A Cognitive Radio Enabled Smart Grid Testbed Based on Software Defined Radio and Real Time Digital Simulator

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***Abstract*—With the development of Smart Grid, there is an increasing need for the inter discipline research, analysis and evaluation, especially in the joint research area of communication system and power system. In this paper, we propose a Cognitive Radio enabled Smart Grid testbed, which is able to provide real time emulation of the real Smart Grid systems. A prototype with USRP N210, data acquisition and actuator module and Real Time Digital Simulator is implemented, which verifies the framework of the proposed testbed architecture. Evaluation cases show that the proposed testbed is able to provide an average of 9.7ms round trip communication latency and validate real time Smart Grid applications such as voltage stability control.**

I. Introduction

Smart grid is considered to be the next generation of the power grid, which provides a bidirectional information flow within the grid [1]. Power system and communication system are deeply coupled in the Smart Grid system, which poses a challenge on the inter discipline research, analysis and evaluation. To address this challenge, versatile Smart Grid testbeds have been proposed, which provide a safe and practical environment for the integration research in systems such as power system and communication system [2].

Smart Grid testbed is an important platform for the application development, analysis, validation, and evaluation. Field test is usually not cost effective and involves safety issue, while theoretical results lack experimental data validation. Therefore, the hardware and simulator integrated testbeds provide an alternative solution for such requirements [3]. Existing Smart Grid testbeds are mostly addressing either power system aspect or communication system aspect, where there is still a lack of platforms to emulate different power system designs and various communication technologies at the same time [4]. To make it more challenging, this inter discipline oriented platform is desired to run at real time, like the practical Smart Grid systems do.

Wireless communication is the most important technology to span the information connection throughout the Smart Grid system. But spectrum resource scarcity is a challenge to accommodate emerging Smart Grid applications with large volumes of data. Advanced wireless communication technologies such as cognitive radio are promising in addressing this issue [5], but its integration to the Smart Grid system is still under addressed, where validation and evaluation are the key challenges [6]. Besides, Smart Grid is an integration of both power system and communication system, where these two systems are deeply coupled in most practical cases. Hence the analysis within a single system, whether power system or communication system, is not enough to fully evaluate the performance in real cases.

To address the above challenges, we propose a cognitive radio enabled Smart Grid testbed in this paper, which is based on Software Defined Radio (SDR) and Real Time Digital Simulator (RTDS). The proposed testbed provides a framework, which supports real time evaluation of both power system and communication system. The various advanced wireless technologies can be implemented as modules, which are then integrated into the system's module pools and reloaded as required. Meanwhile, the RTDS provides closed-in-loop emulation of the power system, where devices can be connected to the RTDS or simulated by models.

II. Cognitive Radio Enabled Smart Grid Testbed Design

New devices, algorithms or applications must be first evaluated before field deployment, which is also true to the Smart Grid. Theoretical analysis is fundamental to the performance guarantee, yet it is still far from satisfied for the field deployment. But the on-site evaluation during development procedure is not practical for most cases, and it has drawbacks such as high cost and safety problem. Therefore a comprehensive testbed is a very attractive solution, which provides a safe environment for analysis, evaluation and debug. In this section, a Smart Grid testbed framework is proposed. The framework is implemented on a prototype, which is illustrated in Fig. 1 and detailed as follows.

A. Real Time Digital Simulator Enabled Power Grid Evaluation

In power system, it is critical to evaluate new or potential control, protection or application before field deployment. Hence a lot of solutions have been used for emulating the operation of power system, both software and hardware solutions, such as Matpower on Matlab, transient network analyser (TNA) and PSCAD. These existing simulators are mostly off-line solutions, which forms the problem in mathematics and then solve them numerically. However, these off-line simulators cannot interact with the grid components in real

Fig. 1. The implemented prototype of Smart Grid testbed running 4 bus power system test case with USRP, RTDS and Data Acquisition and Actuator (DAA) module.

