Simulation and Analysis of Multi-Vector Energy Systems and Relevant ICT Networks

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Abstract: *This paper illustrates a simulation of a dual-energy system, which is combined of distributed electricity and heat network, in MATLAB (version R2018a). The electrical system is a single line network, which consists of 4 buses and 1 distributed generator. The heat network is a hydrothermal system with a circle line structure. It has 2 pipes (supply & return pipe), 2 loads and 1 heat source. These two energy systems are coupled via Combined Heat & Power linkage (CHP). Simulation with Different linkage components (CHP, Heat Pump, Circulation Pump) are compared and then validated in IPSA. Then a communication system (CS) for this dual-energy network is modeled in Network Simulator 3 (NS-3 version 3.30.1). The CS is based on Multiprotocol Label Switching (MPLS) network. The topology of this ICT network is composed of 9 terminals, 4 switchers and 1 control center. All channels are based on Carrier Sense Multiple Access protocol (CSMA). A combined analysis of the energy and ICT network explores the effects of packet drops and packet delay.*

Keywords: *Combined heat & power (CHP), Communication system (CS)Multi-energy, Multiprotocol Label Switching (MPLS), Package drop & delay, State estimation (SE).*

1. INTRODUCTION

In conventional industry, various energy networks, like electricity, gas, heat, water etc. are usually independent systems without affecting others. With the development of industrial integration technology, in order to achieve the requirement of high efficiency, appropriate economy and low Greenhouse Gas emission, the concept of multi-vector energy systems is proposed. In such a system, separate energy systems and different energy vectors will be coupled and cooperate via some linkage interfaces, like CHP, CCGT, Heat/Cooling pump etc. As a result, different single system can be considered as a whole system to apply power flow calculation and SE. Various energy systems can cooperate and interact to make the most of energy storage and dispatch, which would improve the flexibility as well as the reliability of the whole system.
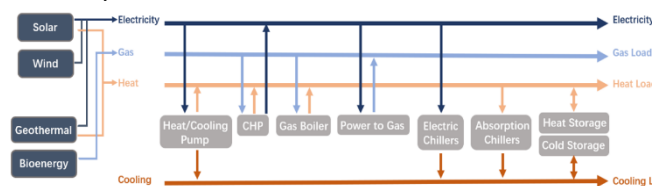

Figure 1. *Diagram of an integrated multi-vector ene8rgy system*

With the development of the power systems, the demands for more efficient and reliable Information and communication technology (ICT) are increasing. Communication systems (CS) is one of the key parts in the Smart Grid, which is also known as cyber-physical power system (CPS) [1]. For energy networks, ICT can make data information and instructions visualized and flow bidirectionally between nodes in systems and between infrastructures and users. It is the guarantee for information, monitoring, control, and protection, which helps to control and coordinate energy networks in multi-vector systems [2]. The main goals of the ICT network can be summarized as follow:

- Making real-time operation to dispatch power efficiently
- Identifying certain aspects related to operation planning such as operation point, working margin, and fault level.
- Identifying the energy flow in systems, like the power generation, power consumption, energy conversion etc.

The ICT systems will be set up based on several internet protocols, such as the Label Distribution protocol (LDP), Multiprotocol Label Switching (MPLS), Carrier Sense Multiple Access & Collision detection (CSMA/CD), etc., which will enable the ICT

networks to label data packets, retrieve the packets' labels, and distribute packets. With the data collection from the phasor measurement units (PMU), the remote terminal units (RTU) and smart meters connected to the ICT network (or SCADA), state estimation (SE) could be carried out. With optimal ICT systems, SE can be more accurate, which can help to locate the energy system working point, analyze operating characteristics, adjust operation plan and predict future peak time and potential fault level. Since the interdependency between CS and energy grids is getting stronger, it is necessary to do some research on the impact of communication network on power systems, such as packet drop & packet delay.

