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The Study of Power Electronic Transformer on Power Flow Control and Voltage Regulation in DC Micro-grid

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***Abstract*—The AC and DC distribution grids between different voltage levels coexist in smart grids, and a reliable connector was needed between them. Power Electronic Transformer (PET) was suitable for being used as public interface to control power flowing between different electricity networks and regulated DC bus voltage, because of its abundant functions and electrical interfaces. In order to take advantage of PET served as a power balance junction, an improved droop control method for DC micro-grid was proposed. Power can flow bi-directionally between DC micro-grid and AC grids by using this method. Then the power distribution was achieved in DC micro-grid and the stability of the DC bus voltage was enhanced. The simulation studies were carried out in three cases: system load mutation, power fluctuation of distributed generation and voltage sag in high voltage distribution network. The simulation results showed that the DC micro-grid was still on stable operation in the cases above, and proved the good performance of the improved droop control method.**

Keywords—Power Electronic Transformer; DC micro-grid; droop control; power flow control; DC bus voltage regulation

I. INTRODUCTION

To solve the problem caused by energy shortage and environmental pollution, Distributed Energy Resources (DER) has received more attention and application. But owing to the troubles of high cost, low capacity, great uncertainty and limited by nature in operation, individual DER was an uncontrollable source for main grid. Micro-gird is a efficient way for DER to connect the main grid to solve above problems and maximize the value[1-3]. The energy mainly generated by DER is DC , or can simply converted to be DC. So, DER can save lots of exchanging circuit links, paralleled in network. DC grid-connection will increase the controllability and reliability, due to its independence of tracking the phase and frequency of grid voltage. As above, dc interconnection is the most ideal type for DER. However, the main part of networks is AC system and the chief mode of microgrid is still AC at present. The hybrid DC and AC grids will be the long-standing structure. Research on DC microgrid should consider the AC grids, but most of available study and research is for individual DC microgrid[4-8], a fewer concern relate to the AC system[9-12].

With the development of power electronic technology, Power Electronic Transformer (PET), improved in recent years, is a new type of power transformer. Not merely PET has some basic functions like traditional transformer: transform-ation, isolation and energy delivery, but also it has AC and DC interfaces in low voltage side[13-17]. Therefore, PET is suitable for application in hybrid grids because its natural connector among ac and dc grids.

A PET, applied in DC microgrid hybrid with ac microgrid, is discussed in this paper and an improved droop control method is proposed. Power can flow bi-directionally between DC microgrid and AC grids by using this method, and then the power distribution was achieved in DC micro-grid. Also, the stability of the DC bus voltage was enhanced.

II. HYBRID NETWORK AND PET STRUCTURE

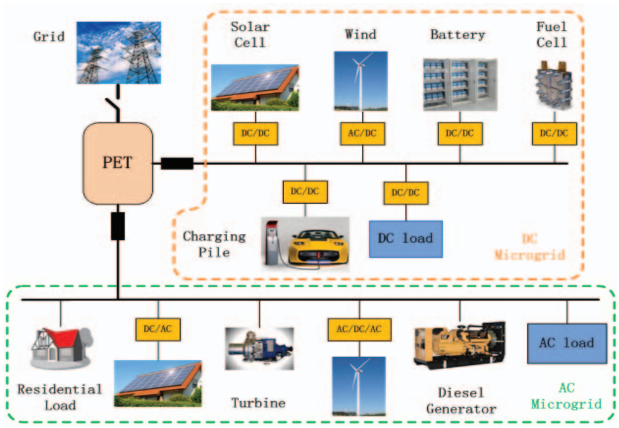


Fig. 1. System structure with AC DC hybrid networks

A typical hybrid networks system shown in Fig.1. The high-voltage utility grid (6kV AC) was divided into low-voltage DC and AC microgrid by PET. Hybrid system can operate in parallel with or isolated from the main power grid.