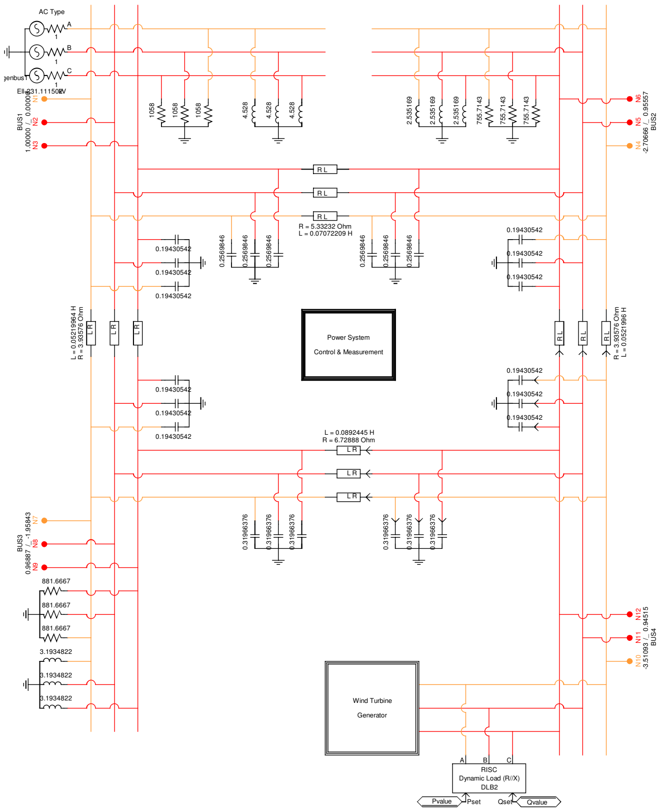


Fig. 2. The implemented 4 bus, 2 generator power system on RTDS.

time like a real power system does. Hence in the proposed Smart Grid testbed, the RTDS system is applied, which has the potential to operate continuously in real time with actual hardware connected in closed-loop [7].

In the proposed Smart Grid testbed, the power system is simulated using the RTDS in real time. The RTDS provides a power system develop environment, where the grid components can be connected through both high voltage interfaces or low voltage I/O interfaces. Besides, the RTDS also provides a model library with common hardware components such as generator, PV panel, wind turbine, SVC and breakers. It also supports customized models, which provides a practical emulation of the real power system. With the RTDS system, the Smart Grid testbed is able to analyse and evaluate a wide range of power system applications, including load flow, control schemes and small signal analysis.

In the prototype RTDS system, the 4 bus power system with one wind farm [8] is modified and implemented, which is given in Fig. 2. The 4 bus power system is also a standard test case that is widely used in the power system researches, which involves the operation of generator, wind turbine, transmission lines, active loads, reactive loads and dynamic loads, as well as the monitor and control of power grid.

B. Software Defined Radio Platform

Unlike traditional radio communication system, SDR defines the components such as mixer and modulator/demodulator as reconfigurable software modules. This architecture enables the SDR based communication system to use different radio fronts and communication protocols with the same hardware. Therefore it makes SDR platform an ideal test and evaluation environment for new and advanced communication technologies in Smart Grid before real world deployment.

In the proposed Smart Grid testbed, we exploit the USRP platform from Ettus, which uses the GNU Radio as development environment. The GNU Radio system running on the computers is a data stream oriented signal processing platform [9]. It processes the baseband communication systems via modularized functions, where the baseband data streams are piped to or from the USRP hardware for transmission or reception. Most system components are modularized on the SDR platform, including Spectrum Sensing module, Machine Learning module, Communication Protocol Pool, Spectrum Sharing module, GUI module and Data Acquisition and Actuator module. With this modularized design, the system is able to replace any parts by reconfiguring the whole system in real time. This feature enables the testbed to be a versatile platform to evaluate, validate and compare different smart grid communication system designs.

In the prototype, the communication system is implemented on USRP N210 running with laptops. The USRP N210 is equipped with CBX daughter board, which provides a wide range of protocol choices available between 1200-6000MHz. All modules are coded in Python or C++. The laptop communicates with the USRP N210 through a gigabyte Ethernet cable. To provide better synchronising performance among different testbed sets, the GPS module BU-353 is applied.

C. Machine Learning Enabled Spectrum Sensing

A great advantage of the Cognitive Radio technology is that it can utilize the unlicensed spectrum for data transmission. This is a very promising way to expand the systems' communication capacity without a huge investment on leasing more spectrum resources. Before any transmission, the transmitter should be aware of the spectrum usage in its surroundings, which is one critical condition for the deployment of cognitive radio based transceivers. Via spectrum sensing, the transceivers can detect the existence of the primary user, who has exclusive usage of this specified spectrum. Then the unused spectrum resources can be exploited for data transmission. In this way, it mitigates the interferences to the primary users' performance. There have been a lot of options for spectrum sensing algorithms, including simple energy detection, wideband sub-Nyquist sampling [5] and machine learning.

