

UUDAT based on the modular multilevel converter and diode bridges for high-voltage DC application

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Abstract: Conventional unidirectional DC/DC converters for high-voltage direct current application employ DC/AC/DC technology and suffer from high converter cost and power loss. To solve these issues, a unidirectional step-up DC–DC autotransformer (UUDAT) is studied. UUDAT is composed of the series connection of diode bridges and voltage source converters. Topologies of UUDAT is detailed. The harmonic and uncontrollability issues are discussed. Control and the possible application scenario for UUDAT are proposed. The ways of dimensioning the voltage and power rating of the components in UUDAT are studied. Extensive simulations on the power system level verified the technical feasibility of UUDATs.

1 Introduction

With the increased penetration of renewable power generation and the developments of technologies such as modular multilevel converter (MMC), high power DC circuit breakers, DC/DC converters, DC/DC autotransformers (DC/DC AUTOs), DC power flow controllers, and DC energy dissipation devices, there have been a significant interest of developing DC grids in the power industry in recent years.

A DC grid requires the interconnection of multiple DC transmission lines at the DC terminals. To interconnect DC transmission lines with different voltage levels, DC/DC converters are used. A number of DC/DC topologies have been proposed in the literature, such as the front-to-front type DC/DC [1], the multiple dual active bridge DC/DC [2], the multilevel modular DC/DC [3], the inductor–capacitor–inductor DC/DC [4], the (DC/DC AUTO) [5], and hybrid cascaded transformer-less DC/DC [6].

Most of the above DC/DC are bidirectional in which DC power can flow bidirectionally between the two DC systems. In certain application fields, such as the DC wind power collection grid [7], the power only needs to flow in a single direction. DC/DC converters could be further optimised to reduce the converter cost in those application fields.

Conventional unidirectional DC/DC at the high-voltage direct current (HVDC) level employs DC/AC/DC technology with a voltage source converter (VSC) and an uncontrolled rectifier connected in a front-to-front mode. The transferred DC power is firstly inverted from DC to AC by the VSC and then rectified from AC to DC by the uncontrolled rectifier. All the transferred DC power needs is two-stage AC/DC converting which results in high converter rating and high operating power loss.

A step-up unidirectional DC AUTO (UUDAT) was briefly introduced in [8]. UUDAT is able to reduce converter rating and operating power loss. This paper further expands the work of Lin *et al.* [8]. Possible applications of UUDATs will be discussed. The comparison of the valve power loss of UUDATs with bidirectional DC AUTO and conventional DC/AC/DC will be presented.

2 Step-up unidirectional DC auto

2.1 Conventional unidirectional DC/AC/DC

Fig. 1a shows the circuit diagram of a conventional unidirectional DC/AC/DC. It is mainly composed of an MMC and an

uncontrolled diode rectifier (DIO). DC power can only flow in a single direction from one DC system E_1 to the other DC system E_2 . The transferred DC power will firstly be inverted by MMC and then rectified by DIO. The power ratings of MMC, DIO, and AC link are the same and equal the rated DC power. Therefore, cost and operating power loss of Fig. 1a are high.

2.2 Topologies of unidirectional DC AUTO

To reduce the converter rating and the operating power loss, Fig. 1b shows the topologies of UUDAT. UUDAT is composed of a series connection of two DIOs (DIO1, DIO3) and one MMC (MMC2). In Fig. 1b, each arm of an MMC is represented by a half-bridge sub-module.

UUDAT is used to transfer DC power from the low-voltage DC system E_1 to the high-voltage DC system E_2 . According to the power flow analysing method of Lin [5], part of the DC power is transferred through the direct electrical connection formed by E_1 and i_{dc2} , and the other part is firstly inverted by MMC2 and then rectified by DIO1 and DIO 3.

2.3 Impact of the DC bias on transformer design

In UUDAT, AC sides of DIO1 and DIO3 experience the DC bias. To stop the DC bias at the diode bridges propagating to the inner AC system of UUDAT, the transformer windings connected to DIO1 and DIO3 need to employ high impedance grounded Y winding or Δ winding configuration, as with HVDC based on the line-commutated converter [9]. As shown in Fig. 1b, DIO1 and DIO3 are connected to the common AC bus through an $Y_n/Y_r/\Delta$ connected AC transformer. The Y-connected windings at the DIO side are grounded through high impedance, which increase the insulation requirement at the neutral of those Y-connected windings. The Δ -connected windings at the DIO side increase insulation requirement between different phases, which also increase the cost.

