DC Connection of Offshore Wind Power Plants without Platform

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Abstract—**This paper introduces the concepts of platformless DC connections of offshore wind turbines. First, the paper describes the possible and preferred wind turbine drivetrain arrangements capable of producing sufficiently high DC voltage. Then, the electrical system designs appropriate for the platformless DC architectures are discussed. After that, the potential economic benefits of direct DC connections of offshore wind turbines are analyzed, showing significant CapEX reduction up to 20-25% when compared to the AC collection and transmission solutions. Control concepts of the wind farm plant and DC connection system are also briefly discussed. The paper concludes that the platformless DC connections would offer lower cost, higher efficiency and enhanced grid support, thus promising for medium and large offshore wind plants in many cases.**

Keywords-Offshore wind, wind turbines, wind power plant, DC collection, DC transmission, platformless

I. INTRODUCTION

Offshore wind resources are becoming a key energy source worldwide. The cumulative offshore wind power installations are expected to reach 153 GW by 2030, highly concentrated in three major markets: Europe, China and the United States [1]. The United States has a vast offshore wind energy resource and in early 2011, the U.S. Department of the Interior (DOI) and the U.S. Department of Energy (DOE) unveiled a coordinated strategic plan to achieve the deployment of 54GW of offshore wind power capacity by 2030 [2]. Further study by the National Renewable Energy Laboratory concluded that the United States could feasibly build 54 GW of offshore wind power for depths less than 30 meters [3].

The capital costs for offshore wind farms are significantly higher than that of onshore wind farms. In addition, offshore wind farms have higher outage and maintenance costs due to harsh operating environment and low accessibility. Recent estimates of the capital cost for offshore wind power in the United States are on the order of $5-6 million per MW [4]. The estimated capital cost of offshore wind project in Europe is about £3.1 million per MW at the beginning of 2014 [5]. Innovative and integrated system solutions are needed to enable a significant reduction of the levelized cost of energy (LCOE). Cost reduction of the electrical infrastructure is an important part of the overall cost reduction efforts. The cost share of the electrical infrastructure (including inter-array cables, offshore substation, high voltage export cables and onshore substation) is about 18% of total capital expenses for the construction of an offshore wind farm [6].

The electrical system for a typical large offshore wind farm comprises wind turbines with their attendant power conversion and transformation devices, a medium voltage AC collection grid, an offshore substation on a platform, a high voltage transmission system, and an onshore substation to interface the wind farm with the power grid. The offshore wind farm collection system typically has a feeder structure and operates at 33-36 kV AC. Wind turbines are connected in parallel by different feeders which are then connected to the platform substation. The choice of transmission technology is mainly determined by the distance of the wind farm from the grid connection point. When the wind farm is not distant from the shore, High Voltage AC (HVAC) transmission systems are used. In cases where the wind farm is far from shore, Voltage Source Converter based High Voltage DC (VSC-HVDC) systems have proven technically advantageous and cost-effective [7-10].

Cost reductions of electrical infrastructure can be achieved by increasing the collection grid voltage from 33-36 kV AC to 66-72 kV AC for large offshore wind farms [11-13]. These include reduction of capital costs for both radial and inter-array cables, implementation of ring array systems and reduction of the number of offshore substations. For small and medium, close-to-shore wind power plants, it might be cost effective to connect wind turbines to onshore substations directly by 66-72 kV AC cables [14]. In this paper, the concepts of platformless DC connections of offshore wind turbines are introduced, which would offer more cost-effective solutions in many cases when compared to the AC collection and transmission solutions. The key technology of such direct DC connection solutions is to use a wind turbine drivetrain that would produce high enough DC voltage output and transmit the power directly onshore with DC cables. The use of DC cables allows for large wind farm connection and significantly longer distance transmission (compared to direct 66-72kV AC connections) without an offshore platform.

The paper is organized as follows: Section II describes the possible and preferred DC wind turbine drivetrain arrangements. Section III describes the electrical system designs appropriate for direct DC connection solutions. Section IV analyzes the potential applications and economic benefits of such DC connections in comparison with AC solutions. Section V briefly discusses control concepts of wind farm and the DC connection system. Section VI gives the conclusions.
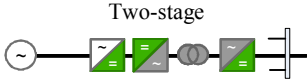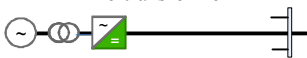
II. WIND TURBINES WITH DC VOLTAGE OUTPUT

This section describes wind turbine drivetrains capable of producing sufficiently high DC voltage output suitable for transmission to shore and technical features of preferred DC wind turbine concepts.