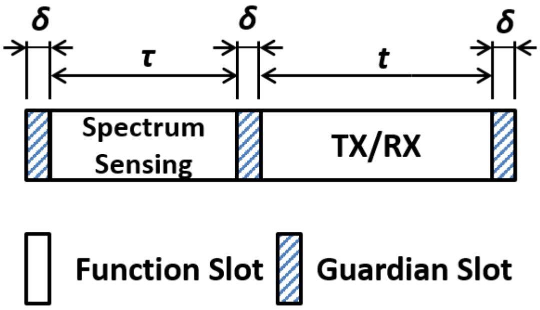


Fig. 3. The frame of spectrum sensing enabled communication network consists of spectrum sensing slot, data transmission and reception slot and guardian slot.

In the proposed Smart Grid testbed, we exploit machine learning algorithms to perform the spectrum sensing. The key concept about spectrum sensing is to learn about the radio frequency environment. The proposed Smart Grid testbed is based on SDR platform, where multiple radio fronts can be exploited via software controls. Hence in this way, this testbed is not confined to specific wireless technologies or frequency bands as most hardware based transceivers do. Thus machine learning can be used as a more versatile spectrum sensing method, which is able to detect a wide range of frequency bands and adapt to different channel features on different frequencies. Besides, as the testbed is built upon SDR platform, it has the potential to evolve the spectrum sensing model along with environmental changes. Each cognitive radio frame can be divided into spectrum sensing slot and data transmission and/or reception slot, where guardian slots may be applied between them, as illustrated in Fig. 3. Within a finely synchronised network, the guardian slots are not necessary, where the efficiency of such network can be given by $\frac{t}{t+\tau}$. On one hand, increasing the sensing time τ will lead to a more accurate spectrum status result, which is essential to the spectrum access decision. On the other hand, the increase of sensing time will reduce network efficiency, which compromises the system's performance. Hence there is a trade-off between the accuracy and time performance in the spectrum sensing algorithms.

In the implemented prototype, we exploit the Extreme Learning Machine (ELM) algorithm as the spectrum sensing algorithm, which is a single hidden layer feedforward neural network [10]. The testbed is able to perform online learning with as little as 10 scans of the frequency bands. The random neurons method is applied with sigmoid as kernel function and 500 neurons. The accuracy threshold for detection is set to be 0.95. Besides, the spectrum sensing algorithm has been modularized, where a spectrum sensing pool is enabled with various choices for different performances. Note that for similar scenarios, the trained model can be transplanted, hence the training procedure is only required when scenarios are changed or no existing model available.

D. Capacity Enhancement via Dynamic Spectrum Sharing

Along with the development of wireless communication technology, the spectrum scarcity problem has been more and more severe. The spectrum resource is one of the critical factors that defines the upper bound of system's throughput. On one hand, it is desirable for the Smart Grid communication network to have an exclusive usage of a certain band of frequencies. But this usually requires a huge investment. On the other hand, the ISM bands are free to use, which can be exploited for data transmission. But it can be noisy and too crowded to use. Therefore, spectrum sharing method is a very attractive method to expand the systems communication capacity. As illustrated in Fig. 4, when the primary users' licensed spectrum resources are not exploited in any dimension such as time, frequency and space, the second user may use them for data transmission temporally. This method is usually referred to as overlay method. The other method is called underlay method, where the second users will communicate with each other under a controlled transmit power, which guarantees that the interference to the primary user is within an acceptable range when they run simultaneously. There have been also hybrid methods combining them to provide a more flexible and efficient spectrum usage [11].

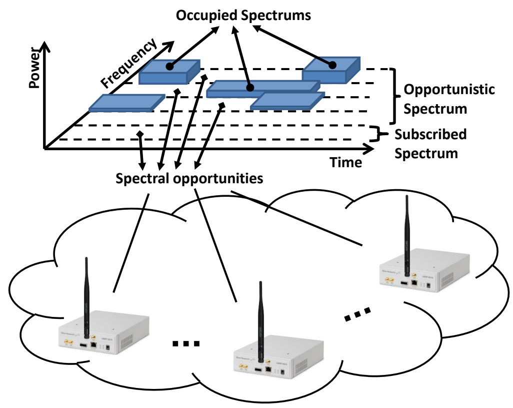


Fig. 4. Cognitive Radio Enabled Smart Grid Communication Networks.