For the conventional DC/AC/DC, as shown in Fig. 1a, high-impedance grounded Y windings or Δ windings will also be used if DIO of Fig. 1a employs the 12-pulse diode bridge. If the 6-pulse diode bridge is used at DIO, the Y_n/Y_n -connected transformer is sufficient to meet the voltage stepping requirement, and there will be a large amount of harmonics in both the inner AC system and DC sides of DC/AC/DC.

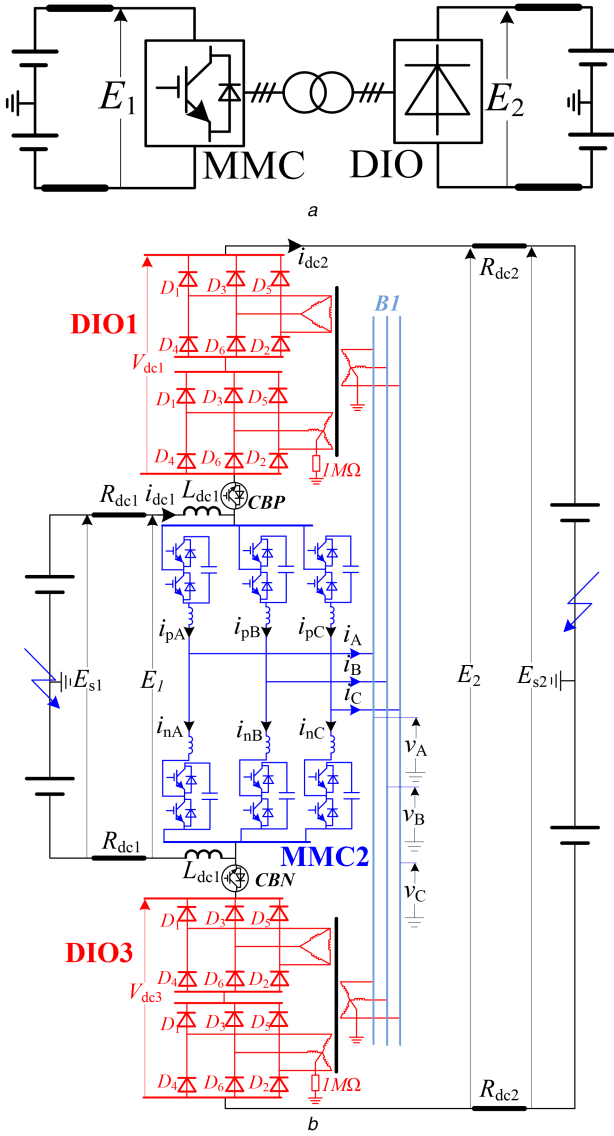


Fig. 1 Topologies of unidirectional DC/AC/DC and unidirectional DC AUTOS

(a) Topology of conventional unidirectional DC/AC/DC, (b) Topology of UUDAT

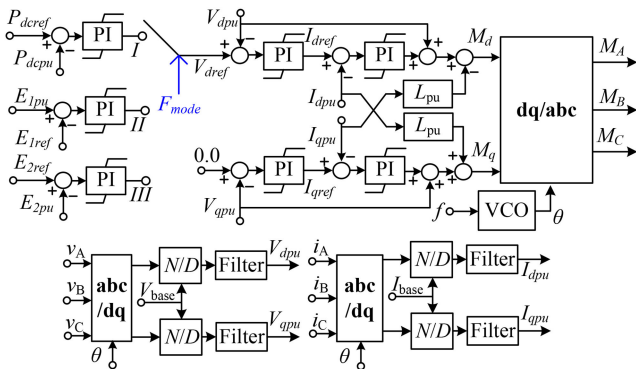


Fig. 2 Control diagrams of UUDAT

The above analysis shows that the DC bias is not a unique problem of UUDATs, but a common problem of unidirectional DC/DC, employing either DC AUTO or DC/AC/DC technology.

