Integrating a Wireless Power Transfer System into Online Laboratory: Example with NCSLab

Zhongcheng Lei, Wenshan Hu(✉), Hong Zhou, and Weilong Zhang

Department of Automation, School of Power and Mechanical Engineering, Wuhan University, Wuhan, China
{zhongcheng.lei,wenshan.hu,hzhouwuhee, weilongzhang}@whu.edu.cn

Abstract. Wireless Power Transfer (WPT) technology is able to transmit electric power from the Tx side to Rx side without any electrical connection, realizing electrical isolation and breaking through the limitations of electric wires. Traditionally, finding the best working point of the WPT system is difficult as there are a great number of coupled parameters to tune. Besides, the experimenter has to be on site to carry out the experiment with limitations such as time, location, safety issue as well as sharing issue. In this paper, a two-coil structure WPT system is integrated into web-based online laboratory NCSLab using a controller and a DAQ (data acquisition) card as well as an user-defined algorithm. With the latest technologies brought in, NCSLab is completely plug-in free for experimentation on the WPT system. The optimum frequency can be easily obtained by setting the system in the sweep-frequency mode using the remote control platform. The remote control platform NCSLab addresses the safety issue and test rig sharing issue by offering experimenter flexibility to carry out WPT experiment anytime anywhere as long as the Internet is available. T he integration of WPT system into NCSLab also provides teachers with a powerful tool for classroom demonstration of state-of-the-art technology.

Keywords: Wireless Power Transfer (WPT) · Remote control · Data acquisition · State-of-the-art technology sharing

1 Introduction

Wireless Power Transfer (WPT) technology has drawn growing attention in recent years. Limitations on electric wires are no longer problems for the transformation of the electric field to the magnetic field, and then to the electric field. In [1], a far-field technique using propagating electromagnetic waves that transfer energy the same way as radios transmit signals is presented. In contrast to the far-field technique, M. Soljacic [2] introduced a near-field (inductive coupling) technique operating at distances less than a wavelength of the signal being transmitted. As the near-field technique requires relatively low frequency compared with far-field technique, it attracts much research attention since it was proposed [3–6].

M.E. Auer and D.G. Zutin (eds.), *Online Engineering & Internet of Things*,
Lecture Notes in Networks and Systems 22, DOI 10.1007/978-3-319-64352-6_26

WPT systems designed in Wuhan University [7–9] use inductive coupling technique. WPT systems in [8, 9] which could be potentially used for high voltage power cable monitoring were first introduced. All of the systems above adopt a simple 2-coil structure easy for implementation rather than 3-coil [10, 11] or even multi-coil structure [12, 13].

Regarding conventional design, the tuning of parameters has been a problem. Traditionally, finding the best working point of the WPT system is difficult as there are a great number of coupled parameters to tune. What's more, the experimenter of the WPT system has to be on site to carry out the experiment with limitations on time and location as well as safety issue.

State-of-the-art technology is able to keep people informed of the latest trends and hotspot in the related field. However, conventional, it is not easy to share students with the latest technology either for cumbersome equipment or device needs careful attention. For a WPT system with complicated structure and even high voltage generated in the Tx and Rx side while energized, classroom demonstration is difficult.

The complicated implementation of physical system makes it impossible for every university and institution to build a set of WPT system. Thus, it is urgent to address the sharing issue to provide open access for experimentation and research, especially for education of state-of-the-art technology.

The tuning issue, education issue along with sharing issue has brought out the idea of Remote Control WPT (RCWPT) system based on networked control [14, 15] which is a hotspot. There are already a great many of online laboratories which can provide remote control of physical equipment. For example, in [16], the remote control of electric and electronic instruments is introduced in NetLab, GOLDi-labs in [17] allows users to remote control a 3-axis portal and in [18] a remote inclined plane laboratory for displacement measurements versus time is presented.

NCSLab (Networked Control System Laboratory) is a hybrid online laboratory which provides both physical and virtual test rigs for remote experimentation. Previously, only physical and virtual test rigs in control engineering are setup in NCSLab. For example, fan speed control system [19], dual tank [20], and DC motor [21].

