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A Hybrid AC/DC Future Grid Solution

IT HAS BEEN OVER 100 YEARS SINCE THOMAS Edison built the first direct current (dc) electricity supply system on 4 September 1882, at Pearl Street in New York City. Many prominent events occurred in the electricity supply industry after that. The first one, "the war of currents," started in 1888. Thomas Edison and his dc distribution system were on one side, and George Westinghouse and Nikolai Tesla with the alternating current (ac) system were on other side. The war "ended" in about 1891 when ac won as the dominant power supply medium. The key behind the ac win was the invention of the transformer that could easily step up medium voltage to high and extra-high voltage for long-distance power transfer from a remote ac generation station to load centers hundreds of kilometers away with lower transmission losses. Transformers can also step down high voltage back to low voltage at load stations to supply the low-voltage equipment. Since the end of the war, ac power systems have been developed and expanded at a tremendous speed from the initial small isolated networks, with each supplying only lighting and motor loads with a few hundreds of customers, to its current scale of super interconnected networks each supplying billions of customers over large geographic areas in one or several countries. The voltage levels and capacities of transmission networks have increased from the first commercialized three-phase ac system with only 2.4 kV, 250 kW in the town of Redlands, California, United States, to the first commercial long-distance, ultra-high-voltage, ac transmission line in China with 1,000 kV, 2,000 MW. Transmission distance has been increased from several miles to over thousands of kilometers (miles). With such major achievements, it is little wonder that the ac power system became the top engineering achievement of the 20th century. Does this mean that dc is gone? The answer is an unambiguous no. What has happened in the past 50 years, such as applications of advanced control technologies in conventional power system loads, the power electronics based high-voltage dc (HVdc) transmission, and the additional renewable power sources in low-voltage distribution system, calls for a rethink about dc and ac in electricity supply systems.

DC Transmission in AC Power Systems

Although significant technical successes have been achieved in HVac, it does not necessarily mean that the ac network is more efficient than the dc grid under the same voltage levels. Debates on dc or ac have never stopped among electrical engineers, and perhaps the jury is still out on this matter. It is well known that a (same size) transmission line can transfer more power with less loss when using dc than ac due to thermal and stability limits. In the first 50 years after the war, engineers enjoyed the convenient and high efficiency of ac transmission, just raise the voltage using transformers for long-distance power transfer. The limitations and problems of ac transmission were hidden by the celebrations. The advantage of dc transmission was re-recognized due to the progress of advanced power electronics techniques. The HVdc Gotland link (Gotland 1), the first fully commercial static plant for HVdc transmission in the world, was in service on the Swedish east coast in 1954. Although the 100 kV Gotland 1, which used a static mercury arc valves-based inverter, can only transfer 20 MW over a 98-km-long submarine cable between Västervik on the mainland and Ygne on the island of Gotland, it indicates the starting of dc penetration inside ac-dominated transmission networks. Since then, many HVdc projects have been constructed and are under construction in existing power systems around the world. The voltage level has also been increased from ±100 kV to ±800 kV. The advantages of HVdc over ac systems for bulk transmission include higher power ratings for a given line and better control of power flows, especially in transient and emergency conditions that can often lead to blackouts. Based on the data from the DC and Flexible AC Transmission Subcommittee of the IEEE Transmission and Distribution Committee by the Working Group on HVdc and FACTS bibliography and records, there are over

table 1. Selected HVdc projects based on voltage level.									
Projects	Year	Rating (MW)	Voltage (kV)	Length (km)	Country				
Gotland 1	1954	20	±100	96	Sweden				
Gotland 3	1987	260	±150	103	Sweden				
Hybrid Inter Island Link	1965	600	±250	609	New Zealand				
Itaipu 1	1984	1,575	±300	785	Brazil				
Volgograd- Donbass	1962/ 1965	720	±400	473	Russia				
Nelson River 1	1973	1,854	±463	890	Canada				
Pacific Intertie	1985	2,000	±500	1,362	United States				
Pacific Intertie	1986	3,150	±600	785	Brazil				
Yunnan- Guangdong	2011	5,000	±800	2,071	China				

table 2. Some typical loads of future power systems.							
Loads	AC	DC	ACwC				
UPS and energy storage							
Electrochemical processes							
Electronics loads							
Electric arc furnace							
Future motor driver							
Heating			\checkmark				
Railway			\checkmark				
Future lighting							
Future air conditioner			\checkmark				