DER units are integrated to DC grids through DC/DC or AC/DC converters, also, integrated to AC grids through DC/AC、AC/DC/AC converters or directly. Changing pile and other new DC DER or loads are linked to DC microgrid , while AC microgrid links traditional AC generator and loads. According to its own characteristics, and considering its convenience and cost, DER can link to the different network. Photovoltaic and wind power can parallel in DC or AC way by considering comprehensive factors like distance and cost of converter. Battery, upper capacitor, fuel cell can connect with the DC line because of unlimited by geographical conditions. And with the popularity of pure electric vehicles and dispersing of DC microgrid, penetration of charging pile will increase; Moreover, traditional gas turbine and diesel generator can provide energy through the AC microgrid.

The hybrid system PET is consist of a cascaded multilevel AC/DC rectifier, Dual Active Bridge (DAB) converters with high frequency transformers and a DC/AC inverter. The traditional 50 Hz transformer is replaced by a high frequency transformer. PET interfaced to 6kV distribution voltage with 380V three-phase output is shown in Figure 2. The PET is rated as single phase input voltage 50 Hz, 6kV, output voltage 50 Hz, 380V, 3 phase/3 wires. The PET consists of a high voltage high frequency AC/DC rectifier that converts 50Hz, 6kV AC to six cascaded 1.6 kV DC bus, six high voltage high frequency DC-DC converters that convert 1.6 kV to 800V DC bus and a voltage source inverter (VSI) that inverts 800V DC to 50 Hz, 380V, 3 phase/3 wires. The DAB stage uses a high frequency transformer with 1.6kV/800V turns ratio to step down the voltage. The regulated 800V DC voltage allows easier connections of some DERs. The output of the DC/AC inverter will connect to the residential houses and provide 380V AC voltages.

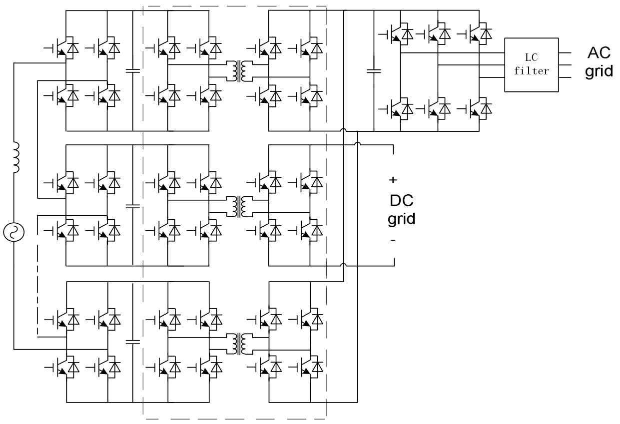


Fig. 2. Topology of PET

III. OPERATION MODE

Influenced by weather, energy fluctuated in DC/AC microgrid, frequently and load power does also. In order to maintain the stability of bus voltage and distribute load power reasonably, energy flow must be bidirectional among system interfaces and the power must get a quick adjustment depending on the signal of interfaces.

Act as a point of common coupling(PCC), PET can coordinate power flow desirably. On the basis of whether its parallel in high-voltage AC grids or not, the microgrid is supposed to operate in two conditions: connected to or isolated from the utility grid. Hybrid system is divide into two conditions under connected-grid mode: power consumption or feedback. And there are three conditions when it off-grid, according to the direction of power flow, shown in Tab. 1.

TABLE I. STATE OF HYBRID MICROGRID

Grid state \ Power flow		P_{hv}	P_{ac}	P_{dc}	St-ate
Grid-connected	Power consumption	forward-flow	bidirection	bidirection	1
	Power feedback	contra-flow	bidirection	bidirection	2
Islanded	AC and DC all light load	zero	zero	zero	3
	DC light load AC heavy load	zero	forward-flow	contra-flow	4
	AC light load DC heavy load	zero	contra-flow	forward-flow	5
	AC and DC all heavy load	zero	zero	zero	6

P_{hv}, P_{ac}, P_{dc} is the power flowed in interface of main grid(HV grids) AC and DC microgrid.

