A Cyber-Physical Modeling and Simulation Environment for Energy Internet

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***Abstract*—In this paper, we propose a Cyber-Physical(Cyber-Energy) simulation model for Energy Internet, which designs the proceeding steps of setting up and revoking the electrical energy transmission path based on integrated infrastructure of information and energy. The model combines the network framework SDN (Software Defined Network) and the VSC-HVDC (Voltage Source Converter based High Voltage Direct Current Transmission technology) as its main features. After illustration of corresponding technologies and the processing steps in details, the simulation is carried out using the*mininet* software for SDN and *PSCAD* software for VSC-HVDC individually. Experimental results show that this modeling can be effectively fulfilled and further improved.**

Keywords-cyber-physical systems; energy internet; SDN; VSC-HVDC; modeling and simulation

I. INTRODUCTION

With the draining of traditional fossil energy and the continually severing global air pollution problem, human begin to explore the new types of clean Distributed Energy Resources (DER). At the same time, energy efficiency in traditional grid needs to be improved, thus the important support role of information communication systems in the grid is being gradually noticed. In order to fulfill the massive access and free share of DER, along with broad information communication between all the components in the grid, the concept of Energy Internet is proposed.

Until now, research on Energy Internet is at the preliminary stage, especially in China, and a few models are proposed at present. One of the popular model is the Cyber-Energy infrastructure integration model proposed in [1]. In this model, the infrastructure of the cyber network and the physical energy network are lied in the same place, even in the same device. This makes the communication and control between the two become very easily, and may further improve the energy efficiency.

In order to implement energy transmission in energy internet through energy routers (or energy switches, which are omitted below), we propose an energy transmitting model based on Cyber-Energy infrastructure integration, set up the corresponding simulation environment and verify its function in this work. This model describes the proceeding steps of energy path set up and revoke in energy internet. By using the Cyber-Energy infrastructure integration, we first set up the communication path in the information space, and record the port numbers used along the path in the information routers. Then, through port mapping (the information router should have the same topology with the energy router based on integration), we can finally set up the energy transmission path. When the energy transmission finished, we can use the similar procedure to revoke the path.

The simulation environment is composed of the *mininet* software for SDN and *PSCAD* software for VSC-HVDC. In the information network part of Energy Internet, we adopt the SDN framework. The SDN framework not only simplifies the control of the network, but also keeps the set up path and revoked path invariant. For the energy network part of Energy Internet, we adopt the VSC-HVDC model (but mainly in the mid or low voltage), as VSC-HVDC is a new type of electrical energy transmission technology suitable for the access of DER and energy sharing between the micro grids.

The structure of this paper is as follows: In Chapter 1 we briefly introduce Energy Internet and the cyber-physical modeling and simulation. In Chapter 2, we will introduce Energy Internet and its basic characters. In Chapter 3, we will introduce the concept of SDN and related *mininet* software. In Chapter 4, we will introduce the VSC-HVDC and related PSCAD software. In Chapter 5 we will illustrate the energy path set up and revoke model mainly in its processing steps. In Chapter 6, we will discuss the model in details, run the simulation and show the relevant simulation results. In Chapter 7, we will conclude and propose further improvement.

II. CYBER-PHYSICAL INTEGRATION AND ENERGY INTERNET

Cyber-Physical integration is a complex, multi-dimensional system integrating computing, network and physical environment [2]. It deeply cooperates the relevant technologies of computation, communication and control. Through technology cooperation, it makes the system more dependable, effective and ease of real-time cooperation. These characters make this technology especially suited for constructing energy internet, and with the development of energy internet, it will bring considerable benefits. The term “Physical” in energy internet referred to electrical energy, and the integration is mainly realized in infrastructure, so we advances the corresponding Cyber-Energy infrastructure integration model as in previous papers[1,3,4,5].

The raw energy internet is more like an access network or a local area network, it accesses the micro grids and connects them with the mainframe grid or interconnects between themselves, so it can be modeled as a middle layer of the grid. But with the developing of energy internet, it can include all the necessary components of the grid, whose performance will be updated by using the information and communication technologies and the idea of Internet. Through information-energy integration, energy internet really realizes the bi-directional energy transmitting on demand and using in balance[3].