130 HVdc finished and ongoing projects. Table 1 shows some milestones of typical projects at different voltage levels; these projects reiterate the strong requirements of dc transmission in high and ultrahigh voltage levels of future power systems.

If HVdc is not enough to shake the dominant position of the existing ac network, recent changes in distribution networks would really make electrical engineers reconsider dc as a viable alternative.

Load Evolution in AC Power Systems

If the ac system offers advantages due to the inherent characteristics of ac machines and the availability of transformers for easy power transfer over long distances to supply the remote ac loads, the gradual changes of load types and distributed generator (DG) in ac local distribution systems provide food for thought with regards to adding dc networks.

The earliest power supply systems were first built to supply the lighting, heating, and motor driving loads. At the initial stages of a dc or ac system, ac or dc loads and generators were specially made to adapt their supply systems. Since ac won the battle and became the dominant supply medium, ac power systems have been boosted at a tremendous speed to today's scale. In ac systems, all loads are forced to adapt ac supply systems. For those inherent dc loads, electrical engineers built the ac/dc rectifiers to connect to ac networks and have not given enough thought to the efficiency of those connections and additional rectifier circuits. The advantages gained from



figure 1. Block diagram of an ac power system without DGs and HVdc.

An important change that has occurred quietly in conventional ac power systems, with the development of advanced control and electronics technologies to improve the efficiency of energy utilization and control flexibility, is the rapid growth of dc loads. When we go back to investigate loads in modern power systems, it is found that dc loads and ac loads with ac converters (ACwC) are in a dominant position in most ac power systems. Pure ac loads have been significantly reduced from time to time. When we are in our offices or at home, facilities such as computers, printers, videos recorders, and TVs surround us, and these are mostly dc loads. Even the conventional ac loads driven by ac motors, such as washing machines, refrigerators, air conditioners, and industrial equipment, are being gradually replaced by ac motors with inverters to control the motor speed and save energy. Although efficient ac fluorescent lamps in modern ac power systems have almost replaced the earliest incandescent bulbs invented by Thomas Edison, which work equally well on ac and dc, it is only a matter of time before they are replaced by more efficient lightemitting diodes (LEDs). Both ac and dc electric arc furnaces (EAFs) in the steel industry are the largest energy users. However, a dc EAF consumes less energy than a corresponding ac EAF with the same production. Industrial electrochemical processes are almost pure dc suppliers. Typical loads in future power systems are shown in Table 2; it can be clearly seen that a large percentage of the future load will be dc load. Do we still need to continue with ac, or should we rethink about dc grid at the distribution level?

Distributed Renewable Sources in AC Power Systems

Another prominent event, which has occurred recently in ac power systems, is the addition of DGs and microgrids (MGs) for the integration of renewable power sources such as wind turbine generators (WTGs), photovoltaic (PV) panels, fuel cell generators, energy storage systems (ESSs), and electric vehicles (EVs) into local distribution systems. Outputs from PV panels and fuel cell generators are dc. WTGs can be built into both ac and dc. Currently, PV systems and fuel cell generators require dc/ac inverters to connect to ac distribution

> systems. A complicated control circuit is also required for each dc/ac inverter to synchronize with 50 or 60 Hz ac systems and to provide high-quality ac currents without harmonics. Battery ESSs need a charging/discharging controller to connect to an ac grid. The penetration of EVs currently is only treated as ac load. Therefore, an ac/dc charging controller is required to charge the battery of EVs. However, EVs can also be used as energy storage to smooth the operation of power systems in the future. If this is the