PET managed energy flow between main grid、AC and DC microgrid and energy can flow bidirectional. PET is a energy provider for some networks, meanwhile, a load for others.

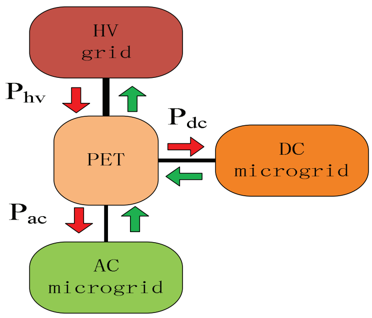


Fig. 3. Energy Stream of Hybrid system

A. Grid-connected Operation

In the grid-connected mode, AC/DC microgrids are connected with high voltage AC grids. All lower level is a resistance load or a current source for main grid when consumed (State 1) or feedback (State 2) power. The grid offers a buffer for any unbalance of microgrid on State 1. Besides, the spare power feed in grids on State 2.

Under this mode, the main grid can meet the power demand of AC and DC microgrid by PET, absorb the extra energy while supported frequency of AC microgrid and there has no energy exchange. In AC microgrid, DER could export the maximum power, advanced real and reactive power, even act as a terminal voltage regulator to regulate outputs. Equally, DER in DC microgrid can realize some functions except output the reactive power. In addition, PET could regulate power balance and support bus voltage.

The magnitude and composition of interface power shown as (1), (2), (3),which has ignored the loss of PET.

$$P_{hv} = P_{dc} + P_{ac} \tag{1}$$

$$P_{dc} = \sum_n P^i_{load-dc} - \sum_n P^i_{DER-dc} \tag{2}$$

$$P_{ac} = \sum_n P^i_{load-ac} - \sum_n P^i_{DER-ac} \tag{3}$$

Therefore, DER would work at maximum power point, energy storage device would charge and discharge independently, and it also can compensate reactive power and regulate terminal voltage. Many papers have already discussed and this article mainly studied how to control power flow effectively and enhance stability of DC bus voltage as well as to realize the maximum power output of DER generation system.

B. Islanded Operation

Islanded mode is more complex and rigid for the control scheme of PET. There has energy exchange and power flow among the microgrid. Power demand of loads should be offered by DER and energy storage devices. So, it is a demanding task for them to have flexible control strategy. And PET has fast power coordination strategy to reduce the operate fluctuation from AC to microgrid. It is a great choice that use droop control to share the load for DER which makes a reasonable distribution for inner power of microgrid. The power requirements of loads and energy storage devices is smaller than outputs of micro sources when devices in light running. So the output power of DER is depending on amplitude, frequency, phase of terminal voltage while it should be able to prorate with other sources. What's more, the corresponding control strategy should be designed for PET to coordinate the power. Therefore, this paper makes an analysis for the four states.

State 3: Self-management of AC/DC microgrid which only supply power for its own loads（light running）. DER in own networks can regulate the power to meet load. And PET need not delivery power but regulate reactive power for AC microgrid. This state shown as:

$$P_{hv} = P_{dc} = P_{ac} = 0 \tag{4}$$

$$\sum_n P^i_{load-dc} \le \sum_n P^i_{DER-dc} \tag{5}$$

$$\sum_n P^i_{load-ac} \le \sum_n P^i_{DER-ac} \tag{6}$$

State 4: The output power of DER in AC microgrid is not enough to support the AC load while DC microgrid has extra power. Hence, the DC would make a supplement for the AC microgrid and PET is designed for deliver energy. This state is shown as follows， $P_{\text{dc-ac}}$ is the power that DC microgrid supplied.

$$P_{hv} = 0 \tag{7}$$

$$\sum_n P^i_{load-dc} < \sum_n P^i_{DER-dc} \tag{8}$$

$$\sum_n P^i_{load-ac} > \sum_n P^i_{DER-ac} \tag{9}$$

$$P_{\text{dc-ac}} = \sum_n P^i_{DER-ac} - \sum_n P^i_{load-ac} \tag{10}$$

State 5: This state is similar with the State 4.The shortage and surplus of power is contrast to state 4.So the energy flows from AC to DC microgrid. This state is shown as follows, $P_{\text{ac-dc}}$ is the power that AC microgrid supplied.