In all, there are 20 virtual rigs and six physical test rigs in NCSLab. However, as one of the advantages of NCSLab, test rigs in geographically diverse locations can be integrated into NCSLab [22]. Theoretically, all test rigs that match the interface of NCSLab can be successfully deployed.

However, it remains to be found whether it is possible to utilize NCSLab to explore the WPT system. For example, whether it is able to remotely find out the efficiency, best working point and optimum frequency of the WPT system. Given that NCSLab is powerful platform that new types of test rigs can easily be deployed into its framework through the pre-customized interface, a WPT system could be potentially integrated into NCSLab as well.

The WPT system is a physical test rig containing multiple electric and electronic parts that all need careful attention. As various widgets such as textboxes, charts and gauges are integrated into NCSLab, it provides convenience to remotely monitor and tune parameters in a visual mode. The WPT system in this paper uses a simple 2-coil structure as other ones in Wuhan University.

The rest of the paper is organized as follows. In Sect. 2, the NCSLab architecture is presented. Two of the specific features of NCSLab are also introduced in this part. Section 3 describes the principle of a two-coil WPT system adopted in this paper. In Sect. 4, the integration of WPT system into NCSLab is explored, in which the controller, USB data acquisition card and control algorithm are discussed in details. Section 5 gives an example of a well-configured monitoring interface of the WTP system in NCSLab. The paper is concluded in Sect. 6.

2 NCSLab Architecture

Evolved through over 10 years with the latest upgradation, NCSLab provides full access at www.powersim.whu.edu.cn/ncslab with the advantage of 24/7 with HTML5 technology fitted in. Apart from common features of remote laboratories [23, 24], NCSLab has its specific features, two of which are introduced as follow.

1. Free from plug-ins
   Web-based online laboratory offers convenience without any software installation. However, potential web crash and updating issues caused by plug-ins remains to be addressed. The finalization of HTML5 provides alternative to other 3D engines which needs plug-ins for rendering. As previous Flash 3D engine is replaced by HTML5 technology in NCSLab [25, 26] with more and more web browsers supporting HTML5, experimenter can conduct various experiments in NCSLab in the web browser free from plug-ins.
2. 3D Virtual roaming
   Apart from the tree structure (laboratory - sub-laboratory - test rig) of the NCSLab, virtual roaming which can be parallelly accessed is also provided for the experimenter. Same as in the physical laboratory, the experimenter can go to the virtual laboratory building with keyboard and mouse. Several sub-laboratory room will appear when walking into the main building. If the experimenter chooses one of the sub-laboratory and walks in, a series of virtual experimental equipment will lie on the virtual desks in front of the experimenter. Each virtual test rig is ready for experimentation if it is "picked up" by the experimenter.

Figure 1 shows the current architecture of NCSLab in Wuhan University. Researchers from all over the world can access the system to carry out experiments with registered username and password as all the test rigs are open for experimentation. Test rigs in control engineering as well as WPT system in electric and electronic engineering are integrated into NCSLab.