2. DUAL VECTOR ENERGY SYSTEM'S SIMULATION

This paper illustrates a simulation of a dual-vector energy system, as shown in Fig. 2. This integrated energy network combined a distribution electricity network and a district heating network. These two energy systems are coupled by a linkage unit, which consists of CHP, heat pump and circulation pump. There is only one coupling linkage, which means the energy conversion is unidirectional rather bidirectional.
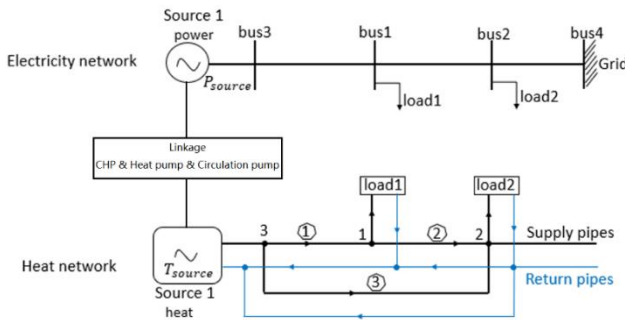

Figure 2. *An electricity and heat combined dual-vector energy system with radial topology*

The power flow direction is from the hydrothermal network to the electricity network. The return heat power of the heat source will be transferred into electricity power via linkage point, which will be regarded as the input to electricity network.

2.1. Electricity networks

The typical computation approach of the power flow is Newton-Raphson, which provides an iterated calculation method for this problem. First, the objective function should be set up. For a single bus, the power balance should be:

$$\dot{S}_{injected} = P_{injected} + jQ_{injected} \qquad (1)$$

$$\dot{S}_{injected} = \dot{V} \cdot \dot{I}_{injected} = \dot{V} \cdot \sum_{i\epsilon n} \dot{Y}^* \cdot \dot{V}^* \qquad (2)$$

represents a vector, $S_{injected}$, $P_{injected}$ & $Q_{injected}$ are the apparent power, active and reactive power injected in the relative nodes, j is the sign of imaginary part, V is the voltage magnitude, $I_{injected}$ is the injected current, Y is the admittance matrix of the relative nodes.

The expression of voltage can be rewritten as:

$$\dot{V} = V\angle\theta \quad \& \quad \dot{V}^* = V\angle - \theta \qquad (3)$$

Substitute the equation (3) into equation (2) to get:

$$\dot{S}_{injected} = \sum_{i\epsilon n} V_k V_i(G_{ki}cos\theta_{ki} + B_{ki}sin\theta_{ki}) + j\sum_{i\epsilon n} V_k V_i(G_{ki}sin\theta_{ki} - B_{ki}cos\theta_{ki}) \qquad (4)$$

G_{ki} is the conductivity between node k and node i, B_{ki} is the susceptance between the node k and node i. (it should be noticed that node k and node i are connected)

Therefore, the objective function of the power flow is established as:

$$\Delta F = \begin{bmatrix} \Delta P_{k,injected} \\ \Delta P_{Q,injected} \end{bmatrix} = \begin{bmatrix} \sum_{i\epsilon n} V_k V_i(G_{ki}cos\theta_{ki} + B_{ki}sin\theta_{ki}) - P_{k,injected} \\ \sum_{i\epsilon n} V_k V_i(G_{ki}sin\theta_{ki} - B_{ki}cos\theta_{ki}) - Q_{k,injected} \end{bmatrix} \qquad (5)$$

ΔF represents the mismatch function.