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case, a discharging controller is required to connect EVs to the grid (V2G). The integration of DGs has changed not only the structure of ac power systems but also power flow direction from uniform to bidirectional in subtransmission and distribution systems. Figure 1 shows a conventional power system configuration and power flow direction without DGs. Figure 2 shows the power system configuration and power flow directions with PV as representative DGs. Figure 2 clearly shows a high appearance of dc



figure 2. Block diagram of an ac power system with DGs and HVdc.

penetration in ac power systems, although the last dc supply system by Con Edison was shut down on 14 November 2007. Figure 2 shows that dc will be everywhere in future distribution systems.

Current Conversions in AC or DC Power Systems

Is it worth upgrading current ac distribution systems into more efficient distribution structures with both ac and dc? The multiple conversions and the associated efficiency losses in current ac distribution systems have to be analyzed.

Conversion Road Maps in AC Power Systems

In an ac power system with DGs as shown in Figure 2, dc from PV panels or fuel cell generators has to be converted into ac using dc/ac inverters before the connection.

If the power from ac sources is finally consumed by ac load, no further conversion is required. For dc load, the power flow road map is ac-dc, and an ac/dc rectifier is required. For ACwC load, the road map is ac-dc-ac, and both ac/dc rectifier and dc/ac inverters are required.

If the power from dc sources is finally consumed by ac load, the road map of power flow is dc-ac, and a dc/ac inverter is required. For dc load, the road map is dc-ac-dc, and both an dc/ac inverter and an ac/dc rectifier are required. For ACwC load, the road map is dc-ac-dc-ac, and a dc/ac inverter, an ac/ dc rectifier, and an dc/ac inverter are required.

Current Road Maps in DC Power Systems

DC grids have shown a resurgence in recent times due to the development and deployment of renewable dc power sources and their inherent advantages for dc loads in commercial, industrial, and residential applications. In a dc power system, ac power from ac sources has to be converted into dc using ac/dc converters before the connection.

If power from dc sources is finally consumed by dc load, no further conversion is required. For both ac and ACwC loads, the road map is dc-ac, and a dc/ac inverter is required.

If power from ac sources is finally consumed by dc load, the road map is ac-dc, and an ac/dc converter is required. For ac and ACwC loads, the road map is ac-dc-ac, and both ac/dc and dc/ac converters are required. The road maps of the power conversion process for individual ac or dc systems are shown in Table 3. Generally, an ac distribution system has more conversion process than a dc distribution system. It should be noted that the power conversion road map does not consider the ac/ac voltage step up/down stage for ac sources and loads connected to ac system, and dc/ dc bulk/boost stages for dc sources and loads connected to dc systems. Table 3 suggests that there will be very little or no conversion process if ac sources and loads are connected to the ac grid and dc sources and loads are tied to dc link. In this case there will be no conversion equipment and related loss.

Hybrid AC/DC Structure for Future Power Systems

For ac power systems with a history of over 100 years, it is very natural to build various embedded converters inside various electrical facilities to adapt to ac. Electrical engineers have never doubted the rationale for the existence of these converters and seldom think about their efficiency. Global warming and limited fossil resources have forced people to pay more attention to renewable energy and the efficiency of energy utilization. As electrical engineers, it is also time for us to reexamine the ac power system structure and its efficiency. Table 3 clearly indicates that there are multiple conversions for an individual ac or dc grid and the advantages of ac sources for ac loads and dc sources for dc loads. Can we eliminate the additional equipment or at least reduce the conversion process? Is it possible to build a hybrid ac/dc power system with both ac and dc links based on current ac infrastructure? Many electrical engineers have investigated adding dc MGs in local distribution systems. A favorable solution is to build a hybrid dc and ac grid at distribution levels, to couple dc sources with dc loads and ac sources with ac loads.

table 3. The road map of power conversion for ac and dc power systems.								
System		DC Load	AC Load	ACwC Load				
ас	dc source	dc/ac/dc	dc/ac	dc/ac/dc/ac				
	ac source	ac/dc	no	ac/dc/ac				
dc	dc source	no	dc/ac	dc/ac				
	ac source	ac/dc	ac/dc/ac	ac/dc/ac				



figure 3. A hybrid ac/dc microgrid system.

