Project #01590001 of the Ministry of Internal Affairs and Communications.

### **[Development Background]**

To construct a wireless power transfer system, a “wireless transfer coupler” is necessary for delivering energy from a high-frequency power source to a load with no contact.

When developing a wireless power transfer system, it is necessary to verify the transfer efficiency.

In the past, “coupling coefficient  $k$ ” was used as an index, and since  $k$  decreases as the power transfer distance becomes longer, it was believed that transmission efficiency would decline.

In 2007 however, MIT (Massachusetts Institute of Technology) announced that they had studied the Q factor (Quality factor) of coils and found that if the Q factor is high, the transfer potential can increase even over long distances, that is, when  $k$  is low.

This proved that it is possible to construct a highly efficient power transfer link if the product of  $k$  and Q is high. Since then, the  $kQ$  product has gained attention as an essential design criterion for wireless transfer.

Through joint development of a system for measuring the  $kQ$  product, Toyohashi University of Technology and Anritsu have made it possible to measure the  $kQ$  product in real time using a Vector Network Analyzer.

Furthermore, a function to simultaneously estimate and display the maximum efficiency  $\eta_{\max}$  (see Reference 3) of a wireless transfer link from the  $kQ$  product using  $\tan\theta$  (efficiency tangent) has also been realized. By using this newly developed measurement system, it is possible to greatly improve prototypes and design high-efficiency couplers of a wireless power transfer.

## **[Overview of Measurement System]**

This newly developed “kQ measurement system” is based on the kQ theory proposed by Professor Takashi Ohira, Director of Research Center for Future Vehicle City at Toyohashi University of Technology and the Vector Network Analyzers MS461xxA, MS463xxA, and MS465xxB produced by Anritsu.

With this system, it is possible to measure the kQ product, which is a design criterion for wireless transfer, in real time.

## **[Main Characteristics]**

Compatible with various coupling schemes such as capacitive coupling<sup>\*4</sup>, inductive coupling<sup>\*5</sup>, and radio wave link<sup>\*6</sup>.

- Calculation and display of kQ product from impedance<sup>\*7</sup> observed at high frequency input and output ports, with reciprocal parts<sup>\*8</sup> composing a wireless power transfer and structure regarded as a black box.

### ■ Improvement of Quality and Efficiency for Research and Development

- Change (scan) power transmission and reception positions to find maximum transmission efficiency

- Improve development speed through early discovery of structures and dimensions

- Rapid discovery of the dependency of optimum transmission frequency on structural parameters.

## **[Technical Information]**

### 1. What is kQ product

K represents the coupling coefficient of a wireless transfer and Q represents the quality of a coil. The kQ product is found by multiplying k and Q, and indicates the essential performance of a wireless transfer, invariant against the impedance of the high-frequency power source and the load (see Reference 1).

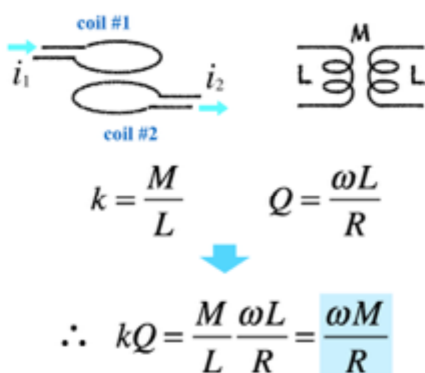
### 2. How to estimate kQ product

The simplest model of a wireless transfer is shown below. Two coils (loops) are placed near to

each other. When a high-frequency current flows in one coil, a current is induced in the other coil. When depicted in a circuit diagram, this is equivalent to a transformer.

When the self-inductance<sup>\*9</sup> of the coil is expressed as L and the mutual inductance between the coils as M, the coupling coefficient is  $k = M/L$ . If the angular frequency of the high-frequency power source is  $\omega$  and the internal resistance of the coil is R, the Q factor is  $Q = \omega L/R$ . From this,  $kQ = \omega M/R$ .

<Simple model of wireless transfer>



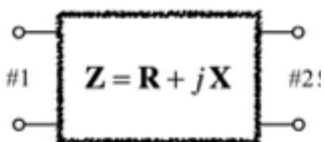
For a simple model like this, the kQ product can be easily calculated.

However, in practice, various schemes are used as wireless power transfer systems, such as capacitive coupling, inductive coupling, and radio wave link. The structure is complex and diverse, so that calculation is not possible with a simple equation like the one given above.

<General theory for calculating kQ product>

The measurement system developed by Toyohashi University of Technology and Anritsu solves the above problem and is capable of finding the kQ product of a wireless transfer with any coupling scheme.

First, a wireless coupler is modeled as a black box as shown in the figure below.



In this figure, #1 indicates a high-frequency input port, #2 indicates the high-frequency output port, and it is assumed that the box can involve various reciprocal elements such as coils, capacitors,

resistors, transformers, transmission lines, printed circuit boards, cables, microwave circuits, antennas (near-field, far field), free space<sup>\*10</sup>, scatterers<sup>\*11</sup>, absorbers<sup>\*12</sup>.