2.2. Heating networks
2.2.1. Hydraulic model:

In hydraulic model, there are flow continuity and loop pressure formulas for water mass flow rates and pressure head loss calculation, which has the similar forms and functions to Kirchhoff's laws in electrical model [5]. The flow continuity function is used to clarify the relationship between water mass flow consumption and input/output mass flow at relative nodes, which is similar to the Kirchhoff's current law [6]

$$\sum \dot{m}_{input} - \sum \dot{m}_{ouput} = \dot{m}_q \Rightarrow A\dot{m} = \dot{m}_q \qquad (6)$$

$\dot{m}_{input}$ and $\dot{m}_{ouput}$ are the input/output water mass flow rates (kg/s), $\dot{m}_q$ is the water mass flow rates (kg/s) at relative nodes, A is direction matrix (The rows and columns in matrix A refer to the number of nodes and pipes [7], +1/-1 represents the mass flow direction is input/output, 0 represents the mass flow is not relevant to the node).

Due to the friction, the water pressure will change with transmission distance along the pipe. The per meter difference of pressure is called head loss [7]. It should be noticed that the total head loss should be zero when the system is in a closed loop. The loop pressure equation is:

$$\sum h_f = Bh_f = BK\dot{m}|\dot{m}| = \sum_{j=1}^{n_{pipe}} B_{ij}K_{ij}\dot{m}_j|\dot{m}_j| = 0 \qquad (7)$$

h_f is head loss (m) in plumbing, K is the resistance coefficient of pipes, i is the sequence of loops, j is the sequence of pipes, B is the direction matrix (The rows and columns in matrix B refer to the number of loops and pipes [7], +1/-1 represents the mass flow direction is same/opposite to defined).

2.2.2. Thermal model:

Compared to the hydraulic model, thermal model is a little more complex with more unknown variables and known conditions. The temperature of both supply pipes and return pipes are denoted as T_s and T_r respectively. Besides that, another scalar is also provided, which is the temperature of the outlet line from the heating load and it is denoted as T_o [6]. Generally, T_s and T_r of the heating supply source are known. Besides, T_o of each load nodes also should be a known variable, as it will be used to calculate the T_s and T_r of load nodes. The relationship between T_o and T_s on the load node can be described as below [8]:

$$\emptyset = C_p \dot{m}_q (T_s - T_o) \tag{8}$$

$\emptyset$ is the heat power of the nodes, C_p is the default water specific heat capacity (J/kg℃), $\dot{m}_q$ is the mass flow rates (kg/s) of the load nodes ($\dot{m}_q$ is also an unknown variables), T_s/T_o is the temperature (℃) of the supply/outlet pipes connected to the load nodes.

Due to the heat loss in the form of heat exchange or heat radiation during the transmission, the temperature will change along the pipes. Thus, the temperature drop formula is needed:

$$T_{end} = (T_{start} - T_a)e^{-\frac{\lambda L}{C_p m}} + T_a \tag{9}$$

T_{end}/T_{start} is the temperature (℃) of the pipe's end/start, T_a is the environmental temperature (℃), λ is the per unit heat loss coefficients (W/(m K)) along the pipes, L is the pipe length (m).

For some nodes, there are over two input pipes connected to it. These kinds of nodes are called mixed nodes and the equation (9) is no longer effective to them [9]. For the mixed nodes, the temperature calculation should be:

$$\left(\sum \dot{m}_{output}\right)T_{output} = \sum(\dot{m}_{input} T_{input}) \tag{10}$$

T_{output}/T_{input} is the mixed temperature (℃) at the output/input of the mixed node.

2.3. Dual-vector energy networks
2.3.1. Coupling linkage model:

For CHP units, the energy conversion is from heat to electricity. The ratio of heat-to-power is determined by the input heat power and output electrical power, which is normally a constant value:

$$C_m = \frac{\emptyset_{CHP}}{P_{CHP}} \tag{11}$$

C_m is the heat-to-power conversion ratio, $\emptyset_{CHP}$ is the output heat power (MW), P_{CHP} is the output electrical power (MW).

For heat pumps, the heat can be transmitted from area with low temperature to high temperature via air compressor [10]. The efficiency function of the heat pumps is :

$$COP = \frac{\emptyset_{HP}}{P_{HP}} \tag{12}$$

COP is the efficiency coefficient, $\emptyset_{HP}$ is the heat power (MW) supplied by heat pumps, P_{HP} is the electrical power (MW) consumed by heat pumps.