$$\sum_n P^i_{load-dc} > \sum_n P^i_{DER-dc} \tag{11}$$

$$\sum_n P^i_{load-ac} < \sum_n P^i_{DER-ac} \tag{12}$$

$$P_{\text{ac-dc}} = \sum_n P^i_{DER-dc} - \sum_n P^i_{load-dc} \tag{13}$$

State 6: Load power is larger than maximum output power of DER in both AC/DC microgrid, that is the overload state. PET didn't deliver power and microgrid must remove some unimportant load to stable the networks.

$$P_{hv} = P_{dc} = P_{ac} = 0 \tag{14}$$

$$\sum_n P^i_{load-dc} \ge \sum_n P^i_{DER-dc} \tag{15}$$

$$\sum_n P^i_{load-ac} \ge \sum_n P^i_{DER-ac} \tag{16}$$

IV. CONTROL STRATEGY

In ac microgrids, Real power generation of a DG is specified based on frequency-droop characteristic. The main idea of this control is to increase the active power generation of DGs when the system frequency decreases. Similarly, for reactive power management voltage-droop (V-Q) is exploited.

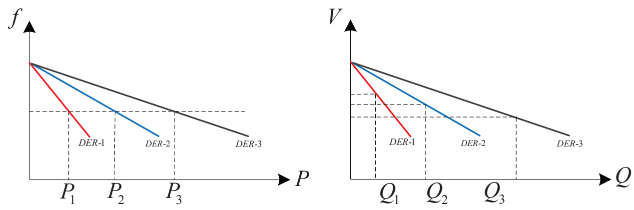


Fig. 4. ω-P and V-Q droop characteristics

Reactive power generation of a DG is determined based on deviations in the bus voltage. Therefore, the DG source acts in response to the measured local voltage deviations caused by either the system or the local load. ω -P and V-Q characteristics could be described mathematically by (17)-(18).

$$P_{ref} = -\frac{1}{k_{\text{p}}}(\omega^0 - \omega) + P_0 \tag{17}$$

$$Q_{ref} = -\frac{1}{k_q}(V^0 - V) + Q_0 \tag{18}$$

$$k_p = -\frac{(\omega_{max} - \omega_{min})}{P_{max}} \tag{19}$$

$$k_q = -\frac{(V_{max} - V_{min})}{Q_{max}} \tag{20}$$

Alternatively, for the dc microgrid the dc voltage-droop (V_{dc}-P) control method is used for power sharing between DG sources in the microgrid. Typical V_{dc}-P droop characteristics can be expressed by (19)–(20).

$$P_{ref-dc} = -\frac{1}{k_{dc}}(V_{dc}^0 - V_{dc}) + P_{dc}^0 \tag{21}$$

$$k_{dc} = -\frac{(V_{dc}^{max} - V_{dc}^{min})}{P_{dc}^{max}} \tag{22}$$

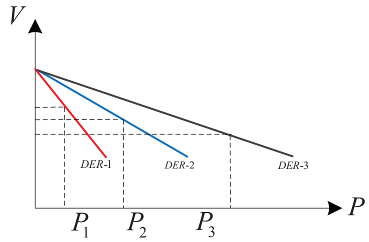


Fig. 5. Vdc-P droop characteristics

A. Control of Grid-connected Operation

During the grid-connected mode, where the frequency of the system is fixed, real power generation of the DG is controlled by the MPPT algorithm of each DER.In high voltage ac side, the Current and voltage was kept in same phase. Therefore, PET was controlled as a “resistance load”. However, in low voltage ac side and dc side, PET was controlled as a stable voltage source. Since there are lots of papers described these algorithms [18-20], they won't be covered here.