3 Control of unidirectional DC auto

3.1 Control of UUDAT

For UUDAT, by increasing the AC voltage of MMC2, the voltage rectified by DIO1 and DIO3 can be increased, E_2 is increased

which increases i_{dc2} . Therefore, the DC power can be controlled by controlling the AC voltage in UUDAT. Fig. 2a shows the upper layer control of UUDAT. The controller is composed of an outer loop DC power/ DC voltage control, a middle-loop AC voltage control and an inner-loop AC current control. Outputs of the upper layer control are the modulation indices in the ABC frame, and a voltage controlled oscillator is used to provide the reference angle for abc/dq transformation.

In Fig. 2a, P_{dcpu} is the per unit value of the DC power, V_{dpu} and V_{qpu} are the dq component of the common bus AC voltage in a rotating dq frame, V_{dref} is the reference value of V_{dpu} , I_{dpu} and I_{qpu} are the dq components of the AC current i_A-i_C , L_{pu} is the per unit value of reactance from the inner electromotive force point of MMC to the common AC bus, and M_d and M_q are the dq modulation indices. The subscript pu of Fig. 2a stands for per unit value taking the rated value of each variable as the base value, the subscript ref stands for reference value.

4 Operation of UUDAT if interfaced to passive components at the load side

DC voltages at the lower and higher voltage sides are important for the successful operation of UUDAT. If the load side of UUDAT is connected to passive components, E_2 will be clamped at E_1 if MMC2 is not in operation. After enabling the mode III control of Fig. 2, E_2 can be controlled to its reference value. Therefore, the DC voltage at the load side of UUDAT can only vary from E_1 to the rated value. The DC voltage at the load side of conventional unidirectional DC/AC/DC could vary from 0 to the rated value if the load side is connected to passive components. Since UUDAT is dedicated for HVDC application, the operating scenario of interfacing the load side to passive components is very rare.

5 Valve power loss estimation of UUDAT and step-down DC-DC autotransformer (DUDAT)

The valve power loss estimation method of [10] which is based on simulations is adopted. The valve power loss of MMC is composed by the insulated-gate bipolar transistor (IGBT) conduction losses, diode conduction losses, IGBT switching losses, diode recovery losses, and IGBT and diode cut-off losses. Only conduction losses are considered in the diode bridges as the recovery charge and leakage current are negligible in the selected diode part number. The last column of Table 1 shows that the valve power loss of UUDAT is around half the valve power loss of unidirectional DC/AC/DC and two-thirds the valve power loss of bidirectional DC AUTO. The bidirectional DC AUTO has higher valve power loss than UUDAT mainly because IGBTs have higher conduction loss than diodes, and there are no switching losses in DIO.

6 Simulating verifications

6.1 Topologies of the simulated systems

To verify control performance of UUDATs, the system shown in Fig. 3 is simulated in power systems computer aided design/electro magnetic transient in DC system (PSCAD/EMTDC). Parameters of UUDAT are listed in Tables 2-4. Information regarding power semiconductors in the tested UUDAT is listed in Table 1.

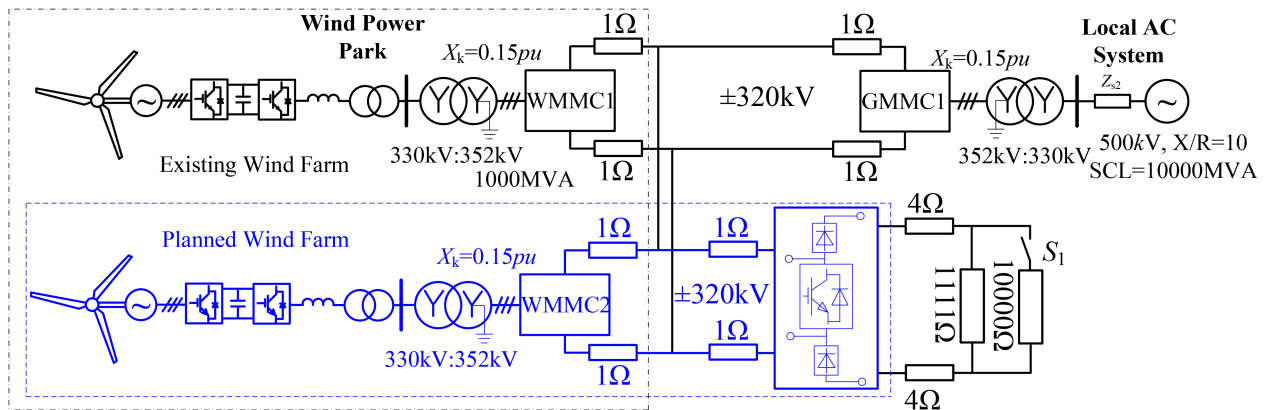
6.2 Parameters of the simulated unidirectional DC AUTOS

UUDAT and DUDAT with topologies shown in Fig. 2 are simulated. Rated values of E_1 and E_2 are, respectively, ± 320 and ± 500 kV, and rated DC power is 1000 MW (Fig. 4).