For circulation pumps, it is used for maintaining the promising water pressure to drive the circulation of water flow [11]. The circulation pump is driven by electricity, which can be regarded as an electrical load, and the power function is [12]:

$$P_{CP} = \frac{\dot{m}_{CP} \cdot g \cdot H_{CP}}{10^6 \cdot \eta_{CP}} \tag{13}$$

P_{CP} is the power consumption (MW) of the circulation pumps, H_{CP} is the head loss (m) of the circulation pumps, η_{CP} is the efficiency of the circulation pump.

For CHP & heat pump combined linkages, the conversion ratio of heat-to-power is:

$$C_m' = \frac{\emptyset_{source}}{P_{source}} = \frac{\emptyset_{CHP} + aP_{CHP} COP}{(1-a)P_{CHP}} \tag{14}$$

Substitute the equation (12) into equation (14):

$$C_m' = \frac{\emptyset_{source}}{P_{source}} = \frac{C_m + a COP}{(1-a)} \tag{15}$$

P_{source} is the output electrical power (MW) of the combined linkage, $\emptyset_{source}$ is the output heat power (MW) of the combined linkage, a is proportion of the electricity produced by CHP, C_m' is the heat-to-power ratio of the combined linkage.

The function of the combined coupling linkage can be expressed as:

$$P_{source} = \begin{cases} \frac{\emptyset_{source}}{C_m} & CHP \\ \frac{\emptyset_{source}}{C_m} - P_{CP} & CHP \cdot Circulation\,pump \\ \frac{\emptyset_{source}}{C_m'} - P_{CP} & CHP \cdot Circulation\,pump \cdot Heat\,pump \end{cases} \tag{16}$$

2.3.2. Integrated energy networks model:

In this dual-vector energy network, the unknown variables and initial conditions are:

Table 1. *Initial conditions and unknown variables of the dual-energy network*

Variables	Initial conditions		Unknown values	
Voltage magnitude	$|V_3|$	$|V_4|$	$|V_1|$	$|V_2|$
Voltage angle	θ_4		θ_1 θ_2 θ_3	
Active power	P_1	P_2	P_3	P_4
Reactive power	Q_1	Q_2	Q_3	Q_4
Mass flow rate			$\dot{m}_1$ $\dot{m}_2$ $\dot{m}_3$	
Supply temperature	T_{s3}		T_{s1} T_{s2}	
Return temperature	T_{o1}	T_{o2}	T_{r1} T_{r2} T_{r3}	
Heat power	ϕ_1	ϕ_2	ϕ_3	

For integrated method, the hydraulic equations, thermal equations and electrical power flow equations are analyzed and solved simultaneously by Newton-Raphson method [6]. As a result, there will be only one matrix of objective functions, and only one Jacobian matrix.

3. ICT NETWORK SIMULATION

3.1. Protocols and concepts of ICT

3.1.1. Label:

A data packet will be labeled before forwarding to the next hop. The information involved by the label is the attributes of the date, including data types, data length, data forwarding method, data processing method, etc. The label attached to the data, is an index to indicate the next hop for the transmitted data. The label will be updated after each hop [13].

3.1.2. Label distribution protocol (LDP):

The Label Distribution Protocol (LDP) is used to establish Multiprotocol Label Switching networks (MPLS) and Label switched path (LSP). There are many routers in the communication networks. Following the existing IP routing table, LPD can be utilized to set up LSP. The basic service of LDP is pseudo-wire, which can be used to simulate nearly every type of wired service. Besides, it can carry almost any kind of data flow.

3.1.3. Label switched path (LSP):

The label switched path (LSP) is the path through the MPLS networks. It is usually established by network transmission protocols, such as LDP, for different purposes. Sometimes, the path is established to create IP virtual private networks, or to guide the data flow through particular paths. Generally speaking, LSP can be regarded as the tunnels between the routers in networks. The LSP is unidirectional. Therefore, it usually set up dual LSP systems to realize the bidirectional communication [14].