B. Control of Islanded Operation

In contrast to the grid-connected mode, PET is expected to manage a bidirectional flow of power between the ac and dc microgrids. In addition the PET should cooperate in power sharing between the energy sources in both microgrids with dissimilar droop characteristics. This is due to the fact that at any instant the PET takes the role of supplier to one microgrid and at the same time acts as a load for the other microgrid. These challenging issues can be handled by exploiting a proper control strategy for the PET to transfer the required power between the microgrids.

PET should recognize all states and manage the whole ac and dc microgrid as discussed in the previous sections. The power management should determine the amount of active power that the PET must transfer from one microgrid to the other. In order to provide the power reference command, the dc bus voltage of the PET and the frequency of the ac microgrid are utilized as input to the power management system. The electrical energy stored in the dc capacitor is

$$W_{dc} = \frac{1}{2} C_{dc} V_{dc}^2 \tag{23}$$

Neglecting the switching losses in the converter $P_{dc} \approx P_{ac}$, the dynamics in the dc capacitor energy is the difference of power transfer between ac and dc microgrids. Therefore,

$$\frac{d}{dt} W_{dc} = \frac{1}{2} C_{dc} \frac{d}{dt}(V_{dc}^2) = P_{dc} - P_{ac} = \Delta P \tag{24}$$

On the other side, considering the characteristic in the ac microgrid

$$\Delta\omega = \omega^0 - \omega = k_\omega \Delta P \tag{25}$$

According to (24) and (25), using the forward Euler approximation with sampling period (T_s) and assuming that the microgrid frequency is constant in this interval, a new droop characteristic for the PET called “ac-dc droop” is defined as,

$$\omega^0 - \omega = \tilde{k}_\omega \left((V_{dc}^0)^2 - (V_{dc})^2 \right) \tag{26}$$

$$\tilde{k}_\omega = k_\omega \frac{C_{dc}}{2T_s} \tag{27}$$

The droop characteristics for active power can be expressed by,

$$\omega^0 - \omega = \tilde{k}_\omega \left((V_{dc}^0)^2 - (V_{dc})^2 \right) \tag{28}$$

$$\tilde{k}_\omega = k_\omega \frac{C_{dc}}{2T_s} \tag{29}$$

$$\tilde{k}_\omega = k_\omega \frac{C_{dc}}{2T_s} \tag{30}$$

Combining (28), (29) and (30), the reference power for the ac microgrid is,

$$P_{ac}^{ref} = k_{ac}[(\frac{1}{\tilde{k}_\omega}(v_{dc,DG}^2 - {V_{dc,DG}^0}^2) + \omega_0) - \omega] \tag{31}$$

According to and Vdc_{ref} and ω_{ref} the amount of power to be transferred via the PET is determined by the two reference power calculated through these two loops. A schematic block diagram of the proposed power control strategy for the PET is depicted in Fig. 6.

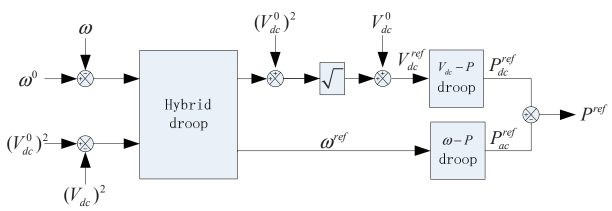


Fig. 6. Power control strategy of the PET

Fig.7 shows the control block diagram of pet in reference frame. The real power reference is determined according to the proposed droop shown in Fig. 5. The active power control loop generates the reference current using PI controller. The current control loop measures the output currents and controls the converter to follow the reference value using PI controller. Finally, the reference voltage for the PWM switching is followed by the current controller according to the reference current.