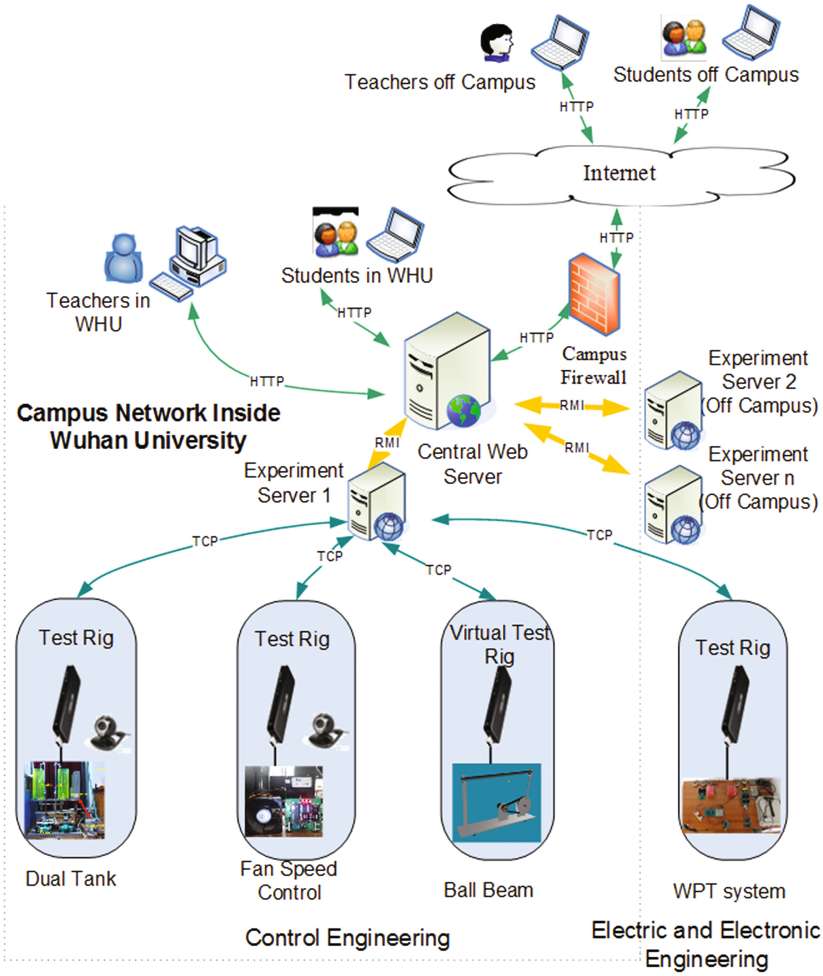


Fig. 1. NCSLab architecture

3 Principle of a Two-Coil WPT System

To provide a RCWPT system, the key issue is to find an appropriate parameter for control using inductive coupling. Another problem to be addressed is to offer observable result for monitoring. Therefore, a simple two-coil structure WPT system is the best option.

The circuit model of two-coil WPT system using magnetically coupled resonator is shown in Fig. 2, in which the Tx coil and the Rx coil share the same resonant frequency. As can be seen in Fig. 2, an AC voltage source drives a RLC branch on the Tx side, which is able to create a high frequency magnetic field on the Tx side. Once the Tx coil is energized at the resonant frequency, the Rx coil can recover the energy from

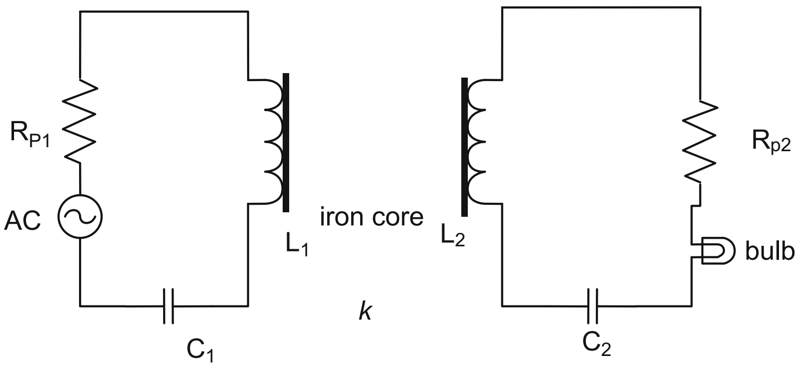


Fig. 2. Circuit model of two-coil WPT system

the field converted from electric power transmitted through the magnetic field between the two coils. Finally the Rx coil can drive a load bulb for observation.