General Hybrid AC/DC Grid Structure I

Figure 3 shows a proposed hybrid ac/dc MG connected to a utility ac grid. There are dc and ac distribution networks connected together through the four-quadrant operating three-phase ac/dc (or main) converters that may be transformerless or with a transformer. DC power generators such as PV panels and fuel cell generators are connected to dc networks through dc/dc boost converters. DC loads such as EVs and LEDs are tied to a dc grid through dc/dc buck converters. AC loads with speed control motors are connected to dc link through dc/ac converters. DC energy storage such as batteries and super capacitors are connected to the dc grid through bidirectional dc/dc converters. The threephase ac network of the hybrid grid, which can also be the existing low-voltage distribution network, is connected to the utility grid through a transformer. AC power generators, such as wind turbine and small diesel, are connected to the ac network through transformers. AC energy storage such as flywheels are connected to the ac grid through ac/ ac converters and transformers. AC loads such as ac motors and heaters are connected to ac networks. The voltage level of the ac grid is 200 or 400 V. There are still no standard voltage levels for the dc grid. The voltage levels currently used in some test systems are between 12 and 1,000 V, which depend on the converter and system requirements. This hybrid structure reduces the multiple conversions to a minimum.

Grid Operation and Control

Two operating modes of a hybrid grid are the grid-tied mode and autonomous mode. Stable and reliable grid operation mainly depends on the main converters, ESSs, and dc and ac power conversion systems on both sides. The system can be controlled centrally by an energy management system and can also operate under decentralized control.

Grid-Tied Mode

In this mode, the utility grid operates as the swing bus of the hybrid grid to balance load demand and supply. Power surplus in the hybrid grid will be sent to the utility grid, and power shortage in the hybrid grid will be supplied by the utility grid. Utility in this case is like energy storage with an infinite capacity for the hybrid grid. Therefore the ESSs in the hybrid grid are not critical and can be eliminated. All renewable conversion systems are controlled to operate in the maximum power point tracking (MPPT) mode to harness maximum energy from renewable sources. The functions of the main converter are to maintain a smooth power transfer between the ac and dc buses, provide a stable dc bus voltage, and reduce harmonic injection into the utility grid. One important function of the main converter is to solve the unbalance problem of the utility grid caused by the unbalanced loads connected to the ac network. When the output of the dc sources is larger than the dc loads, the main converter acts as an inverter and transfers power from the dc to the ac side. Otherwise, the main converter transfers power from the ac to the dc side. When the total power is greater than the total load in the hybrid grid, it will inject power into the utility grid. Otherwise, the hybrid grid will receive power from the utility grid.

Autonomous Mode

In this mode, ESSs at the dc grid or diesel generators at the ac grid operate as energy buffers for balancing power surplus and shortage and for maintaining the system stability under various grid operating conditions. Converters of the renewable power sources may operate in the MPPT or off-MPPT mode based on ac frequency and dc voltage.

When dc voltage or ac frequency (or both) is low, the renewable sources should operate in the MPPT mode and the controllers of the ESSs should operate in the discharging mode or diesel generator will produce more power. The main converter is controlled to transfer power between ac and dc links based on load and resource conditions on the two sides.

When dc voltage and ac frequency are high, which indicates that there is energy surplus from both sides, the diesel generator will produce less power, the controllers of ESSs should operate in the charging mode to store energy, and the main converter is controlled to transfer power between ac to dc sides based on resource conditions. If all ESSs are fully charged, the output of the diesel generator is zero and voltage/frequency on both sides are still high, some of resource converters should operate in the off-MPPT mode.