3.1.4. Multiprotocol label switching (MPLS):

Multiprotocol Label Switching is a technique rather a service. It can deliver nearly anything from IP VPNs to Ethernet. In conventional internet, when a router receives IP packets, it will only receive the information about the destination, without any other message about how to deliver it. It slows down the data flow speed significantly, since every distribution of the router should refer to the complex routing tables. It will impact some data required high quality, like IP video data.

MPLS will establish pre-determined routes at the beginning of the data transmission process. When the data packet is produced, a label will be attached to it, which involves the forwarding equivalence class (FEC). All the routers in the network have the FEC table. Once the packet starts to be delivered, routers will use the label as index for the FEC table, rather than carry out header analysis. In this way, MPLS networks are able to process packets with specific characteristics in a consistent method, thereby reducing network-wide routing delays. MPLS can only operate after the establishment of LSP. And the key point of the MPLS is the label. The MPLS label is composed of four components, Label, Experimental, Bottom-of-stack, Time-to-live [15].

3.1.5. Carrier sense multiple access/Collision detection (CSMA/CD)

Carrier sense multiple access creates a regulation, which determines the communication methods in a shared communication media. The collision detection is an extension of the CSMA, which determines the solutions for transmission collisions. Transmission collision means several terminals are trying to send data packets through a same channel.

During the process, the station monitors will supervise the data channel. Only when the channel is free, the station will start to send data packet. Then the transmitter will keep monitoring the channel to check the data collisions. If there is no collision, the data transmission will be successful. However, if collisions occur, the station will stop immediately, and begin to send interferential signal (Jam signal) to inform other stations. The stations will then wait for another appropriate time to try it again [16].

3.2. ICT for energy networks

In the distribution network of electrical systems, the plenty of sensors are the main source of electrical data. Generally, these kinds of sensors are some synchro-phasors monitoring units, such as the phasor measurement units (PMU) and the remote terminal unit (RTU). These synchro-phasor measurement units can actively obtain the real-time data with the rate of 10-60 samples per second [17].
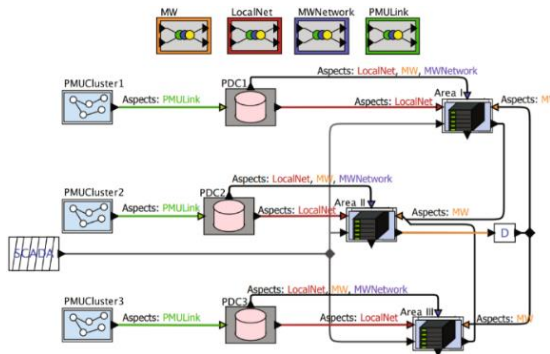
Figure 3. *A typical framework of the ICT network for a distribution network [17]*

From the Figure 3, there are three aspects of the ICT network model with different topology.

For the LocalNet, it models the inter-area links as a server with probabilistic delay characteristics, which involves three kinds of communication links:

- PDC to Area: Local area links are used for PMU readings sending to areas used in distributed network.
- PDC to Middleware: The links used for sending PMU data to middleware layer for data collection and SE.
- Area to Area: P2P connection between areas. The connections determine the topological layout of adjacent areas in power grid.

For the MWNetwork, it models the network connecting PDCs to middleware (MW). In the Figure 4.3, this layer provides a channel to carry the PMU data to middleware.

For PMULink, it is an aggregation of links connecting each PMU to local PDC.

3.3. NS3

In this paper, the simulation of the ICT network will be modeled in NS3 (version 3.30.1). NS3 is a discrete-event network simulator [18]. It mainly focuses on the research of the communication protocols and networks. The motivation of the NS3 is to establish a solid simulation core that is easy to model and debug. It can be interconnected with real world and allow the real internet protocols to be implemented in NS3.