As we have already proposed in [6],the developing of electrical energy, especially in information communication technology (ICT), can be divided into three stages. The first stage is in digital and informational stage, ICT serves the electrical energy industry and brings the advantages of convenient and fast. The second stage is in intelligent stage, which sets up smart grid. In this stage, ICT becomes the necessary part of the infrastructure of electrical energy, by combining information and energy streams. The third stage is cyber and physical (energy) integration, which integrates the infrastructures of electrical energy and information communications in energy internet[4].

Energy internet can be seen as the update version of smart grid (smart grid 2.0). Although having great performance improvement, smart grid only uses informational and communication technologiesto make an intelligent gridand solve the basic problems such as efficiency, security, reliability, electrical energy quality and so on[7,8].Energy internet totally reforms the infrastructure framework of electrical energy transmission taking example by Internet.By using this infrastructure, it makes energy exchange as conveniently as the information release in information internet.Through comparison, the key differences between energy internet and traditional energy infrastructure lies in that the former realized the characters of open, interconnected, peer and sharing [1], while the latter only realized partly.

Because the exchange of energy is totally different from that of information, so the existing network frameworks are not suited for the running of energy internet, and we cite a new one in this issue: SDN+VSC-HVDC.

III.SIMULATION ENVIRONMENT: SDN AND THE MININET

SDN is a new type of network framework, it separates the data plane and control plane[9-12]. All the control functions are aggregated into the control node, and the routers only perform the packet transmission functions. The routers transmit the packets using the flow items inside of itself, and the flows items are produced by the control node, and transmitted to the routers through a security communication channel. When a new packet arriving in the routers, the device first finds matched flow items. If not any, it will send the packet to the control node, then the control node will create anew flow item based on the needed network function and send it to the routing device. Then, when following packets arrive, it will simply be archived in the routing device using flow items and perform the action in the matched flow item, such as packet drop or forward.

As shown in figure I, the control plane has two interfaces: northern interface and southern interface, which connect the applications layer and the data plane accordingly.

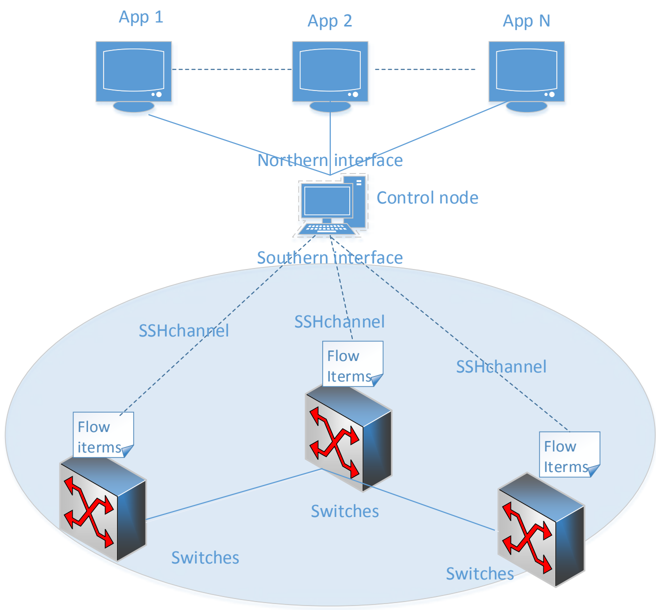

FIGURE I.SDN FRAMEWORK

By this means, the routers avoid the complex settings and chaotic adding of functions in traditional routers. It can add new network functions and change existing functions easily, like firewall deployment in the whole network. The most advantage for researchers is that SDN can arbitrarily (virtually) partition the network, so we can easily experiment the network’s new functions in the same network and do not influence the running of existing network utilities.

The SDN framework basically uses *openflow* protocol [13, 14], one of its realization is *openvswitch*, and you can realize yourself functions based on it such as in [15, 16].

As the easy control and deploy of the network functions in SDN, and the transmission of energy has a higher demand in controllable and reliable than information, we choose SDN as the basic communication network for the information transmission part of energy internet. Another advantage we choosing SDN is that once the route is set up, unless being deliberately modified by the controller or there is a topology change influencing this path, the route can exist all the times, which coincides with the demand of steady communication path (and energy path) in energy internet.

Mininet is a light weight simulation software especially suited for the experiment of SDN. It can simulate all the relevant functions of SDN, and support up to 4096 nodes, which can be either virtual network objects or real network utilities. More important, almost all the functions deployed in *mininet* can be directly transplanted to real SDN networks without any modification, so we choose *mininet* as the simulation tool for running SDN related functions.