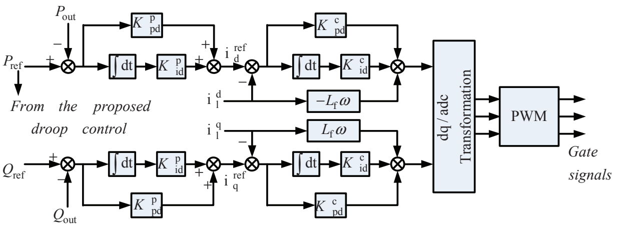


Fig. 7. Control block diagram of PET

V. SIMULATION

The simulation was performed in PSCAD/EMTDC using building blocks from the Master libraries and self-made blocks for assembling the network and PET shown in Figs.1. Network simulation model was show in Figs.8. PET simulation model was show in Figs.9

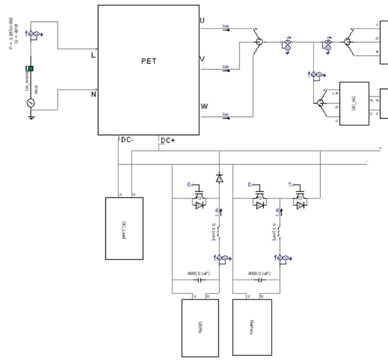


Fig. 8. Simulation model of Network

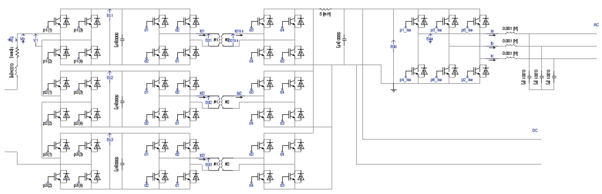


Fig. 9. Simulation model of PET

TABLE II. PET PARAMETERS

HV grids	6KV
rated power	300KVA
switching frequency	1kHz
capacitor voltage (high voltage side)	1600V
DC bus voltage	800V

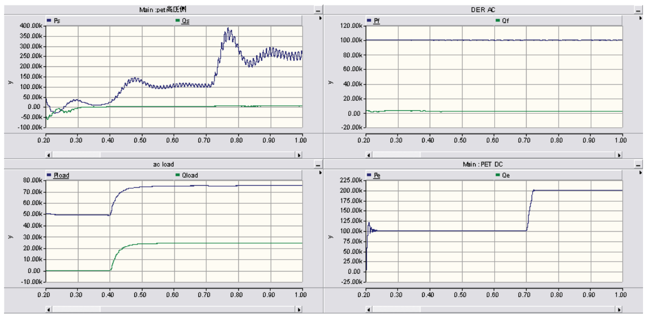
The system and controller parameters are given in Table II . The magnitude and frequency of ac bus voltage are the same with the utility grid. The voltage range chosen was mainly based on the withstand voltage of semiconductor switches and hence capacitor voltage(high voltage side) of 1600V and dc-link voltage of 800 V were used.

The simulation studies are carried out in three cases: systemload mutation, power fluctuation of distributed generation and voltage sag in high voltage distribution network.

A. Case 1

In this case, load change in AC microgrid and DC microgrid is simulated while the powerflow through the PET is changed.

The power curves of PET high voltage side, PET DC link , DERs of AC microgrid and AC load are shown in Fig. 10. DERs in the AC microgrid share the power 100kw. Load change from 50kw active power to 75kw active power and 25kvar reactive power in 0.4s in AC microgrid. Similarly, in DC microgrid, load regulation from 100kw active power to 200kw active power in 0.7s. PET provide the remaining power requirement, transferred from high voltage utility grid.



(a) Power input in PET from utility grid; (b) AC DER output; (c) AC load consumption; (d) DC output of PET.

Fig. 10. Case 1: load change of hybrid microgrid.

The voltage response to the fluctuation of load is shown in Fig.11. It can be seen that the dc bus voltage fluctuation slightly during the transient process of load step in 0.4s and 0.7s. But the DC bus voltage can recovers within 0.1s after step.