4. SIMULATION RESULTS AND DISCUSSION

4.1. Modelling of the dual-vector energy network

The iteration of the Newton Raphson in Matlab simulation is seven times (as shown in Fig. 4), which shows the integrated algorithm model is convergent.
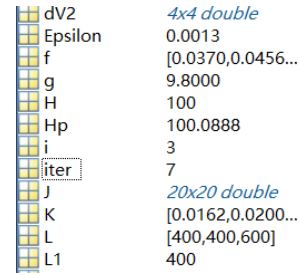
Figure 4. *Iteration number shown in the partial simulation results*

The Fig. 5(a) shows the value of the unknown variables before the iteration, which is calculated with the initial conditions. And the Fig. 5(b) shows the value of the unknown variables after the iteration, which is calculated via the integrated method.
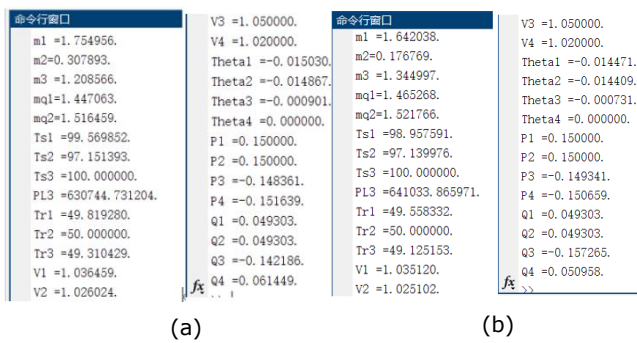

      (a)   (b)

Figure 5. *(a) The value of the variables before the iteration (b) The value of the variables after the iteration*

Comparing the Fig. 5(a) and Fig. 5(b), it is obvious that, the values of the unknown variables are updated, which can prove the Newton-Raphson method is carried out normally.

Table 2. *The results of MatLab compared with the reference data*

Variables	m_1	m_2	m_3	T_{s1}
Simulation	1.6420	0.17680	1.3450	98.9576
Reference	1.6417	0.17646	1.3449	98.9575
Variables	T_{s2}	T_{r1}	T_{r3}	
Simulation	97.14	49.558	49.125	
Reference	97.14	49.558	49.125	

There is not much difference between the two series of data. With small errors, the accuracy of the integrated method is validated. Nevertheless, for further analysis, these subtle differences may be due to the approximate calculation of the Reynolds number Re in the iteration in this dissertation. As the resistance coefficient of the pipe 'K' depends on the Reynolds number, it will further affect the head loss h_f dominated by K. And then all the results will be affected just like the domino effect.

Table 3. *The results of MatLab compared with IPSA results (Coupling linkage is CHP)*

Results	V_1	V_2	θ_1	
MatLab	1.03390	1.02418	0.05089	
IPSA	1.03392	1.02421	0.05088	
Results	P_3	P_4	Q_3	Q_4
MatLab	0.4931	-0.1931	0.1803	-0.0409
IPSA	0.4931	-0.1889	0.1798	-0.0412

From the Table 3, there is not much difference between the MatLab results and the IPSA simulation results, which means the validation of the model in MatLab is proved.

From the Table 4, it shows the influence on unknown variables' results of the electricity network with different coupling linkage in the dual-energy network.

Table 4. *Comparison of different linkage components*

	CHP	CHP&Pump	CHP&Pump&HeatPump
V_1	1.0339	1.0339	1.0351
V_2	1.0242	1.0242	1.0251
θ_1	0.0509	0.0500	-0.0145
θ_2	0.0185	0.0181	-0.0144
P_3	0.4931	0.4887	0.1497
P_4	-0.1931	-0.1929	0.1461

When the linkage components are CHP & Circulation pump & Heat pump, the power injected on bus 4 P_4 is positive, while under the other two conditions, P_4 is negative. The reason is that, with heat pump, the output of linkage component from the heat network to electrical network is reduced, as heat pump will consume some power. Thus, both linkage component and power grid inject active power in electrical network. Nevertheless, in the other two cases, the power injected on bus 4 P_4 are all negative. That is because, in these two cases, the heat-to-electricity power can not only support the distribution system, but also has some surplus energy to offer to the power grid. Although, the circulation pump will absorb some electrical power, it is a minority of the conversion power.