IV. SIMULATION ENVIRONMENT: VSC-HVDC AND PSCAD

The SDN network controls the transmission of bit information, but the final goal of Energy Internet based on SDN is to control the transmission of energy flows between the energy routers.

Using Energy Internet, we can dynamically reserve the transmission lines and energy power for one another .This will contribute to the robust of the grid, and avoid the N-1/N-2problem. Also should be noticed, there are spirit differences in the exchange of information and energy (electrical), there is loss in energy transmission, the transmission and receive of energy must be synchronized, the energy storage can’t be easily fulfilled, etc. Although having clear differences, the network topology can be referenced easily.

VSC-HVDC is a new generation of discrete current transmission technology[17-21], it is based on the voltage source converter (VSC), Insulated Gate Bipolar Transistor (IGBT) and Pulse-Width Modulation (PWM)technologies. Using these ones, the grid can work in the status of no-source commutation, and the needed capacity will be reduced largely.

VSC-HVDC can manage the active power and reactive power individually and provide the active power and reactive power support in emergency situations. Using this technology, we can supply the electrical energy to the no-source grid without phase change voltage, avoid phase change failure and no need to communicate between the convertor stations. Now by using VSC-HVDC, we can also easily construct the multi-end discrete systems such as in [22]. Compared to traditional grid transmission technology, VSC-HVDC has the advantages of flexible, easyto control, steady, high modularize, high quality, low volume, high transmission density and low cost. At the same time it can be “plug-and-play”. So, VSC-HVDC can be a non-negligible choose in constructing energy internet.

Using the PLC (power line communication) technology, the communication and energy transmission in energy internet can share the same transmission medium such as HV overhead lines and HV cables, which largely reduces the constructing cost. When realizing PLC, we need to consider the impact of noise and harmonic interference in this medium. As the distance may be long and the voltage may be high, we need to combine the lumped parameter model and the distributed parameter model to analyze the spectrum characters of power line, and decide the working frequency and communication bandwidth of the PLC varied in time.

VSC-HVDC can be simulated in the PSCAD software. PSCAD/EMTDC (Power Systems Computer Aided Design) is a widely used simulation software for Electromagnetic Transients, its core is EMTDC (Electromagnetic Transients including DC), PSCAD provides the graphical operating interfaces for EMTDC[23, 24].

From PSCAD, we can simulation the electrical energy transmissions (using VSC-HVDC) in Energy Internet. It can open or close the switches on demand, and show the results on transmitted current and voltage in short time interval.

V. MODELLING AND SIMULATION

In the integrated Cyber-Energy infrastructure, we can control the information and the electrical energy transmission at the same time. As below processing steps show, we can first set up and revoke the information transmission path, then by port mapping between the information routing ports and the electrical routing ports, we finally set up and revoke the electrical energy transmission path.

This model contains the controller for SDN and that for energy internet. They co-work with each other to realize the running of energy internet (shown in figure II).

Below introduces the processing steps, the first one is for the transmission path set up (shown in figure III).All the packets in these steps are sent using UDP/IP protocol stack.

Step1. Using the information collected from all micro nets (including network status data, energy scheduling data and other data in DC systems), the control node determines the source and the destination micro net needed to transmit the electrical energy, and other information, such as the transmitting time, energy transform strategies and energy quantities can also be obtained. At the same time, it determines the corresponding communication hosts in the two micro nets.