Using Kirchhoff's voltage law (KVL), the two-coil model depicted in Fig. 2 can be analyzed as

$$I_1(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}) + j\omega I_2 M = V_s \tag{1}$$

$$I_2(R_2 + j\omega L_2 + \frac{1}{j\omega C_2}) + j\omega I_1 M = 0 \tag{2}$$

where $R_1 = R_{p1}$, $R_2 = R_{p2}$ and the M is the mutual inductance between the Tx and Rx coil. The relationship between coupling coefficient k and mutual inductance M are

$$M = k\sqrt{L_1 L_2}$$

To simplify the two circuit Eqs. (1) and (2), Z_1 and Z_2 are defined as the impendence of the both circuit loops as

$$Z_1 = R_1 + j\omega L_1 + \frac{1}{j\omega C_1},\ Z_2 = R_2 + j\omega L_2 + \frac{1}{j\omega C_2}$$

The two KVL Eqs. (1) and (2) can be solved as

$$I_1 = \frac{Z_2 V_s}{Z_1 Z_2 + \omega^2 M^2},\ I_2 = -\frac{j\omega M V_s}{Z_1 Z_2 + \omega^2 M^2} \tag{3}$$

4 Implementation of Integrating a WPT System into NCSLab

A WPT system is able to transmit electric power within a reasonable distance. To achieve wireless power transfer, a great many of electronic devices are needed for the practical implementation. Figure 3 demonstrates the diagram of the practical implementation. In Tx side, a H-bridge high frequency inverter is used to convert the DC to AC. On Rx side, a high speed bridge rectifier made of Shockley diodes is used to rectify AC to DC.

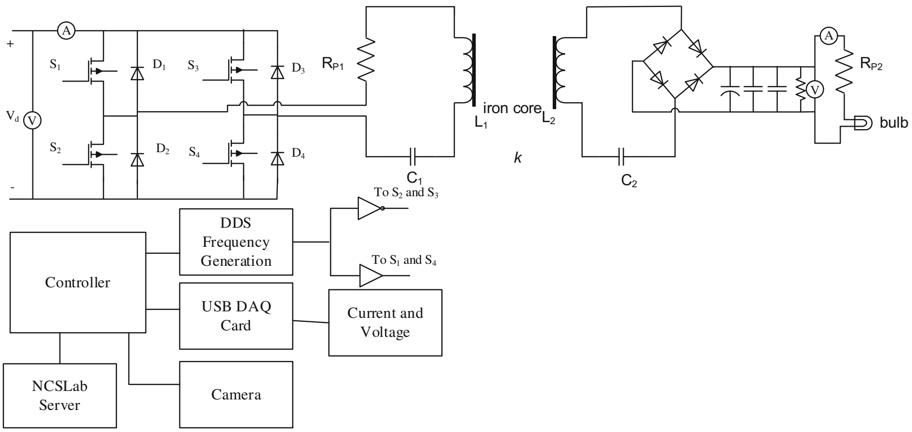


Fig. 3. Diagram of practical implementation

Figure 4 shows the RCWPT system in the physical laboratory, it can be seen that there is no electric connection between the Tx and Rx coils. The physical system can definitely be used for hands-on WPT experiment on site with forementioned limitations. After integration, the RCWPT system called *Wireless Power Transfer* in NCSLab can be accessed at http://www.powersim.whu.edu.cn/ncslab in the Complicated System sub-laboratory for remote experimentation.

Due to the relocation of the laboratory, there is no enough space for the WPT system. Thus, the current WPT system is setup at the corner of the laboratory. For the sake of legibility, the system in Fig. 4 used a picture taken in May, 2016, which is exactly the same system as the current one except for the distance between the two coils. The location of the system demonstrates the advantage of the RCWPT for saving space.

Apart from basic electronic components, in order to integrate the WPT system into NCSLab to build a RCWPT, a controller, a USB DAQ (Data Acquisition) card and an algorithm are three key factors.