The impedance matrix (Z matrix) of the wireless transfer is measured by a Vector Network Analyzer. The resulting Z matrix is decomposed into its real part R and imaginary part X as ( $\mathbf{Z} = \mathbf{R} + j\mathbf{X}$ ), and by substituting such elements into the "first kQ theorem" shown below, the kQ product is calculated (see Reference 2).

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} + j \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix}$$

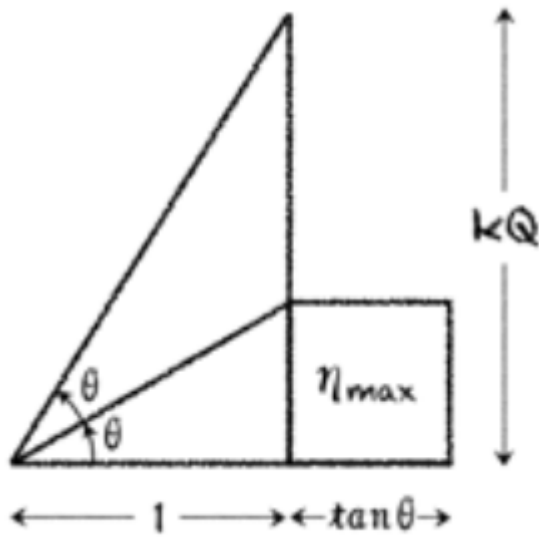
$$kQ = \frac{|Z_{21}|}{\sqrt{|\mathbf{R}|}} = \frac{\sqrt{R_{21}^2 + X_{21}^2}}{\sqrt{R_{11}R_{22} - R_{12}R_{21}}} \quad \text{"First kQ Theorem"}$$

<Relationship between kQ product and  $\eta_{\max}$ >

It was discovered that the kQ product has the following relationship with the maximum efficiency  $\eta_{\max}$  of a wireless transfer. (see Reference 3)

$$\begin{cases} kQ = \tan 2\theta \\ \eta_{\max} = \tan^2 \theta \end{cases} \quad \text{"Second kQ Theorem"}$$

$\theta$  is a parameter that relates kQ and  $\eta_{\max}$ .  $\tan\theta$  is called "efficiency tangent" (and is considered analogous to the dielectric loss tangent  $\tan\delta$ ). The above relationship can be simply illustrated in the chart given below.



As indicated in the chart, to construct a highly efficient wireless transfer system, it is first necessary to increase  $kQ$ . This needs to be considered before providing external reactor elements<sup>\*13</sup>. This is because once energy is lost in the transfer coupler, it cannot be retrieved regardless of how many external elements are added. This is why  $kQ$  is an essential design criterion for a wireless transfer.

<References>

- [1] A. Kurs, et. al., "Wireless power transfer via strongly coupled magnetic resonators," Science, vol.317, pp.83-86, July 2007.
- [2] Takashi Ohira, "Maximum available efficiency formulation based on a black-box model of linear two-port power transfer systems," IEICE Electronics Express, vol.11, no.13, pp.1-6, June 2014.
- [3] Takashi Ohira, "Angular expression of maximum power transfer efficiency in reciprocal two-port systems," IEEE Wireless Power Transfer Conference, pp.228-230, Jeju, May 2014.
- [4] Takashi Ohira, "Welcome to  $kQ$  theory for wireless power transfer," IEICE Journal, vol.98, no.10, pp.885-887, Oct. 2015. (Japanese), Copyright (c) 2015 IEICE

## [Glossary]

### **\*1 kQ**

An index showing the performance of a wireless transfer. The higher value indicates the higher ability for transferring power.

### **\*2 Wireless Power Transfer System**

A system that transfers power without using a power cable

### **\*3 Energy Harvesting**

A technology that collects (or “harvests”) infinitesimal amounts of energy from the peripheral environment and converts such energy to electricity.

### **\*4 Capacitive Coupling**

A wireless power transfer technique where power is transferred using coupling of an electric field generated between electrodes on the transmitter and receiver sides.

### **\*5 Inductive Coupling**

A wireless power transfer technique where power is transferred using coupling of a magnetic field between coils on the transmitter and receiver sides.

### **\*6 Radio wave link**

A wireless power transfer technique where power is transferred by emitted radio waves.

### **\*7 Impedance**

A parameter that represents the ratio between voltage and current in an AC circuit, and indicates a property of opposition to alternating current.

### **\*8 Reciprocal Elements**

Elements whose transfer performance does not change when the input port and output port are switched. These parts do not necessarily have a symmetrical structure.

**\*9 Inductance**

The proportion of the voltage induced across both ends of a coil or an adjacent coil by the change in the current flowing through the coil.

**\*10 Free Space**

Space in which electromagnetic waves can propagate without being affected by reflection or diffraction caused by peripheral obstacles.

**\*11 Scatterer**

An object which reflects incoming electromagnetic waves in multiple of directions. Also referred as a “radio wave scatterer.”

**\*12 Absorber**

A device that absorbs and internally converts incoming electromagnetic waves to thermal energy. Also referred to as a “radio wave absorber.”

**[Exhibiting Company]**

**Anritsu Corporation**

**[Exhibition stage and Booth Number]**

**Key Technologies Stage, 5K49**

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