System Control

The system can be centralized or decentralized. The main objectives of system control, consisting of individual controls of inverters, converters, and charging/discharging controllers, are to maximize energy harvest from renewable sources and minimize power transfer between ac and dc sides under different system load and resource conditions.

Hybrid DC/AC Grid Structure II

This structure is a special case of the structure I as shown in Figure 3. The difference is that there are no dc sources and energy storage at the dc side, and only dc and ACwC loads are connected to the dc side. The ac grid is connected to the utility grid. This simple structure can be easily upgraded for most existing distribution systems. In this case, the main converters operate as ac/dc rectifiers. Power quality is an important issue



figure 4. A prototype of the hybrid grid structure II.



figure 5. A hybrid ac/dc microgrid at the WERL, NTU.

in the local distribution system with the increased penetration of nonlinear loads due to their harmonic current injection into the grid. One of the main functions of the main converter is to control the harmonic injection to the ac bus. Moreover, threephase unbalanced loads are ubiquitous in distribution systems and can cause large negative sequence currents. The polluted grid current will increase the loss and reduce the efficiency of the network. Therefore the second function of the main converter is to compensate harmonic and reactive power as well as unbalanced loads on the ac side. A prototype of the hybrid grid structure II and its control block diagram are shown in Figure 4. The ac grid is represented by three-phase voltage sources v_{SA} , vsa and vsa. Unbalanced three-phase ac distribution with harmonics is represented by an unbalanced and nonlinear load. The output of the main converter is the dc grid. The structure will provide a clean and balanced three-phase current.

Main Advantages of Hybrid AC/DC Grids

From the analysis, multiple conversions have been reduced to a minimum due to both dc and ac links in the hybrid structure. The advantages of the hybrid grid can be summarized as follows:

- The elimination of unnecessary multiconversion processes means a reduction of total conversion loss.
- The elimination of embedded rectifiers for dc and ACwC loads in the current ac grid means the simplification of equipment and cost reduction of electronic products.

- ✓ The connection of all dc loads to the dc side of the hybrid grid will make it easy to control harmonic injections into the ac side through the main converters, thus guaranteeing high-quality ac in the utility grid.
- ✓ The dc grid can solve negative and zero sequence current problems caused by unbalanced loads in ac distribution systems, and the neutral wire in subtransmission may be eliminated and the related transmission losses reduced.

Existing DC and Hybrid DC/AC Grids

There are several dc and hybrid grids that have been proposed and tested for industrial systems, commercial facilities, residential buildings, and data centers around the world. The efficiency of dc and ac transmission and distribution considering multiconversions has been compared. The loss of dc transmission is lower than that of ac, and dc grids also have less of a conversion process compared with ac. When combining both ac and dc in local distribution systems, the conversion process can be further reduced to a minimum. Two pioneering demonstrations of dc systems have been tested at the Lawrence Berkeley National Laboratory, with 10% energy savings recorded for the entire data center, compared to a very efficient ac baseline case.

A hybrid dc/ac grid is under construction at the Water and Energy Research Laboratory (WERL) with support from Schneider Electric Singapore and Nanyang Technological tie ac and dc grids together. An 18-kW ac source, 7.5-kW wind turbine generator simulator, 4.5-kW programmable load, and 3.3-kW resistive load are connected to the ac grid. The ac grid can also be connected to the utility grid and to the ac MG in the NTU clean energy research laboratory. A 20-kW dc programmable source, 14.5-kW programmable load, a 3.3-kW resistive load, 1.45-kW solar simulator, and 28.8-kWh battery storage are connected to the dc grid. A 5-kW PV system can be connected to the ac grid by a dc/ac grid tied inverter and can also be switched to the dc grid through a dc/dc booster converter. A 1.2-kW fuel cell generator with a 5-kWh hydrogen tank as energy storage is connected to the ac grid and can also be switched to the dc grid. The illustrative hybrid system is shown in Figure 5. The aim of this hybrid grid is to provide a test bed for investigating different hybrid grid infrastructures ✓ studying the individual and coordination control technologies for various inverters and converters ✓ testing suitable voltage levels for the dc grid, which can facilitate the connection of various dc sources and