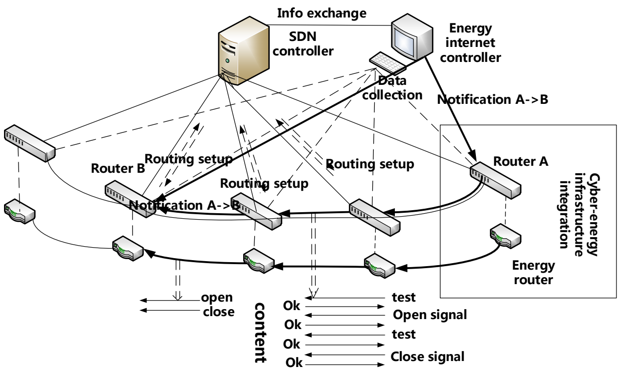

FIGURE II.ENERGY INTERNET MODELINGUSING SDN AND CYBER-ENERGY INTEGRATION

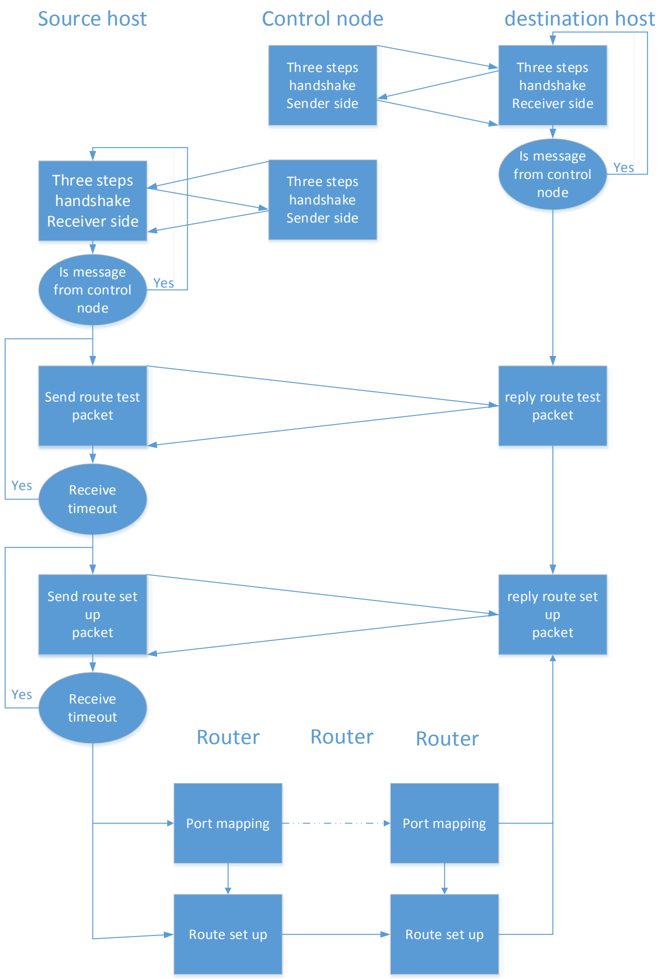

FIGURE III. ROUTING SETUP PROCESSING STEPS

Setp2. The control node sends the transmission task packet to the source communication host and destination communication host, each carries the corresponding destination IP address and the source IP address respectively. In order to ensure the continuous supply of electricity, we can send this packet before the needed time point, and carry the demanded time point information in this packet, then energy internet takes actions according to this time point. So energy internet can set up or revoke the routing path on time and transmit the electrical energy continually.

Step3. The communication between the control node and the source(or destination) communication host in step2 will be processed like a three steps handshakes in TCP set up session, which contains information as “request”-“reply”-“confirm”. It will be finished in turn. First being performed is the communication with the destination node, then it will block to wait for the finishing of that with the source node.

Step4. Based on the destination IP address, the source communication host first sends a routing test packet. In SDN, this packet is used to test the route reachability and/or set up the flow items in the corresponding routers lied in the path between the source and destination host.

Step5. After ensuring the packet is from the source node, the destination communication host replies, containing information like “ok”. (Every request will be replied, so this makes the communication proceeding connection-oriented, both in information and energy, and the reliability is ensured.)Upon receiving the routing test reply packet, the source node sends the routing setup packet. As SDN will function, the transmission path this packet followed will be the same as the test packet’s transmission path. At the same time, it makes the energy routings in DC transmission path invariable. So the management of the path can be easier compared to traditional network.

Step6. When this packet is transmitted along the path, each router it passed (distinguished through special information in this packet) will record the used port numbers inside of themselves.

Step7. Upon receiving the routing setup packet, the destination node will send a reply packet with possible confirm information. Also, the transmission port numbers along the path will be recorded, which should be in reversed order with previously recorded port numbers.

Step8. After checking the port numbers’ validity (in reversed order of the two port number sequences, if is not match, the topology maybe changed), by using the port numbers recorded and the port mapping between the information routers and the electrical energy routers, we can finally set up the electrical energy path.

The setup of network routing and the fulfilling of the above processing is only the necessary condition of the routing setup in energy transmission, the former will be controlled by the latter. Even if the network realized the function listed above, if there is no acceptable condition in energy transmission (based on the status of electrical devices, the regional demand in electrical using, the electrical quality demand and other factors influencing the setup of energy routing paths), the routing setup will be invalid, so the fault management is also needed.