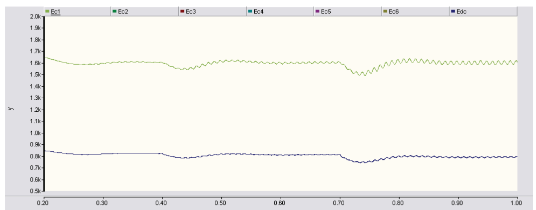


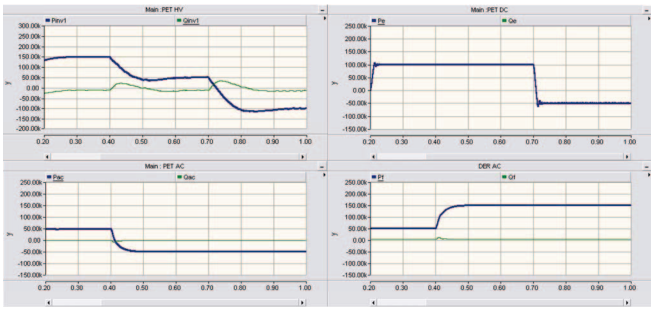
Fig. 11. Case 1 Voltage response of dc bus

B. Case 2

In this case, the output power of DERs in AC microgrid and DC microgrid is changed while the power flow of P_{hv}, P_{ac} and P_{dc} through the PET is changed.

In time 0.4s, the output power of AC DER is increased from 50 kW to 150 kW. Similarly, in time 0.7s, DC microgrid is varied from absorbing power 100 kW to output power 50 kW. Then, power transferred from both AC and DC microgrid to high voltage utility grid, through PET. The power curves of PET high voltage side, PET DC link, PET AC interface and D-ERs of AC microgrid are shown in Fig. 12.

The voltage response to the fluctuation of output power of DERs is shown in Fig.13. It can be seen that the dc bus voltage can be kept stable during the transient process of DERs power variation in 0.4s and 0.7s.



(a) Power input in PET from utility grid; (b) DC output of PET; (c) AC output of PET; (d) AC DER output.

Fig. 12. Case 2:output power fluctuation of DERs

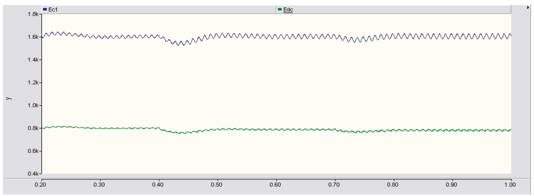


Fig. 13. Case 2: Voltage response of dc bus

C. *Case 3*

In this case, the voltage of utility grid DERs is drooped 10% in 0.4s and 20% in 0.7s, respectively. The voltage wave is shown in Fig. 14. It can be seen that the capacitor voltage(high voltage side) fall only a little and the dc bus voltage can be kept stable during the process, shown in 15.

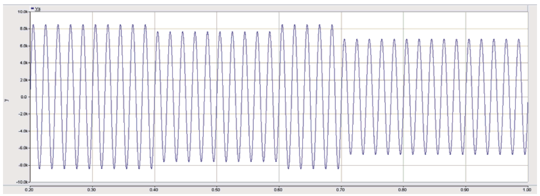


Fig. 14. Case 3: voltage droop of utility grid.

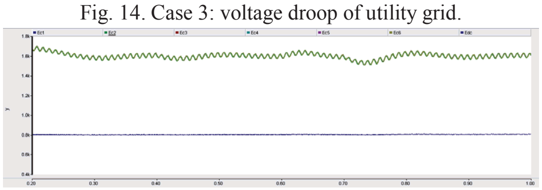


Fig. 15. Case 3: Voltage response of dc bus

VI. CONCLUSION

The hybrid DC and AC grids will be the long-standing structure. PET is suitable for application in hybrid grids because it's natural connector among ac and dc grids. An improved droop control method is proposed for PET using in the hybrid microgrid. Power can flow bi-directionally between DC microgrid and AC grids by applying this method, and then the power distribution was achieved in DC micro-grid. Also, the stability of the DC bus voltage was enhanced. The simulation results showed that the DC micro-grid can operate stably through the adjustment of PET, and proved the good performance of the improved droop control method.

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