A. DC Wind Turbine Drivetrain Arrangements

This paper only considers permanent magnet synchronous generators (PMSGs) in the wind turbine, because most offshore wind turbines at power levels above 5 MW use this kind of generator. Table 1 below shows the three basic DC wind turbine drivetrain options.

Table 1 DC drivetrain arrangement options

Simplified one-line arrangements	Typical generator ratings
Two-stage	Voltage: 0.69…6.6 kV Frequency: 10…120 Hz
Transformerless	Voltage: 6.6…13.8 kV Frequency: 10…120 Hz
Pre-transformer	Voltage: 0.69…6.6 kV Frequency: 50…120 Hz

1) Two-stage (rectifier and DC/DC converter)

In this arrangement, the variable voltage, variable frequency output of the generator is first rectified and then stepped up to a higher DC voltage [15]. The use of a dc-dc converter, which is typically composed of three sub-stages - an inverter, a transformer, and a rectifier, results in higher complexity and lower efficiency. The rectifier part could be a passive diode or thyristor rectifier to keep costs down, but then appropriate means for obtaining auxiliary and startup power have to be considered.

2) Transformerless

In this arrangement, the output of the generator is already at a high enough voltage so that it only needs to be rectified. Although this has the fewest number of power conversion components, it requires that the generator windings be able to tolerate fairly high voltage stresses, which results in a higher cost design.

3) Pre-transformer

In this arrangement, the output of the wind turbine generator is connected to a step-up transformer before rectification. This arrangement strikes a balance between the complexity, efficiency, and design requirements. The technical features of this preferred option are discussed in the next subsection.
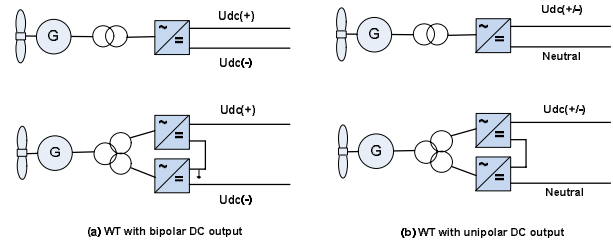
B. Pre-Transformer DC Wind Turbines

1) Basic drivetrain arrangement

For multi-MW scale wind turbines, use of a medium or high speed PMSG – with rated frequency of 50 Hz or higher – may be preferred as it allows lower combined mass and cost of the gearbox and generator (compared to a gearless or low-speed system). The output voltage of the generator is expected to be between 690V–6.6kV. The pre-transformer arrangement is most suited for such a system. A conventional line frequency transformer can be used as the "pre-transformer" because the flux, which is proportional to the ratio of voltage and frequency, never exceeds its rated value over the entire range of operation. The challenge of this arrangement is the implementation of a high voltage, low current converter to convert 33-66kV AC power to the corresponding DC power.

2) Power conversion system

The power conversion system can produce unipolar or bipolar DC output from wind turbine and can be implemented with different converter topologies and arrangements. Fig. 1 shows the schematic of pre-transformer wind turbine drivetrains. In each wind turbine, the AC output of generator is transformed to a higher voltage by a step-up transformer and then rectified to a corresponding DC voltage by an active ac-dc converter.

(a) WT with bipolar DC output   (b) WT with unipolar DC output

Fig. 1 Pre-transformer wind turbines with DC voltage output

A modular multilevel converter (MMC) topology is preferred for the active rectifier since these topologies are able to reach high terminal voltages with relatively low voltage switching devices. Depending on the functionality requirements, the MMC topology based active rectifier could be implemented with half-bridge cells, full-bridge cells, or hybrids. For wind energy conversion applications, low frequency operation would not be an issue, because converter would not operate below cut-in wind speed.

III. ELECTRICAL SYSTEM DESIGNS

In this section, the electrical system designs appropriate for platformless DC connection architectures are discussed.