Table 2 shows the power rating and voltage rating of the MMC and the diode bridge in the tested UUDAT. Without considering DC fault isolating capability, the rated DC voltage of the diode valve of DIO1 and DIO3 is 188.5 kV (total voltage rating of the two D1 of DIO1). To protect DIO1 and DIO3 from overvoltage during E_1 fault, the voltage rating of the diode valve of DIO1 and

Table 1 Semiconductor information and valve power loss estimation results of different DC/DC

DC/DC converter	Semiconductor information	Power loss under rated DC power, MW	Valve power loss ratio
UUDAT	DIO1, 3: 5SDD 06D6000, total 500 diodes per DIO1, 3;	$P_{DIO1}^{loss} = P_{DIO3}^{loss} = 0.589$	0.61%
—	MMC2: 5dSNA 0600G651000, 200 HBSM per arm	$P_{MMC2}^{loss} = 4.93$	—
DC AUTO under step-up mode	MMC1, 3: 5SNA 1200G450300, 72SBSM and 40 HBSM per arm;	$P_{MMC1}^{loss} = P_{MMC3}^{loss} = 2.85$	0.96%
—	MMC2: 5dSNA 0600G651000, 200 HBSM per arm	$P_{MMC2}^{loss} = 3.89$	—
step-up DC/AC/DC	DIO: 5SDD 06D6000, total 2100 diodes per DIO	$P_{DIO}^{loss} = 2.46$	1.25%
—	MMC: 5SNA 1500E330305, 400 HBSM per arm	$P_{MMC}^{loss} = 10.02$	—

**Fig. 3** Test system with high-voltage side of UUDAT connected to the passive DC load**Table 2** Power and voltage ratings of the MMC and diode bridges in UUDAT

Ratings	Basic case	Additional rating to protect over E_1 fault	Total rating
VDIO1, 3, kV	188.5	61.5	250
VMMC2, kV	640	0	640
PMMC2, MW	360	0	360

Table 3 MMC2 in UUDAT

Name	MMC2
arm inductor, H	0.165
submodule capacitance, μ F	2344
rated submodule voltage, kV	3.2
number of sub-modules per arm	200
number of SBSM per arm	0

Table 4 Parameters of the AC transformers

Name	UUDAT
number of transformers	2
rated power per transformer, MW	180
winding configuration	Y/Y/ Δ
rated line-line AC voltages, kV	352/83/83
leakage reactance, pu	0.1 pu

DIO3 is increased up to 250 kV. The power rating of the AC transformer connected to DIO1 and DIO3 is 180 MVA.

Table 3 lists the parameters of MMC1 and MMC3 of UUDAT and MMC2 of UUDAT. The DIO1–DIO3 are modelled, with each diode valve represented by a single diode. The smoothing reactor L_{dc1} is set to be 0.1 H.

Table 4 lists the parameters of transformers in the simulated UUDAT. Winding configurations of these transformers are shown in Fig. 1. The primary windings are connected to the AC terminals of MMC, while the secondary and tertiary windings are connected to diode bridges.

6.3 Simulations of supplying the passive DC load through UUDAT

Fig. 5 shows the simulation results of Fig. 3. The closed-loop DC voltage control of UUDAT is disabled before 1.0 s and enabled after 1.0 s. The load switch S_1 shown in Fig. 3 is initially closed and is opened at 2.0 s and further closed at 2.5 s.

Fig. 5a shows that before 1.0 s, E_2 is the same as E_1 . After enabling the closed-loop DC voltage control, E_2 is controlled to its reference value. When S_1 (shown in Fig. 3a) is switched off to disconnect the 10% DC load at 2.0 s, E_2 will be temporarily increased and when S_1 is switched on, E_2 will be temporarily decreased.