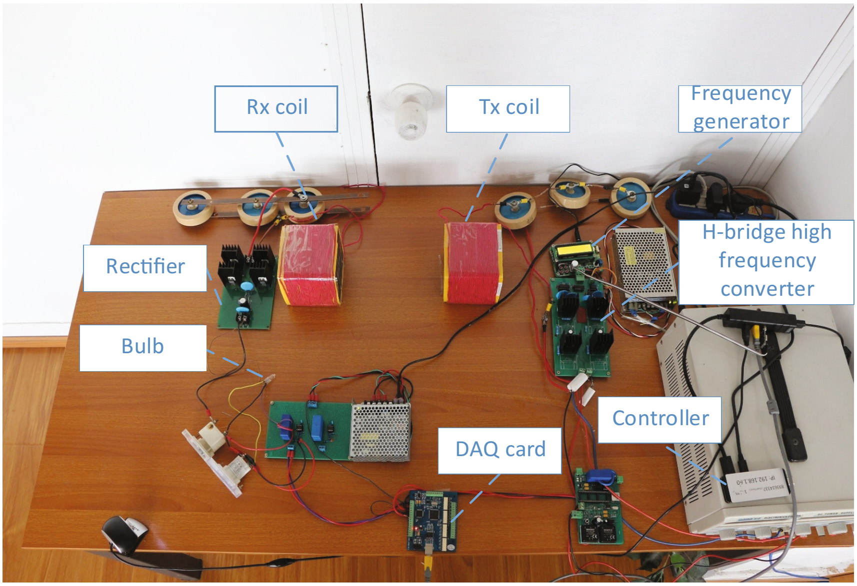


Fig. 4. Remote controlled WPT system (taken in May, 2016 in the old laboratory)

4.1 Windows-Based Controller

Actually, the controller for the RCWPT system is a Windows-based mini PC running communication and camera-supporting program all the time. Figure 5 demonstrates the controller based on mini PC bar. The USB interface board is mainly used.

The camera API is running to support the 24/7 monitoring of the system. For the RCWPT system, two cameras are connected to the controller. One camera is for the overall system. The other is for part of the system, or more precisely, the monitoring of the bulb, ammeter and voltmeter. The ammeter is for the measurement of output

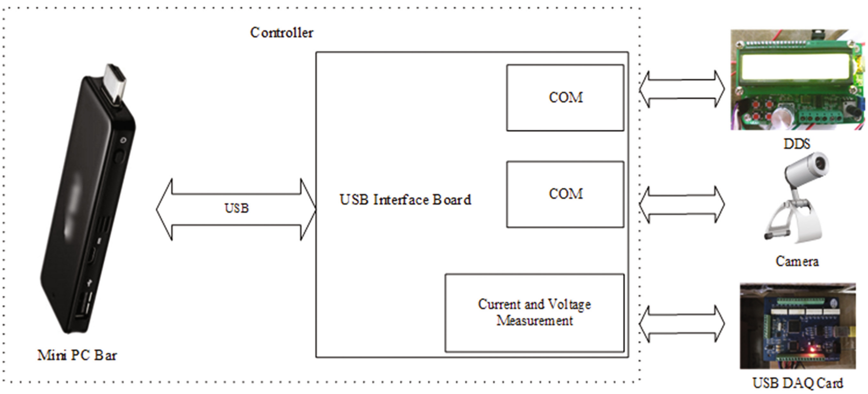


Fig. 5. Controller based on mini PC bar

current, and the voltmeter is to measure the output voltage. The experimenter is able to watch the monitoring result in the web page, in which the brightness of the bulb shows the output power of the system.

Traditionally for other WPT systems in Wuhan University, a direct digital synthesizer (DDS) module controlled by a MCU (microcontroller unit) is adopted to generate the accurate square wave exciting signal [9]. Using the keyboard on the MCU controller, the output frequency can be tuned from 0.1–1 MHz with the step size of 10 Hz. To achieve remote control of the WPT system, the controller is connected to the frequency generator. Parameters such as inciting frequency, sweep frequency and sweep amplitude can be remotely reset as long as it can be found from the control algorithm.

4.2 USB DAQ Card

Another functionality of the controller is the communication with the USB DAQ card. The USB DAQ card is used for collecting signals like the current and voltage both in the Tx and Rx side. It should be noted that the collected current and voltage are measured from the DC side in both the Tx and Rx side, which can be seen in Fig. 3. Using the collected current and voltage, the input power and output power can be calculated. Thus, the transfer efficiency can be obtained.

The DAQ card also monitors the command between the test rig and the server. Command such as algorithm uploading and downloading as well as parameters tuning are under its surveillance.