A. Feeder Topologies

Fig. 2 shows typical feeder topologies for wind farm collection grids, including radial feeder, bifurcated radial feeder, single-sided ring and double-sided ring [16]. Radial system is the most straightforward concept and has a lower installed cost due to the low complexity with regard to the amount of switchgear required. The layout can be optimized in terms of string routing and cable cross-sections. Bifurcated radial feeder topology is similar to the radial system except it uses one feeder circuit breaker to

switch two sub-feeders. Inter-array cable faults or wind turbine faults can be isolated with appropriate switching devices at wind towers, and the wind turbines not connected to the faulted feeder section could then resume normal operation. However, any feeder circuit breaker failure or export cable failure will result in complete loss of feeder generation. Ring type layouts can address some of the security issues of the radial designs by joining pairs of radial strings with a cable between the furthermost wind towers from the collector substation. The improved security comes at the expense of longer cable runs for a given number of wind turbines for the single-sided ring or higher cable rating requirements for the double-sided ring.
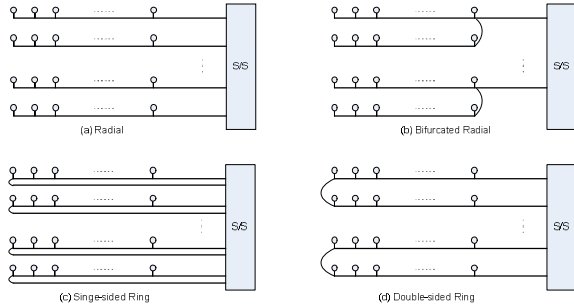

Fig. 2 Feeder topologies for wind farm collection grids

B. Platformless DC Architectures

Two main variants of the platformless DC architectures are shown in Fig 3 and Fig 4, which are characterized by the points where the power outputs from individual feeders are aggregated at the onshore substation.
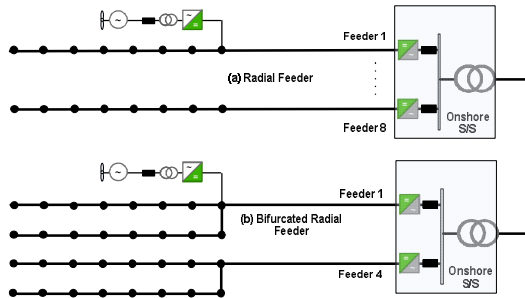

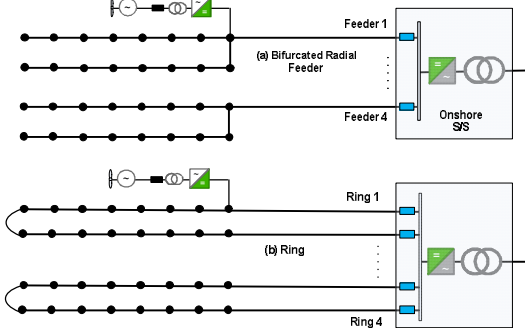**Fig. 3 DC architectures with AC aggregation**

Fig. 4 DC architectures with DC aggregation

With AC aggregation, feeders are connected to the AC bus of the onshore substation through individual inverters. AC breakers can be used to disconnect a faulted feeder from the AC bus. With DC aggregation, feeders are connected to the DC bus of the onshore substation and then converted to AC power through parallel inverters. DC switching devices are needed to disconnect a faulted feeder from the DC bus. Ring type layouts may not be appropriate for the architectures with AC aggregation due to higher rating requirements for the grid-interface inverters in addition to high rating inter-array and export cables.

C. Preferred Operating Configurations

Wind turbine rectifiers, inter-array and export cable systems and onshore grid-interface inverters can form a DC connection system in various operating configurations. Considering both technical and cost challenges, the DC output voltages of wind turbines are limited to certain potential levels. On the other hand, higher DC transmission voltages are desirable for economic use of cable capacities and efficient power delivery. As such, there is a need for optimal coupling between the DC wind turbines and the DC collection and transmission system.