Fig. 5b shows the DC currents; their waveforms follow the same rule as switching off/on of loads.

6.4 Simulations of integrating wind power using UUDAT

Fig. 6 shows the simulation results of integrating wind power through UUDAT. The system of Fig. 6 is simulated. GMMC1 and GMMC2 are, respectively, configured to control their DC terminal voltages. WMMC1 and WMMC2 are configured to control the AC voltage of each of the wind farms. UUDAT is configured to control its transferred DC power.

The power reference of UUDAT is stepped from 0 to 1.0 GW at 1.0 s, stepped from 1 GW to 0 at 1.8 s, and further stepped from 0 to 1.0 GW at 2.5 s. A rate limit of ± 5 GW/s is applied at changing of the power reference. Power of the two wind farms is the same and stays at 500 MW before 3.0 s. Wind power oscillations are applied from 3.0 s.

Fig. 6a shows that P_{gmmc2} changes with the change of the power reference of UUDAT. GMMC1 acts as the balancing terminal of the system. After applying wind power oscillations, the P_{gmmc2} still stays unchanged and GMMC1 balances all the wind power oscillations.

Fig. 6b shows the power reference of UUDAT and the DC power measured at higher voltage side of UUDAT. It is seen that the DC power closely tracks the power reference.

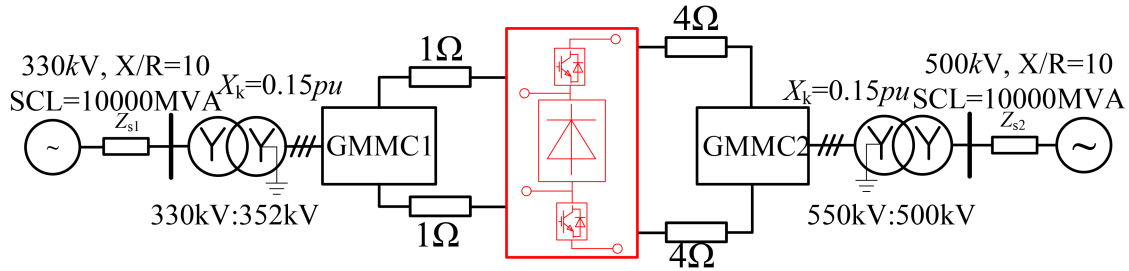


Fig. 4 Test system with DUDAT interfacing two MMC converters

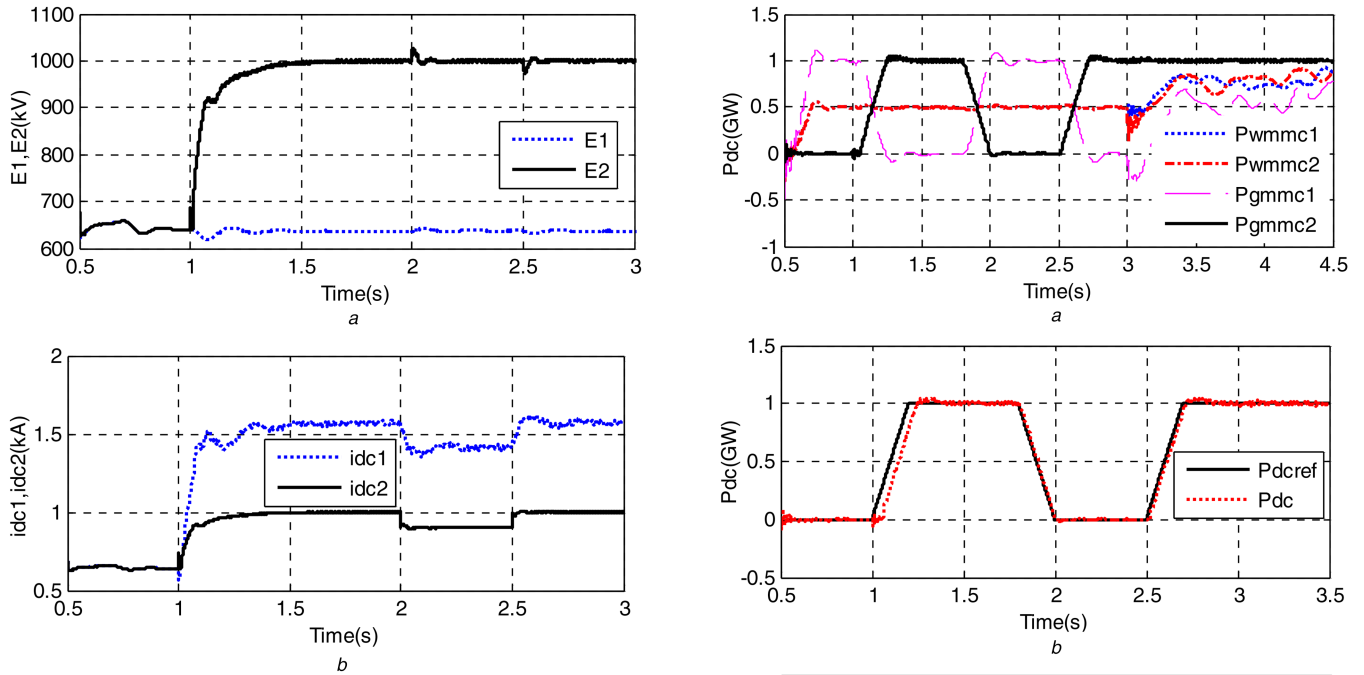


Fig. 5 Simulation of powering passive load through UUDAT
(a) DC voltages at higher and lower voltage sides of UUDAT, (b) DC currents at higher and lower voltage sides of UUDAT