4.3 Sweep-Frequency Algorithm

The sweep-frequency algorithm is designed in MATLAB/Simulink, and built in Real-time Workshop (RTW). Figure 6 shows the sweep-frequency algorithm in detail. *Setting out* and *Feedback* blocks are two user-defined functions concerning sweep-frequency setting and signals retrieving. After the design and compilation of the algorithm, it is uploaded to the server in the web interface. Program running in the controller can communicate with the algorithm.

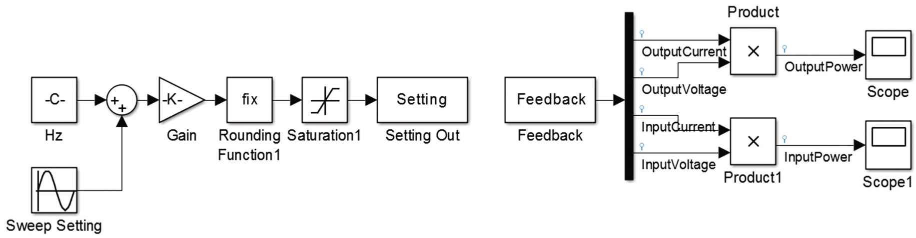


Fig. 6. Sweep-frequency algorithm

The parameters in the algorithm such as frequency “Hz” block and sweep frequency and amplitude in “Sweep Setting” block can be found and tuned in the tree structure of the monitoring and control interface of NCSLab, and signals such as input current, voltage and output current and voltage could be monitored using various widgets offered by NCSLab.

5 Monitoring and Control of the WPT System in NCSLab

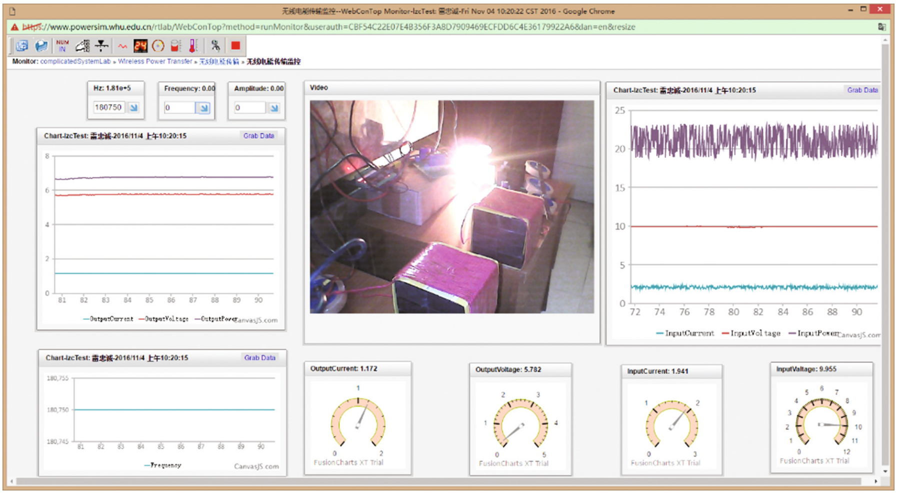
A WPT system can be integrated into NCSLab using hardware and algorithm mentioned in Sect. 4. The remote control platform NCSLab adopts Web structure, which means experimenters don’t have to install any client applications. With the latest technologies brought in, the platform is completely plug-in free, so the experimenter just has to register and login to conduct the experiment on RCWPT system.

As the WPT system is for remote control rather than power delivery, the power transfer efficiency and transferred power is not the priority in this paper, thus, the RCWPT system is built without precise calculation. With the use of various widgets provided by NCSLab, the system is able to monitor signals and parameters such as current, voltage, power and frequency. Parameters such as frequency and sweep-frequency amplitude can be easily controlled in the user-defined interface. Signals can be collected easily using widgets like charts and gauges. More importantly, it helps to remotely explore the optimum transfer frequency by tuning the exciting frequency, sweeping frequency and sweeping amplitude.