The preferred system operating configuration is shown in Fig 5. The basic configuration comprises two wind turbine clusters, one producing positive-valued DC output and one producing negative-valued DC output, and a bipole DC transmission system. The neutral terminals of the two wind turbine clusters are connected therefore resulting in an aggregated wind energy source with bipolar DC output. The aggregated wind energy source is then interconnected to the onshore inverter substation through a DC transmission system comprising a positive pole cable, a negative pole cable, preferably including a neutral cable. In practice, a neutral cable is needed because the power outputs of the two clusters are not equal most of the time under normal operations and the ground return currents may be strictly restrained. With the neutral cable in service, monopole operation of the DC connection system is possible under certain component forced outages or scheduled maintenance.
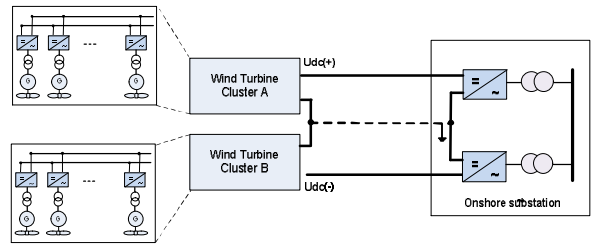

Fig. 5 Preferred system operating configuration

For large wind farms, the basic configuration shown in Fig 5 could be expanded with more wind turbine clusters and bipole DC transmission systems. The neutral cable could be shared by parallel bipolar DC transmission systems. Each wind turbine cluster could comprise multiple radial feeders or sub-feeders.

IV. POTENTIAL ECONOMIC BENEFITS

In this section, the potential economic benefits of platformless DC architectures are discussed in comparison with the best applicable AC solutions.

A. Potential Sites for Direct DC Cconnection

The wind sites suitable for direct DC connection solutions are essentially the same as for AC connection solutions. These include both medium and large wind power plants for a broad range of rated capacity and distance to shore. In Europe, offshore wind farms have moved further from shore and into deeper waters over years. However, there are still a significant portion of the consented offshore wind projects that are within the distance less than 60-70km from shore and water depth less than 35m. Fig. 6 shows the average water depth and distance to shore of in-operation, under-construction and consented offshore wind farms at beginning of 2014 in Europe [17].
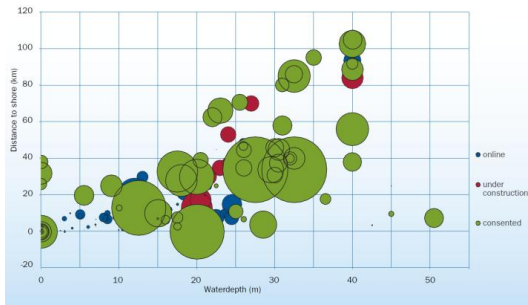

Fig. 6 Water depth and distance to shore of offshore wind projects in Europe [17]

In the United States, the recent National Offshore Wind Energy Grid Interconnection Study (NOWEGIS) has evaluated availability and potential impacts of interconnecting large amounts of offshore wind energy into the transmission systems [18]. As part of the study, offshore wind delivery system technologies and topologies have been evaluated for connecting 76 wind sites with a total capacity of 54GW. These 76 wind sites were selected from Pacific, Gulf, Lakes and Atlantic regions based on the estimated LCOE. As shown in Fig 7, more than half of the selected wind sites are within 70 km distance from onshore interconnection substations (i.e., the point of common coupling, PCC), accounting for about 50% of the targeted 54GW capacity.
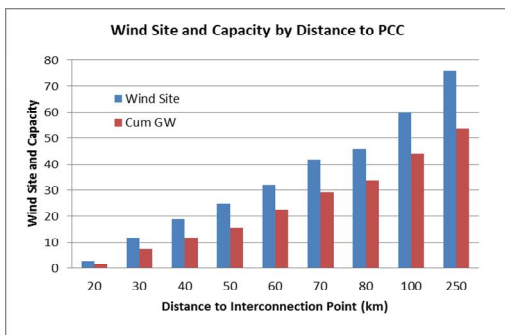

Fig. 7 Distribution of wind sites and capacity by distance to onshore interconnection points [18]

B. Potential Economic Benefits

The proposed platformless DC connections would potentially offer lower capital cost, higher efficiency, higher reliability, and enhanced grid support in comparison with AC solutions. The expected CapEX savings are mainly contributed by elimination of offshore substation and use of DC transmission cables.

By eliminating the offshore platform, the estimated cost savings would be about 15-20% of total investment of electrical infrastructure. In average, the capital cost for an offshore wind power installation is about 5-6 M$ per MW and the share of electrical infrastructure is about 18% of total investment. For a 300MW offshore wind farm, the average capital cost of the electrical infrastructure would be about 270-320M$. The cost range of example 300MW AC platforms (132/33kV, 25 x 22 x 18 meters, weighing 2000 tons) is 38-44 M€ [19] or 50-58 M$ (1 Euro = 1.3 USD).