In the proposed testbed design, the system has access to both licensed and unlicensed frequency band via dynamic spectrum sharing. Once the spectrum sensing results indicate spectrum opportunities, the testbed system selects the best communication channel to use. With protocol pool on the SDR platform, the testbed is able to switch to different wireless communication protocols, including but not confined to IEEE 802.11, IEEE 802.22 and IEEE 802.15 protocols. Besides, due to the reconfigurable radio front, the proposed testbed is able to communicate at any available frequency bands, which only depends on the support of the radio frequency board module. This design enables the testbed adaptive to a wide range of scenarios, since ISM bands can be regarded as licensed to the testbed, which can be the case where no exclusive bands are available in home area smart grid application scenarios.

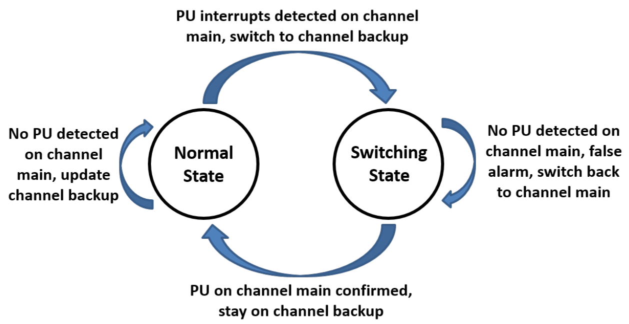


Fig. 5. Two states Finite State Machine for channel access management.

In the prototype, the IEEE 802.11a/p/g protocols [9] on the frequency band 2.4GHz and 5GHz have been adapted for validation purpose, where the encoding options include BPSK 1/2, BPSK 3/4, QPSK 1/2, QPSK 3/4, 16QAM 1/2, 64QAM 3/4, 64QAM 2/3 and 64QAM 3/4. A two state Finite State Machine (FSM) is used for channel access management purpose, which is illustrated in Fig. 5. The mechanism of the two state FSM is designed to avoid the interruption to the primary user and frequently jumping between channels, which is given as follows.

- State 0:
  If primary user is not using the main channel, system stays in State 0 and updates the backup channel. Else the main channel is logged as previous channel, then system switches to backup channel and goes to State 1.
- State 1:
  If primary user is not using the previous channel, it is false alarm and system switches back to the previous channel and goes to State 0. Else the system stays with this channel and goes to state 0.

E. MAC Protocol Data Unit Format

In order to be transmitted and decoded by transceivers, messages are formatted into data frames according to the applied protocols. The date passed from the upper layer will be treated as Service Data Unit (SDU), then it will be attached with some necessary information. For example, in MAC layer, the data from network layer is called MAC layer SDU (MSDU). Then it will be attached with some frame control and address information bits to form the MAC layer Protocol Unit (MPDU), which will be decoded in the MAC layer on the receiver. In the proposed Smart Grid testbed, the data to be communicated between transceivers are manipulated in the MAC layer level. The designed MSDU format is illustrated in Fig. 6, where the meaning of each field is given as follows.

- In Message Type field, the message type of this frame is indicated. The applied message types include control command, measurement, calibration and network command.
- In Node ID field, the data source transceiver node ID is included. Within the whole power grid, each power bus is assigned with a unique ID.
- In Data field, the information to be communicated is included. The contents vary with different message types.
- In Channel Status field, the spectrum sensing results and channel status information are included. In the prototype, the PU channel and SNR are included.
- In Spectrum Sharing Control field, the spectrum sharing related commands and data are included, which depends on the spectrum sharing mechanism. In the prototype, the backup channel is indicated in this field.
- In Time Stamp Field, the generation time for this frame is stamped in this field. This information is important for time-critical Smart Grid application.

5bytes	1byte	10bytes	6bytes	3bytes	5bytes
Message Type	Node ID	Data	Channel Status	Spectrum Sharing Control	Time Stamp

Fig. 6. MAC layer Service Data Unit format.

F. Data Acquisition and Actuator (DAA) Module

The data acquisition components are bridges between the SDR based communication system and the RTDS based power system. In real Smart Grid application scenarios, the data acquisition is fulfilled by different dedicated sensors, such as Voltage Meter and Watt Meter. In the meantime, the control command is executed by the actuators, such as controller and breaker.