For example, if the control quantities, status information or electrical parameters passed the threshold, the energy router feeds the corresponding fault information to the information routers, and based on the protection strategy of the energy router, it conforms to the information router for rescheduling the transmission route.

In the course of energy transmitting in energy internet, we can use VSC-HVDC to control the quality and the format of electrical energy. Although VSC-HVDC is a very non-linear equipment, it has good quality control functions of electrical energy in itself. Through PWM and related loop feedback control functions in VSC-HVDC, there can be little distortion in the frequency and amplitude of the current and voltage in transmission. The control function can be realized individually and jointly, the latter one may have better performance. In order to avoid adding the complexity of the energy internet in quality control of electrical energy, we can deploy this function only in the outside direction of the micro grid.

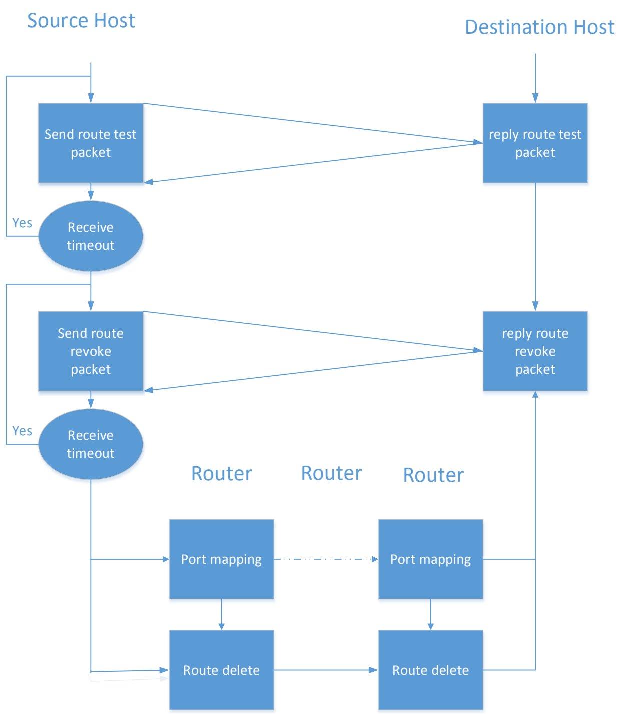

FIGURE IV.ROUTING REVOKE PROCESSING STEPS

When electrical energy transmission is finished, we can revoke the transmission route as follows (shown in figure IV).

Step1. When transmission proceeding finishes, the source communication host first sends a routing test packet, which is also used to test the path reachability. And the destination host checks whether the packet is from the source node and simply replies.

Step2. Upon receiving the reply packet, the source communication host sends the routing revoke packet. Like in path set up proceeding, the transmitting port numbers along the path will be recorded.

Step3. In SDN, unless topology changes(path break up) in the corresponding path, the energy transmission revoke path should be the same as the set up path. If topology change really happens, the energy transmission will be halted, and by energy checking (no energy is detected in the following path in the threshold time period), we can detected the routing failure, so no revoking is needed. And the new routing path will not have the energy transmitted, so the revoke demand also doesn't influence the routers in the new routing path (as validity checking failed). Other faults can be detected and handled in the similar means.

Step4. The destination communication host sends the reply packet, and records the transmission ports along the path.

Step5. After checking the valid of the port sequence and ensuring it is the same with set up port sequence, then by using the port mapping technology, the path is revoked.

The proceeding list above will consider the real network condition, like packets drop and retransmissions. For example, when control node is communicating with source node and destination node, as in the three setup handshake, the communication will be repeated if the control node is either the source host or the destination host in the received packets (though the really realization will be more complex), so to adapt to transmission failure. And when sending the routing test packet or routing set up and revoke packet, the sender will repeated several times if it can't receive the reply in threshold time. And the receiver will reply whenever the request is received.

In order to realize above processing steps, we need to set up communication task between the *mininet* software and the PSCAD software. In *mininet* simulation, we record all of these port numbers, and check their validity in whole as described above, and send to the electrical simulation software (PSCAD) through socket communication. And because the *mininet* is running in Ubuntu in the *vmware* virtual machine, but the PSCAD is running in Windows8. We need to set up the socket for communication between the two. Making the problem more difficult, the corresponding *mininet* functions to be modified and executed are running in the kernel space, which leads to that traditional socket dependent functions in user space can't be directly used. We finally find a socket library - *ksocket* library, which realizes the similar socket functions using the underlying kernel functions. When the port numbers' information is sent to the windows operating system, it can be used to set up the electrical path in the PSCAD.