Further CapEX reduction would be contributed by DC cables, which require less copper, and hence are typically 1/3 less expensive than AC cables for transmitting the same level of power. For example, a 850 MW transmission system could be implemented with three single-core 500kV AC cables (1500 mm^2, 1080A, 460-660 Euro/meter per cable) or bipolar 320kV DC cables (1500 mm^2, 1350A, 345-518 Euro/meter per cable). As another example, a 350MW transmission system could be implemented with one 3-core 245kV AC cable (1200 mm^2, 950A, 748-1150 Euro/meter) or bipolar 150kV DC cables (1200 mm^2, 1188A, 230-460 Euro/meter per cable). Similar cost advantages could be expected for 50-60kV DC cables in comparison with 66-72kV AC cables. This makes direct DC connection solution more advantageous than direct AC connection solutions.

The proposed DC architectures would also reduce collection and transmission losses and thus increase the net output of wind farm. Finally, by eliminating offshore substation and having grid interface converters at the onshore substation, the overall system maintainability and grid support capability would be greatly improved.

It is expected that the cost of active rectifier required for pre-transformer wind turbine would be lower than the cost of full power converter used in conventional wind turbine. A full power converter comprises a rated generator-side rectifier and typically an over rated grid-side inverter for provision of reactive power. The cost of onshore substation will increase due to the need of grid-interface inverters. However, the cost of inverters would be largely balanced by the cost savings from eliminated offshore substation, passive and dynamic reactive power compensation devices which are typically needed in AC solutions.

In the following subsections, two example case studies are presented on the potential CapEX savings of electrical system with direct DC connection solutions. The analysis is performed for the electrical system architectures with AC aggregation as shown in Fig 3. The following costs are included in the CapEX calculation model:

- Wind turbine generator, transformer and converter
- Inter-array cables
- Offshore platform
- Electrical offshore substation
- Export cables
- Onshore substation
- Substation switchgear

For simplicity, the total required reactive power compensation for AC solutions is assumed to be 50% of the wind farm rated capacity, with 50-50 capacity split between passive and dynamic compensation devices.

C. Case Study - Medium Wind Power Plants

Fig 8 shows cost comparison for an example 200MW wind power plant. In this example, 132kV and 245kV AC connections with 33kV AC inter-array cables might not be competitive for distance less than 40 km due to high cost of offshore platform. The comparison shows significant cost savings of 60kV DC direct connections (double circuits) than 72kV AC direct connections (three circuits) an132 kV AC connections (double circuits). The cost savings of 60kV DC direct connections become less significant when compared with single circuit 245kV AC connections.
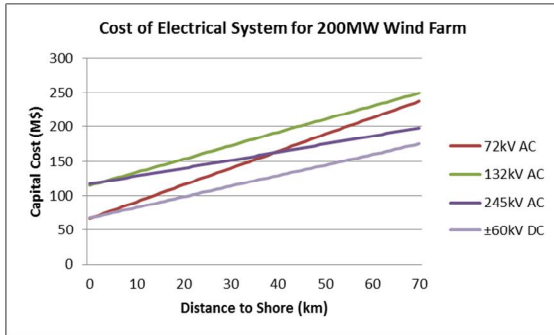

Fig. 8 Cost comparison for an example 200MW wind farm

D. Case Study –Large Wind Power Plants

Fig 9 shows cost comparison for an example 600MW wind power plant. In this example, 72kV AC direct connections become not interesting due to high costs of export cables while 60kV DC direct connections are till cost-competitive than 132kV AC solution. Similarly, the cost savings of 60kV DC connections are reduced when compared to 245kV AC connections.
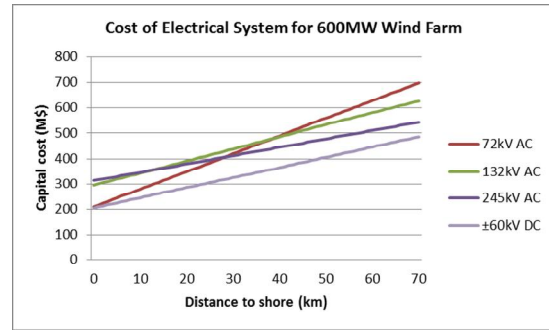

Fig. 9 Cost comparison for an example 600MW wind farm

In summary, the preliminary comparison shows that 60kV DC direct connections would be cost competitive up to 20-25% of CapEX savings when compared to 72kV AC direct connections or 132kV AC connections; and about 10-20% CapEX saving when compared to 245kV AC connections.