In the proposed Smart Grid testbed, the power system operation is emulated with RTDS, where the required sensors and actuators are implemented by functions in RTDS system as well as the DAA module. The measurement outputs and control inputs are fulfilled via low voltage interfaces such as the analogue output from RTDS GTAO or RTDS GTFPI module, analogue input from RTDS GTAI module, digital output from RTDS GTDO module and digital input from RTDS GTDI module. More sophisticated grid control modules are also supported by the designed Smart Grid testbed, where high voltage interfaces are exploited. The DAA module consists of a micro controller and extended supportive circuits, such as bypass filter, DAC module and ADC module.

In the prototype, we apply the ARM MBED NXP LPC 1768 development board as the core of DAA module between RTDS and SDR platform. The MBED module provides versatile interfaces for various purposes, including CAN, PWM, I2C, SPI, Serial, ADC and DAC. The MBED micro controller is programmed to feed the USRP with RTDS GTFPI analogue outputs on demand, while the RTDS control input is achieved via RTDS GTAI interface connected with MBED Analogue Output interface.

III. Smart Grid Testbed Evaluation

The proposed testbed is a versatile experimental platform, which is able to perform the evaluation on both power system and communication system. In order to evaluate the proposed testbed, we implement a prototype with two USRP N210, one USRP B210, three laptops, one MBED system, one set of RTDS system and two GPS modules in the Smart Grid Laboratory at Durham University. The prototype provides an evaluation of the proposed testbed framework with all the proposed features, including power system and control system based on RTDS, data acquisition and actuator via MBED and cognitive radio enabled SDR based on USRP system. In this paper, two evaluations including communication latency and voltage stability control application are detailed as follows.

A. Communication Latency

Communication latency is one of the most concerned parameters in Smart Grid, which is especially true when wireless communication systems are involved. In Smart Grid, there are many delay sensitive applications, where the measurements have to be collected for a real time status monitoring, and the control commands have to be executed within a valid time period.

Therefore, in the prototype, the round trip delay performance has been evaluated. On the transmitter side, a measurement frame is tagged with UTC time as illustrated in Fig. 6, which is synchronised via GPS module. Once the measurement frame is decoded in the MAC layer on the receiver, a calibration frame containing the transmitted frame's time stamp is replied. Then in the MAC layer on the transmitter side, the round trip communication latency is analysed and recorded. Note that in normal operations such as the voltage stability control to be detailed in the next part of this section, the total latency will have other contributors, such as making decisions and running power flows. Thus the evaluated time performance is the minimum achievable latency which only accounts for the communication delay.

On the transmitter side, 800 logs on the round trip time stamps are collected. The histogram of the time performance is given in Fig. 7. A statistical study on the data suggests that the average round trip latency is 9.7ms, where the maximum latency is 12.0ms while minimum latency is 6.9ms. The prototype can achieve a latency on the level of 10ms, which is very promising in enabling the various time critical Smart Grid applications [1].

B. Voltage Stability Control

From the power system aspect of Smart Grid, voltage stability is one of the core power quality parameters. The voltage has to be controlled within a normal range, where too high or too low voltages will damage the devices or reduce their lifetime.

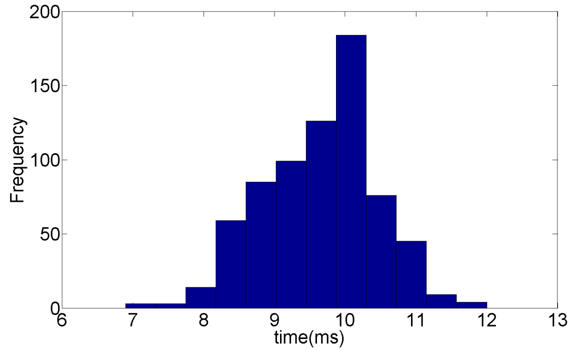


Fig. 7. The round trip time performance.

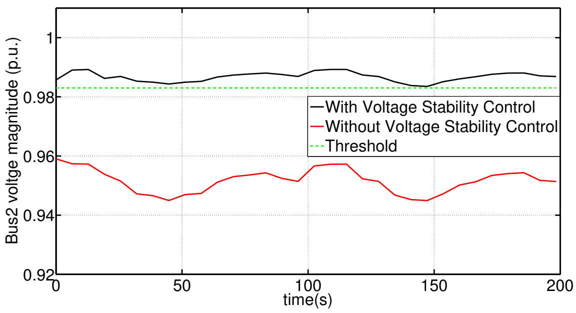
In order to provide an in-depth evaluation of the prototype, a voltage stability control system has been implemented and evaluated. On the RTDS, the modified 4 bus power system with one generator and one wind farm has been emulated. The wind farm attached to bus 4 is able to tune the reactive power production, which can be used to maintain the voltage stability in both local grid and whole grid. A large dynamic load is connected to bus 4, which varies with time to simulate the real cases.