The proceedings listed above doesn't consider the security factors, but it can be easily implemented. To defend attacks and exclude the information packets which are not from the control node, the host in the communication can install the firewall application. And we can use the authentication method in the communication between the control node and the source host and the destination host to prevent fake path relevant commands. And as the characters of the electrical energy transmission, the replay attack can't reach its purpose.

By adding the electrical energy control and distribution devices or components, we can fulfill the unicast and multicast at the same times (not realized now), which also includes energy path segments reusing. We can add a port using count item in the device. Each time the port is open(being used), we increase the count by one. Each time the port is closed, we decrease the count by one, if there is a path broken, by using energy detection, the count is set to zero, and the port in the disconnection part of the multicast can be closed.

VI.EXPERIMENTALRESULTS

In order to transmit the information of port numbers, we use three components for simulation, which contains *mininet* software, a socket forward file, and PSCAD software, the processing model is illustrated as in figure V.

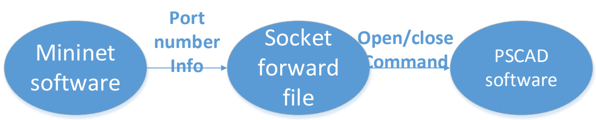

FIGURE V. INFORMATION FORWARD MODEL

In this model, the *mininet* first produces the port numbers along the route path, then it transmits this information to the socket forward file lying in the Windows. After checking the validity of the port numbers, the file generates the routing open/close commands to the PSCAD software, which executes the commands and the route can be opened or closed.

In order to verify this model, we first set up the topology. As we choose the cyber-energy integration, the topology of the information network part and the grid part will basically the same. But in order to realize the control function, we add a controller in the information network part.

We first set up a simple three hosts' information topology shown in figure VI and a two nodes' grid topology shown in figure VII, but they can be more complex as far as you can design.

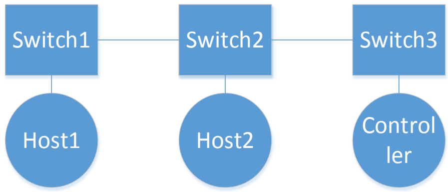

FIGURE VI. INFORMATION TOPOLOGY

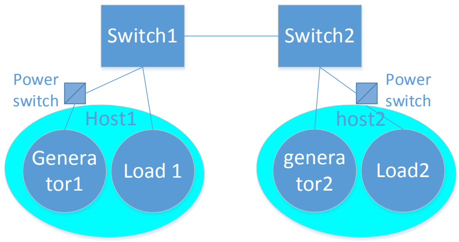

FIGURE VII. GRID TOPOLOGY

The whole simulation is illustrated as follows. At the beginning, the PSCAD begins to run and all switches are closed, then the switches are all open and the *mininet* transmits the route set up command to the PSCAD, the switches along the route are closed so the route is established, after a time interval (which can be changed), the *mininet* transmits the route revoke command to the PSCAD, so the relevant switches will be opened.

The whole processing will be repeated two times. At the first time, it is transmitting the energy from host2 to host1. At the second time, it is transmitting the energy from host1 to host2. The results of the three components are shown below.