V. CONTROL CONCEPTS

This section outlines the control functions of the wind power plant and the DC connection system.

A. Primary Control Tasks

There are three controllable subsystems in the main power conversion chain from the wind turbine to the onshore AC grid: the wind turbine mechanism, the variable frequency rectifier, and the grid-tie inverter. The wind turbine mechanism comprises various mechanisms that allow the control of the power generated according to the wind speed and direction. The variable frequency rectifier largely controls the generator for maximum power production. The grid-tie inverter largely controls the interface of the wind farm to the grid. Table 2 gives a high-level view of what is controllable via these three subsystems. One may note that the control duties of the various subsystems are identical to those that would be performed in a typical offshore wind power plant with AC collection and transmission.

Table 2 Control duties for various subsystems in a dc-connected offshore wind power plant without a platform

	Wind turbine mechanisms	Generator-side converter	Grid-side converter
Quantities to control	Blade pitch; Nacelle yaw	Generator active and reactive power, speed	DC voltage and Grid-side reactive power
Quantities to sense or estimate	Wind speed; Wind direction	Generator current and voltage; Generator speed and/or torque; DC current and voltage,	Grid-side current and voltage; DC current and voltage,
Description of control	• Standard pitch drive to adjust the blade angle according to the wind speed; • Standard yaw drive to turn the nacelle in the direction of the wind	• Adjust speed ω to maximize power output from turbine-generator (MPPT); • Regulate the d- and q-axis currents in the machine to match the torque produced by the wind (the d- and q-axis currents effectively control generator active and reactive power)	• Regulate the DC bus voltage on the feeder; • Regulate the reactive power into the grid according to command from the grid operator

B. Secondary Control Tasks

In addition to the primary control tasks of maximum power point tracking, generator control, DC voltage regulation, and AC grid reactive power control, there are secondary control tasks to be performed in the wind farm. The most important of them include fault ride-through, auxiliary power systems, black start, etc. These secondary control tasks will not be further discussed in this paper.

C. Coordinated Control

With the grid-side converters co-located at the onshore substation, the controllability and dynamic performance of the wind power plant can be enhanced with advanced control strategies. These include improved reactive power management, fault ride-through, frequency and voltage support to the power grid. Fig 10 shows an example wind farm and direct DC connection system with a central controller implemented at the onshore substation.
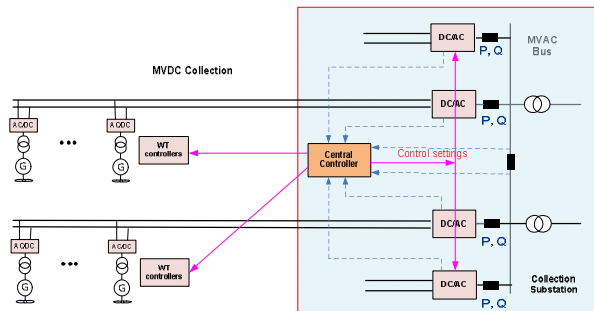

Fig. 10 Control of wind farm and direct DC system

Based on the received orders from TSO and the local measurements, the central controller generates the switching (On/Off) commands and the setting parameters of grid-side converter controllers using the built-in control logics and/or algorithms. The control controller might also generate the setting parameters of generator-side converter controllers and wind turbine pitch controllers. In this case, fast communication channels from the central controller to wind turbine controllers might be needed.

VI. CONCLUSIONS

Platformless DC connection systems for offshore wind power plants have been proposed, which would offer lower cost, higher efficiency, and enhanced grid support in comparison with AC solutions. By eliminating offshore substation and having grid interface converters at the onshore substation, the overall system maintainability and availability would be greatly improved. This design concept may become a greater advantage as wind farms move into deeper water and offshore platforms potentially become even more expensive.

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