4.2. Modelling of ICT network

The topology of the ICT network is visualized via the software NetAnim, which is shown in the Fig. 6:
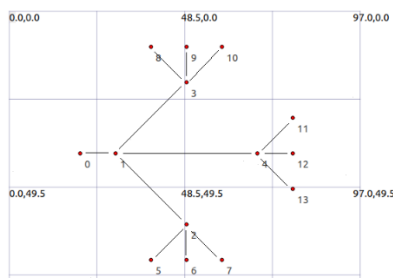
Figure 6. *The topology of the ICT network simulation*

All the data channels are established based on the CSMA protocol. The data rate of the CSMA channels is 10Mbps with 5000ns delay, while the data rate of P2P channel is 100Mbps with 2ms delay. The node 1-4 are switchers, which are configured based on the openflow protocol. With the openflow protocol, all these four nodes will operate as the MPLS node. The node 0 is set up as the control center, and the node 5-13 represent the four buses and power source in electricity network and the three nodes and heat source in heat network respectively. The application server is installed on node 0, while the application clients are installed on node 5-13. All the data distribution process will obey the CSMA/CD protocol regulations.

Figure 7. *The results of the ICT network simulation*

From Fig.7 it proves that the ICT network is successfully modeled according to the communication aspect. The server starts at 1 seconds which is consistent with the code. The data transmission process is beginning at 2 seconds which also matches the code. It is terminated at 2.023 seconds. That is because, the number of the packet sent by each client is only one with 1 second interval. And the receiving time of the client is the time, when the feedback from the server returns to clients.

4.3. The impact of ICT irregularities

This paper reviews a case about a co-simulation of an electrical distribution network and an ICT network in paper [19]. It mainly focuses on two types of the ICT irregularities, the packet drop and packet delay.

- For packet delay: It means a packet cannot be transferred instantaneously.
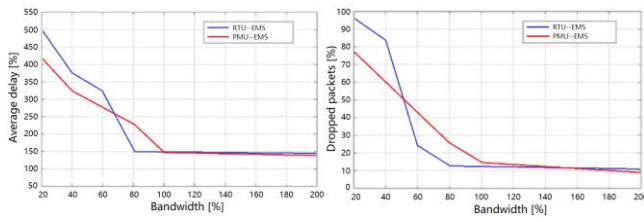- For packet drop: It means a packet will be lost (dropped) and never received at the final destination.

Figure 8. *Average delay and dropped packets of different bandwidths*

Form Fig. 8, higher bandwidth will have less impact by the packet delay and the packet drop. Since with higher bandwidth, the packets will be transferred faster and the time of queueing will be reduced, which will alleviate the packet delay and reduce the probability of the packet drop. However, when the bandwidth reaches a certain value, the delay and drop will not keep decreasing, which is caused by the default attributes of the channels.
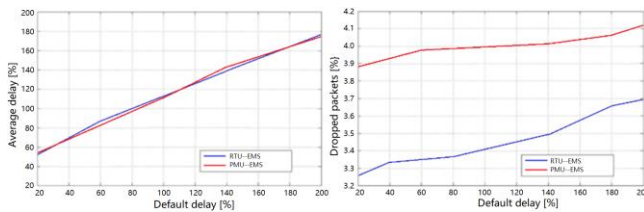