In order to analyse the power transfer efficiency and optimum frequency, data such as the input and output power, and working frequency should be collected. In particular, to obtain the optimum frequency, the WPT system should be set in sweep-frequency mode, which is shown in Fig. 7(a). The resonant frequency is 180.75 kHz at the distance of 13 cm with sweep frequency 0.4 and sweep amplitude 1000 Hz, the transfer efficiency can be obtained. Figure 7(b) shows the RCWPT system working at resonant frequency, in which the output current and voltage are 1.172 A and 5.782 V, respectively. It can be calculated that the output power is 6.777 W. From Fig. 7(b), it can be seen clearly that the bulb is brighter than the moment in Fig. 7(a), in which the output current and voltage are 0.8707 A and 2.782 V, respectively, and the output power is 2.422 W.

Once the state-of-the-art WPT technology is integrated into NCSLab, it is able to provide remote access for the teachers and students. On one hand, the teacher can clearly explain the RCWPT system through classroom demonstration. On the other hand, the students can carry out the WPT experiment individually anytime anywhere with customized control and monitoring interface. The integration brings technology close to students with less cost and more convenience.

(a)



(b)

Fig. 7. RCWPT system in NCSLab (a) working at sweep-frequency mode (frequency at 1.8075 kHz ± 1000 Hz, ω = 0.4) (b) working at 1.8075 kHz

6 Conclusion

In this paper, a WPT system is deployed into the NCSLab framework. The integration of WPT system into NCSLab benefits from various monitoring and control widgets of NCSLab. The optimum frequency and best working point can be easily obtained by setting the WPT system in the sweep-frequency mode using widgets of the NCSLab, which shows the results in a visual and intuitive interface. Thus, the system can be adapted to the best working point by resetting the frequency obtained previously, which could make the system working at the best condition and achieve the highest output power. The remote control platform provides flexibility for the experimenter to remotely perform experiment anytime anywhere as long as the Internet is available, which address the tuning issue as well as the safety issue at the same time. Using NCSLab, the WPT system is able to be integrated into online laboratory for remote experimentation for both classroom demonstration and experiment by students, which brings state-of-the-art technology close to students.

Acknowledgement. This work was supported by the National Natural Science Foundation (NNSF) of China under Grant 61374064.

References

1. Sample, A.P., Yeager, D.J., Powledge, P.S., Mamishev, A.V., Smith, J.R.: Design of an RFID-based battery-free programmable sensing platform. IEEE Trans. Instrum. Meas. **57** (11), 2608–2615 (2008)
2. Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J.D., Fisher, P., Soljacic, M.: Wireless power transfer via strongly coupled magnetic resonances. Science **317**(5834), 83–86 (2007)
3. Inagaki, N.: Theory of image impendence matching for inductively coupled power transfer systems. IEEE Trans. Microw. Theory Tech. **62**, 901–908 (2014)
4. Kiani, M., Jow, U.-M., Ghovanloo, M.: Design and optimization of a 3-coil inductive link for efficient wireless power transmission. IEEE Trans. Biomed. Circuits Syst. **5**(6), 579–591 (2011)
5. Sample, A.P., Meyer, D.A., Smith, J.R.: Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer. IEEE Trans. Industr. Electron. **58**(2), 544–554 (2011)
6. Beh, T.C., Kato, M., Imura, T., Oh, S., Hori, Y.: Automated impedance matching system for robust wireless power transfer via magnetic resonance coupling. IEEE Trans. Industr. Electron. **60**(9), 3689–3698 (2013)
7. Deng, Q., Liu, J., Czarkowski, D., Kazimierczuk, M.K., Bojarski, M., Zhou, H., Hu, W.: Frequency-dependent resistance of litz-wire square solenoid coils and quality factor optimization for wireless power transfer. IEEE Trans. Industr. Electron. **63**(5), 2825–2837 (2016)
8. Zhou, H., Zhu, B., Hu, W., Liu, Z., Gao, X.: Modelling and practical implementation of 2-coil wireless power transfer systems. J. Electr. Comput. Eng. **27**, 1–8 (2014)
9. Hu, W., Zhou, H., Deng, Q., Gao, X.: Optimization algorithm and practical implementation for 2-coil wireless power transfer systems. Am. Control Conf. (ACC) **2014**, 4330–4335 (2014)
10. Kang, S.H., Choi, J.H., Harackiewicz, F.J., Jung, C.W.: Magnetic resonant three-coil WPT system between off/in-body for remote energy harvest. IEEE Microwave Wirel. Compon. Lett. **26**(9), 741–743 (2016)
11. Moon, S.C., Kim, B.C., Cho, S.Y., Ahn, C.H., Moon, G.W.: Analysis and design of a wireless power transfer system with an intermediate coil for high efficiency. IEEE Trans. Industr. Electron. **61**(11), 5861–5870 (2014)
12. Yin, J., Lin, D., Lee, C.K., Hui, S.Y.R.: A systematic approach for load monitoring and power control in wireless power transfer systems without any direct output measurement. IEEE Trans. Power Electron. **30**(3), 1657–1667 (2015)