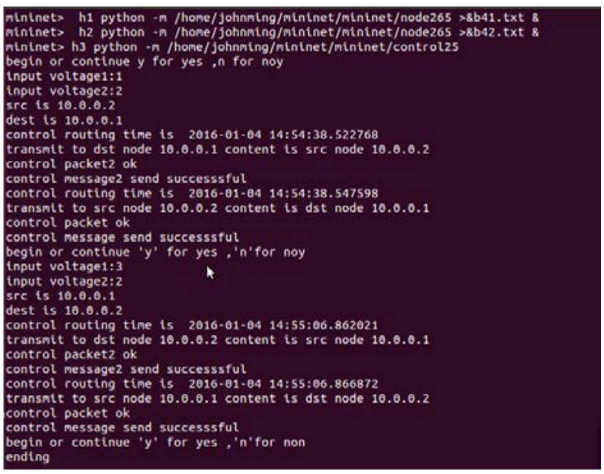

FIGURE VIII. RESULTS FOR CONTROLLER

src_IP is 10.0.0.2

transmit to dst_address 10.0.0.3 message is ok

transmit to dst_address 10.0.0.2 message is ok111

test open road reply

open received time is 2016-01-04 14:54:38.603027

transmit to dst_address 10.0.0.2 message is ok1357

node open in line

transmit to dst_address 10.0.0.2 message is ok111

test close road reply

close received time is 2016-01-04 14:54:53.631976

transmit to dst_address 10.0.0.2 message is ok2468

node close in line

FIGURE IX. RESULTS FOR NODE1 AS A RECEIVER

programme begin

dst_IP is 10.0.0.1

transmit to dst_address 10.0.0.3 message is ok

control routing received, time is 2016-01-04 14:54:38.578478

control data is 10.0.0.1

send packet,destination host is 10.0.0.1

receive reply packet

test road message send/receive successsful

open send time is 2016-01-04 14:54:38.601928

send packet,destination host is 10.0.0.1

receive signal reply packet

open send and receive successful

send packet,destination host is 10.0.0.1

receive reply packet

test close send/receive successsful

close send time is 2016-01-04 14:54:53.630732

send packet,destination host is 10.0.0.1

FIGURE X.RESULTS FOR NODE2 AS A SENDER

```
192.168.163.1 192.168.47.1 Connect to server...
loop enteredhere passed157320000000000000000000000000000000000000000001310packet r
eceived192.168.163.128
here passed123750000000000000000000000000000000000000000013104  6  2  1  1  2  6
 4
route can be set up573200000000000000000000000000000000000000001310
2375000000000000000000000000000000000000000013104  6  2  1  1  2  6  4
3 and 3route can be deleteinput cmd,q for quita
here passed12375000000000000000000000000000000000000000001310packet received192.1
68.163.128
here passed157320000000000000000000000000000000000000000013101  2  6  4  4  6  2
 1
route can be set up237500000000000000000000000000000000000000001310
5732000000000000000000000000000000000000000013101  2  6  4  4  6  2  1
3 and 3route can be deleteinput cmd,q for quit_
```

FIGURE XI. RESULTS FOR SOCKET FORWARDING

Figure VIII-X shows the running results of the *mininet* part, it includes the information produced when sending and receiving the relevantrouting packet.

FigureXI shows the running results of socket forwarding, it includes the information of routing port numbers.

Figure XII shows the signal value in PSCAD. There are three phases in grid, but we only show one phase here. The above line represents the switch status of the generator (left for node1, right for node2, below is the same), and 0 for close (energy passing), 1 for open (not energy passing). The below line represents the status of the switcher, but 1 for close (in fact, it’s a sequence of 0 and 1 alternatively), 0 for open.

Figure XIII shows the current value in the load of node1 and node2. As we can see when the energy is transmitted from node2 to node1 (in the middle part of the two figures). The current amplitude in node1 increases. But when the energy is transmitted from node1 to node2 (in the right part of the two figures). The current amplitude in node2 increases.

Figure XIV shows the voltage value in the load of node1 and node2. When there is energy transmitting, the voltage keeps constant, when there is not, the voltage shakes.