Two sets of SDR platforms are exploited. One set is attached to bus 4, which is referred to as bus node set. It monitors the dynamic load and control the reactive power output from the wind farm on the RTDS via the DAA module. Another set simulates the control center, which communicates with the bus node set to collect measurements and sends the reactive power generation values. On the control center side, the power system state estimation is performed via the power flow algorithm, while the wind farm reactive power production is calculated via the following algorithms.

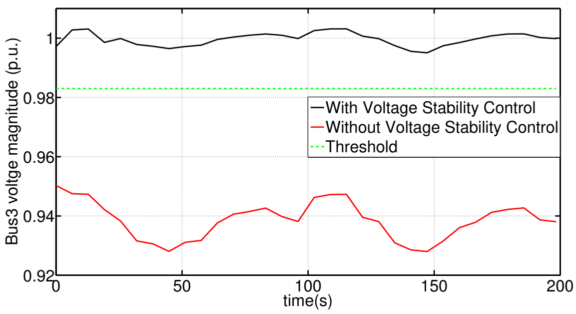
$$\Delta \mathbf{Q} = \mathbf{H} \Delta \mathbf{V}, \tag{1}$$

where $\Delta \mathbf{Q}$ is the required additional reactive power generation and $\mathbf{H}$ is the Jacobian matrix associated to the current power system status, which is obtained via power flow algorithm. $\Delta \mathbf{V}$ is the voltage difference between the current states and the threshold voltage magnitudes. In the implemented system, this desired threshold voltage magnitude is set to 0.983 p.u..

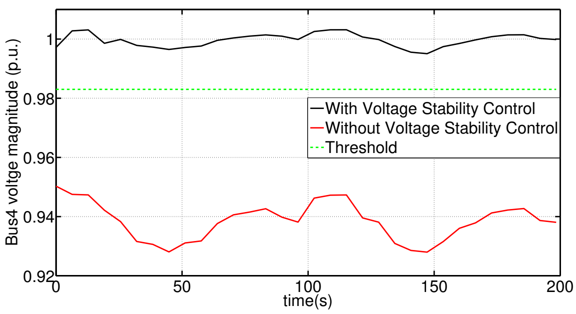
The system is running with IEEE 802.11 a/g/p protocols on the 2.4GHz and 5GHz frequency band. The 5.8GHz frequency band for IEEE 802.11p is assumed to be the primary user's band, which is less crowded in spectrum and has wider bandwidth. An ELM model is trained and exploited for the fast spectrum sensing purpose. Besides, another set of SDR platform is implemented with USRP B210 to simulate the primary user, which may occupy one channel on 5.8GHz at any time. Tests show that when the primary user appears, the implemented FSM channel access management in Fig. 5 is able to switch to the backup channel to avoid interference.



(a) Bus 2 voltage magnitude with v.s. without voltage control.



(b) Bus 3 voltage magnitude with v.s. without voltage control.



(c) Bus 4 voltage magnitude with v.s. without voltage control.

Fig. 8. Bus voltage magnitude performance improvement via the implemented voltage control system on the prototype.

With the real time feature of the testbed, the system is able to provide timely control to stabilize whole grid's voltage magnitudes above the threshold 0.983 p.u., as indicated in Fig. 8a-8c. It can be also indicated from these figures that, the voltage magnitudes are maintained within the range of 0.983-1.010 p.u., which is in a more stable state than the case without control. Also due to the timely control, the variation of the voltage magnitude profile is more desirable than the case without control.

IV. Conclusion

In this paper, we proposed a Smart Grid testbed based on SDR platform and RTDS system. Besides, the Cognitive Radio technology was employed in the communication system, where the spectrum sensing was enabled via machine learning algorithm. The power system was emulated via the RTDS system in real time, where the interfaces between USRP and RTDS systems were supported by a designed DAA module. Two evaluations were performed on the implemented prototype, including communication latency and voltage stability control system. Results showed that the proposed testbed can provide an average of 9.7ms round trip communication latency, and support the real time applications such as voltage stability control. The prototype validated that the proposed Smart Grid testbed was able to provide a comprehensive development environment for both power system and communication system. In the future work, we will implement an extended protocol pool to enable the evaluation of dynamic protocol switching. While on the power system side, we will try to evaluate more real time applications.

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