Fig. 6c shows that because of the 12-pulse diode bridge, harmonics are observed at the AC current of MMC2 at full DC power.

Fig. 6d shows output AC voltage of MMC2 under full DC power. Harmonics are also observed.

7 Conclusion

UUDAT is composed of the series connection of diode bridges and MMCs, and is further optimised by DC AUTO for application where only the single power flow direction is required. UUDAT have lower converter rating and operating power loss compared with bidirectional DC AUTO and unidirectional DC/AC/DC. Upper layer controller for UUDAT is composed by an outer power or DC voltage loop, a middle AC voltage loop and an inner AC current loop. The control enables UUDAT to successfully control either its transferred DC power or DC terminal voltages. Possible application scenario of using UUDAT to transfer surplus wind power from a lower voltage DC system to a higher voltage DC system is proposed. Valve power loss ratio of UUDAT is around 1/2 the valve power loss ratio of unidirectional DC/AC/DC and 2/3 the valve power loss ratio of bidirectional DC AUTO. Extensive simulations verified the feasibility of using UUDAT to transfer wind power, using UUDAT to power resistive load. Technical feasibility of UUDAT is verified in PSCAD.

8 Acknowledgments

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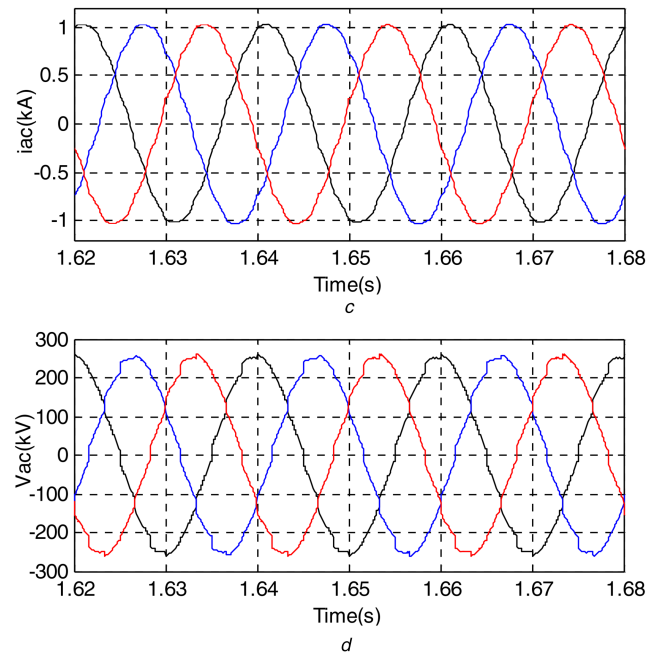


Fig. 6 Simulation of integrating wind power through UUDAT
(a) DC power of WMMC1, WMMC2, GMMC1 and GMMC2, (b) DC power reference and DC power of the UUDAT, (c) Output AC current of MMC2 at full DC power, (d) Output AC voltage of MMC2 at full DC power

9 References

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