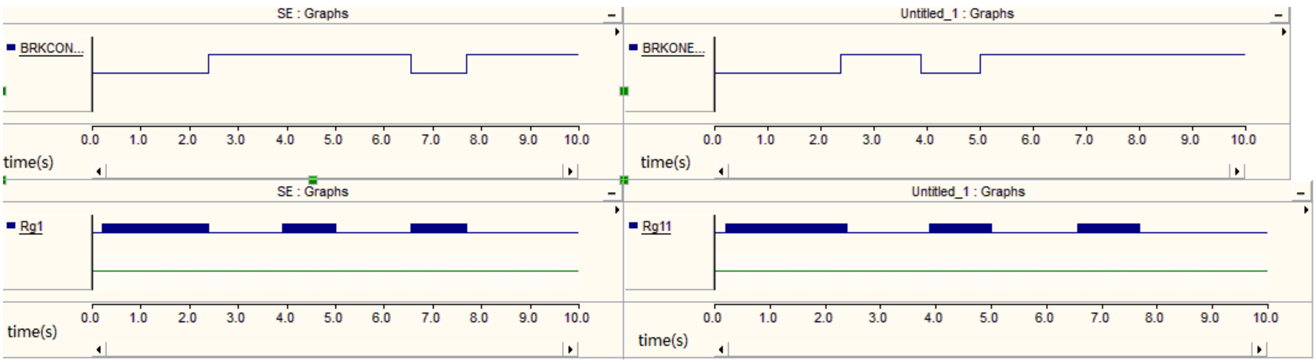

FIGURE XII. RESULTS FOR SIGNAL VALUE IN PSCAD

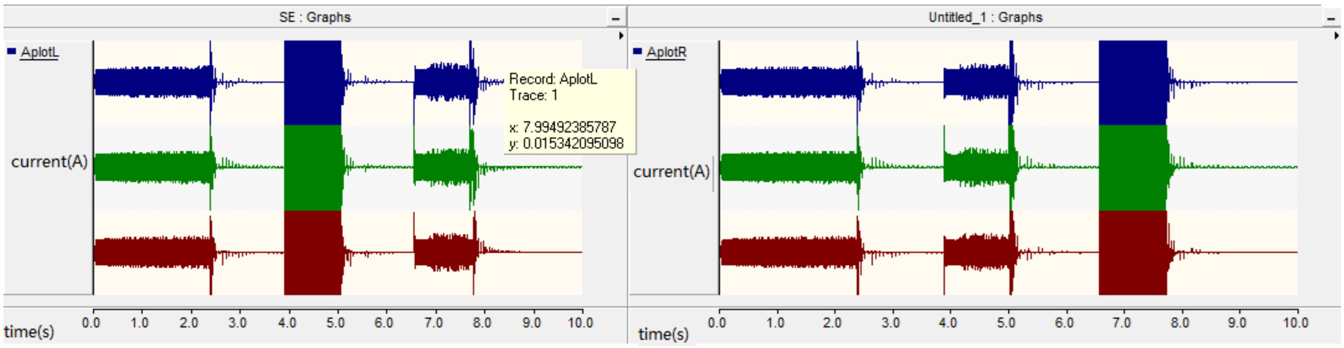

FIGURE XIII.RESULTS FOR CURRENT VALUE IN PSCAD

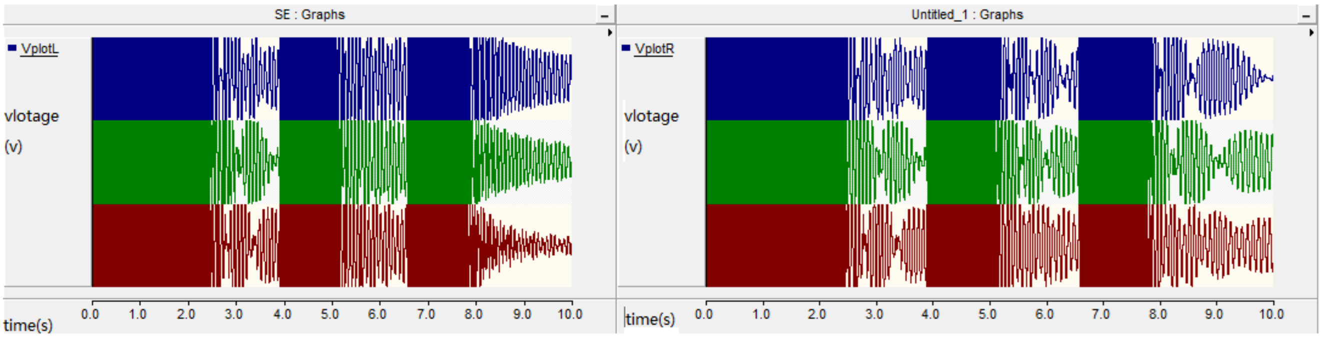

FIGURE XIV. RESULTS FOR VOLTAGE VALUE IN PSCAD

VII.CONCLUSIONS

This paper advances a cyber-physical model and relevant simulation environment of energy internet in electrical energy path set up and revoke processing steps. It combines two software, one is *mininet* running the SDN, and the other is *PSCAD* running VSC-HVDC. The processing steps are illustrated in details and considers the real network communication environment like packet drop or retransmission situation. Then the relevant experiment is executed. As the experiment result shows, it givesa reasonable result and verifies the feasibility of the model.It also further verifies the rationality of the Cyber-Energy infrastructure integration model we advanced in previously papers [5].

The next step of this work is to realize the energy multicast and power distribution when transmission pathsare partly sharedby different source and/or destinations. Also the security options need to be deployed and realized as the following work for constructing a reality energy internet. Also energy detection in the energy router and fault management needs to be realized as auxiliary tools to complete the simulation model.

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