Figure 9. *Average delay and dropped packets of different default delay*

From Fig. 9, it is not difficult to find, the rate of the average delay and the dropped packet is significantly increasing with higher default delay. The reason is the packet needs more time to be sent, which will lead to longer queueing time. As a result, the risk of the packet drops increases.
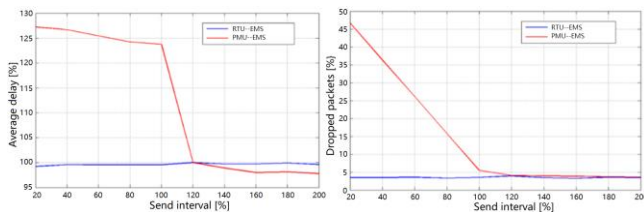

Figure 10. *Average delay and dropped packets of different interval [19]*

From Fig. 10, it is obvious that, with higher interval, the rate of delay and drop will decrease. Higher interval means longer time to take for sending packets, which leads to less sent packets in a certain period. Then there will be less queueing, thus the rate of both delay and drop will decrease. Nevertheless, the delay and drop data of the RTU seems not be affected. That is because, the interval ratio is much bigger than the interval of RTU data. In such case, the RTU data will only be affected by the default attributes of channel.
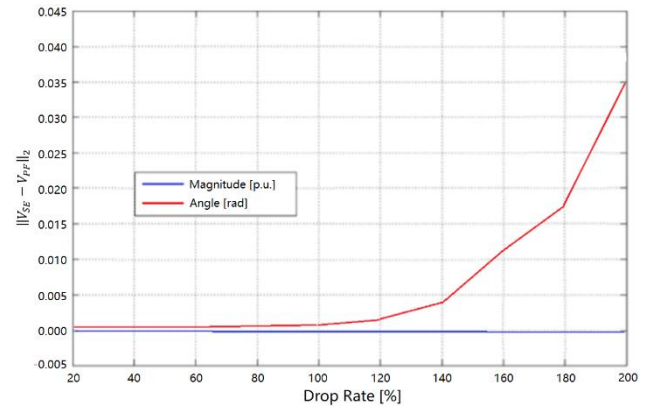

Figure 11. *The mean square errors with different drop rate*

From the Fig. 11, it shows that high drop rate may decrease the measurements for state estimation. And less measurements could lead to higher angle of the mean square errors. In summary, the ICT irregularities could cause the energy measurements missing, which brings negative impact on state estimation for power systems.

5. CONCLUSIONS

There are mainly two parts of this paper. One is the modelling of the dual-vector energy system combined heat and electricity, the other one is the simulation of the ICT network.

For the part of the dual-vector energy system, the iteration time is 7, which is reasonable enough to prove the mathematical model of this energy network is converged. Compared with the input values, the unknow variables is obviously updated, which means the Newton-Raphson process is carried out normally, and the programming code is correct. Since the error between the results and the reference data is really small, which can be ignored, the validation of the dual-energy network model in MatLab is confirmed. Besides, compared with the simulation in IPSA Power, the MatLab model can be proved to be successful. In short, the model of the dual-vector energy network is successfully established and the characteristics of the integrated energy network is proved.

For the ICT part, this paper reviews some basic and typical protocol needed in the establishment of communication network. Following the methodology of the ICT simulation, an ICT network has been set up in NS3 (version 3.30.1). From the results, the data can be distributed in the network, and the data flow is visualized, which indicates the ICT network simulation is successful. Then it analyses the impact of ICT irregularities. For the communication networks with wider bandwidth and longer interval, the impact would be less serious, while for the communication network with larger default data delay, the impact would be much more terrible. For the power system, ICT irregularities would cause

power measurements missing, which will bring negative influence on the state estimation.

Future works:

- For the dual-vector energy network, this radial network with unidirectional power flow could be replaced by a network of loop topology with bidirectional power conversion.

- The dual-energy network is static. It could be changed to a dynamic model, which can carry out the state estimation and reveal more interdependency between the thermal and electrical variables.

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