University (NTU), Singapore. The illustration diagram of the hybrid ac/dc grid is shown in Figure 5. The hybrid grid consists

of a 400-V, three-phase ac grid with eight nodes and a 380-V dc

grid with eight nodes. Both ac and dc grids can be connected

into radial or ring configurations. Two bidirectional converters

- investigating new problems due to the connection of dc sources and loads
- developing new inverters and converters for reliable operation of the hybrid grid
- testing newly developed dc protection and metering equipment
- developing energy management system(s) for hybrid MGs.

Problems to Be Solved for Future Implementation

dc loads

Although the hybrid grid can reduce the unnecessary processes of dc/ac and ac/dc conversions compared with an individual ac or dc grid, many practical problems exist for implementing it. It is not economical and also difficult to build a new dc grid to replace the existing ac distribution infrastructure. It takes time to find the right way to upgrade the current ac distribution systems into hybrid ac/dc grids. The second problem is to define standard voltages for the dc grid. Standard dc voltages have to be determined for easy connection of popular dc loads considering the current ac voltages. Besides hybrid infrastructures, home and office products also will have to be redesigned without the embedded ac/dc rectifiers. Therefore it is a long-term process for the implementation of the hybrid ac/dc grid. The hybrid grids can be easily implemented in new buildings. For the old buildings that need to upgrade distribution systems due to the integration of PV systems, new LED lighting systems, and EV charging systems, there exists a good opportunity to use the hybrid grid. New metering, protection, and grounding equipment are also required for the hybrid grid.

Conclusion

For over 100 years, ac power systems have developed and expanded to today's scale and have provided tremendous power and convenience for the rapid advancement of modern society. Electrical engineers have become used to building various embedded conversion converters for various loads to adapt to ac. Problems that have come to the fore due to global warming and limited fossil fuel resources require electrical engineers to rethink about efficiency of energy utilization for conventional ac power systems and to reexamine current ac transmission and distribution structures. Although it is difficult to implement this new structure in current acdominated local distribution systems, hybrid ac/dc grids and hybrid energy grids with dc/ac/thermal will be the future for high-efficiency energy supply systems. DC and ac systems coexisting in harmony due to advanced power electronic techniques will provide more green and high quality energy with the highest efficiency.

For Further Reading

M. E. Baran and N. R. Mahajan, "DC distribution for industrial systems: Opportunities and challenges," *IEEE Trans. Ind. Appl.*, vol. 39, no. 6, pp. 1596–1601, Nov. 2003.

A. Sannino, G. Postiglione, and M. H. J. Bollen, "Feasibility of a dc network for commercial facilities," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1409–1507, Sept. 2003.

D. Salomonsson and A. Sannino, "Low-voltage dc distribution system for commercial power systems with sensitive electronic loads," *IEEE Trans. Power Delivery*, vol. 22, no. 3, pp. 1620–1627, July 2007.

M. Ton, B. Fortenbery, and W. Tschudi. DC power for improved data center efficiency. Lawrence Berkeley National Laboratory, CA [Online]. Available: http://hightech.lbl.gov/ dc-powering/

D. J. Hammerstrom, "AC versus dc distribution systems: Did we get it right?," in *Proc. IEEE Power Engineering Society General Meeting*, June 2007, pp. 1–5.

X. Liu, P. Wang, and P. C. Loh, "A Hybrid ac/dc microgrid and its coordination control," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 278–286, 2011.

P. Wang, X. Liu, C. Jin, P. C. Loh, and F. Choo, "A hybrid ac/dc micro-grid architecture, operation and control," in *Proc. 2011 General Meeting IEEE Power Engineering Society*, Detroit, MI.

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