13. RamRakhyani, A.K., Lazzi, G.: Interference-free wireless power transfer system for biomedical implants using multi-coil approach. Electron. Lett. **50**(12), 853–855 (2014)
14. Lai, J., Zhou, H., Lu, X., Yu, X., Hu, W.: Droop-based distributed cooperative control for microgrids with time-varying delays. IEEE Trans. Smart Grid **7**(4), 879–891 (2016)
15. Lu, X., Yu, X., Lai, J., Guerrero, J.M., Zhou, H.: Distributed secondary voltage and frequency control for islanded microgrids with uncertain communication links. IEEE Trans. Indus. Inf. doi:10.1109/TII.2016.2541693
16. Nedic, Z.: Demonstration of collaborative features of remote laboratory NetLab. In: 2012 9th International Conference on Remote Engineering and Virtual Instrumentation (REV), pp. 1–4 (2012)
17. Henke, K., Vietzke, T., Hutschenreuter, R., Wuttke, H.D.: The remote lab cloud 'GOLDi-labs.net'. In: 2016 13th International Conference on Remote Engineering and Virtual Instrumentation (REV), pp. 37–42 (2016)
18. Stefka, P., Zakova, K.: Displacement measurements versus time using a remote inclined plane laboratory. In: 2016 13th International Conference on Remote Engineering and Virtual Instrumentation (REV), pp. 435–439 (2016)
19. Hu, W., Liu, G.-P., Zhou, H.: Web-based 3-D control laboratory for remote real-time experimentation. IEEE Trans. Industr. Electron. **60**(10), 4673–4682 (2013)
20. Hu, W., Zhou, H., Liu, Z.-W., Zhong, L.: Web-based 3D interactive virtual control laboratory based on NCSLab framework. Int. J. Online Eng. **10**(6), 10–18 (2014)
21. Lei, Z., Hu, W., Zhou, H., Zhong, L., Gao, X.: A DC motor position control system in a 3D real-time virtual laboratory environment based on NCSLab 3D. Int. J. Online Eng. **11**(3), 49–55 (2015)
22. Hu, W., Liu, G.-P., Rees, D., Qiao, Y.: Design and implementation of web-based control laboratory for test rigs in geographically diverse locations. IEEE Trans. Industr. Electron. **55** (6), 2343–2354 (2008)
23. Santana, I., Ferre, M., Izaguirre, E., Aracil, R., Hernández, L.: Remote laboratories for education and research purposes in automatic control systems. IEEE Trans. Industr. Inf. **9**(1), 547–556 (2013)
24. Maiti, A., Maxwell, A.D., Kist, A.A.: Features, trends and characteristics of remote access laboratory management systems. Int. J. Online Eng. **10**(2), 30–37 (2014)
25. Lei, Z., Hu, W., Zhou, H.: Deployment of a web-based control laboratory using HTML5. Int. J. Online Eng. **12**(7), 18–23 (2016)
26. Hu, W., Lei, Z., Zhou, H., Liu, G.-P., Deng, Q., Zhou, D., Liu, Z.-W.: Plug-in free web based 3-D interactive laboratory for control engineering education. IEEE Trans. Industr. Electron. doi:10.1109/TIE.2016.2645141