

R/X Ratio Influence on Short Circuit Current of Doubly-Fed Induction Generator Based Wind Turbines

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Abstract—The peak short-circuit current and the initial symmetrical short-circuit current of the doubly-fed induction generator (DFIG) are essential quantities for protection system design and network stability analysis. The different configurations, parameters and controller settings as well as the R/X ratio influence those quantities. This paper investigates the influence of different values of R/X ratio on the short-circuit quantities of the doubly-fed induction generator based wind turbine (DFIG-WT). The IEC-60909 definitions were used for calculation of short-circuit quantities and the results show that it is not adequate.

Index Terms—Doubly-Fed Induction Generator, Wind-Turbine, Short-Circuit, IEC-60909

I. INTRODUCTION

The strong expansion in wind power plant (WPP) installations led to establishment of new grid codes [1], in order to preserve system stability during abnormal operations. The new grid codes dictate new requirements regarding grid support. In order to correspond with the new grid codes, the WPP must remain connected to the grid during grid faults and ride through them. The new stipulated requirements have created new challenges for wind turbine (WT) manufacturers. However, due to the high control flexibility offered by the doubly-fed induction generator (DFIG), the fulfillment of the grid codes requirements could be easily achieved [2]. Additionally, the DFIG offers other advantages, like the usage of partial rated converter and moderate costs, which with the high control flexibility the DFIG offers, have promoted it to be the favorable technology used by the WT manufacturers. Fig. 1 shows the DFIG-WT configuration system.

The DFIG short-circuit response has been treated widely in literature [3], [4], [5], and different expressions describing the short-circuit current were provided [6] [7]. However, most of the short-circuit current expressions describe the short-circuit response only under crowbar ignition. The DFIG short-circuit response under continuous rotor voltage control and/or partial voltage drop was not adequately addressed in literature.

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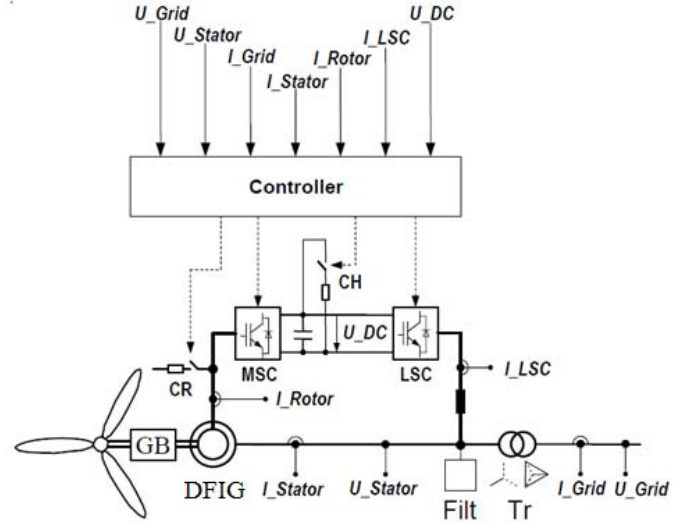


Fig. 1 DFIG-WT schematic diagram

The peak short-circuit current i_p and the initial symmetrical short-circuit current I_k^+ are important for protection system design and network stability study [8]. The estimation of those quantities directly from the DFIG parameters especially under continuous rotor voltage control is difficult due to the fast reaction of the controller, which influences the short-circuit quantities and behavior, also the influence of the R/X ratio i_p as well as the decaying rate of the transient components has been yet not investigated. This paper addresses the influences of different R/X ratios on i_p of different configurations of DFIG-WT when connected to strong and weak networks.

II. SHORT-CIRCUIT QUANTITIES CALCULATION

i_p as well as I_k^+ can be directly estimated from transient calculations. However, due to network complexity the transient calculation would not be convenient, as it is tedious and time-consuming process. Therefore, a set of reliable equations, which directly estimate the short-circuit current quantities, are required.

IEC-60909 offers simplified and reliable procedures based on equivalent voltage source calculation and correction factors for short-circuit current quantities calculation with sufficient

accuracy [9], where I_k^+ can be directly calculated using the subtransient impedance Z^+ of the electrical equipment as given in (1), also i_p can be directly calculated from I_k^+ as given in (2). However, the value of factor κ , which is dependent on the R/X ratio (3), is required first to calculate i_p .

$$I_k^+ = \frac{cU_n}{\sqrt{3Z^+}} \quad (1)$$

$$i_p = \sqrt{2\kappa I_k^+} \quad (2)$$

$$\kappa = 1.02 + 0.98e^{-3R/X} \quad (3)$$

According to IEC-60909 there are three different methods for R/X ratio calculation in meshed network, they are:

1. Uniform R/X ratio (Method A)
2. R/X ratio at short circuit location (Method B)
3. Equivalent frequency f_c (Method C)

A. Method A

The factor κ is calculated based on (2) taking the smallest ratio of R/X in all branches.

B. Method B

The R/X ratio is calculated from the equivalent impedance seen from the short-circuit location. A correction value 1.15 modifies the factor κ to cover inaccuracies caused by using R_k/X_k ratio from network reduction with complex impedances.

C. Method C

The equivalent impedance seen from short-circuits location is calculated assuming $f_c = 20\text{Hz}$, then the R/X ratio is calculated by:

$$\frac{R}{X} = \frac{R_c}{X_c} \cdot \frac{f_c}{f} \quad (4)$$

III. SIMULATION STUDY

A. Network Configuration

Two different network configurations with different ratings were used. In the first network configuration, a 3-winding transformer connects a 6 MW DFIG-WT to a 170 MVA network feeder then a 34 MVA network feeder. In the second network configuration, a 2-winding transformer connects a 2 MW DFIG-WT to 52 MVA network feeder then to a 10 MVA network feeder. The different network configurations are shown in Fig. 2. A fault is applied at the zero crossing of the voltage with a fault impedance value that creates always a 40%-45% voltage drop at the DFIG-WT terminals. The network feeder R/X ratio as well as the fault impedance is varied from 0.01 to 1.2. Prior to the fault both DFIG-WTs were operating at 1.0 p.u active power set point, unity power

factor, and 1.2 p.u rotational speed.

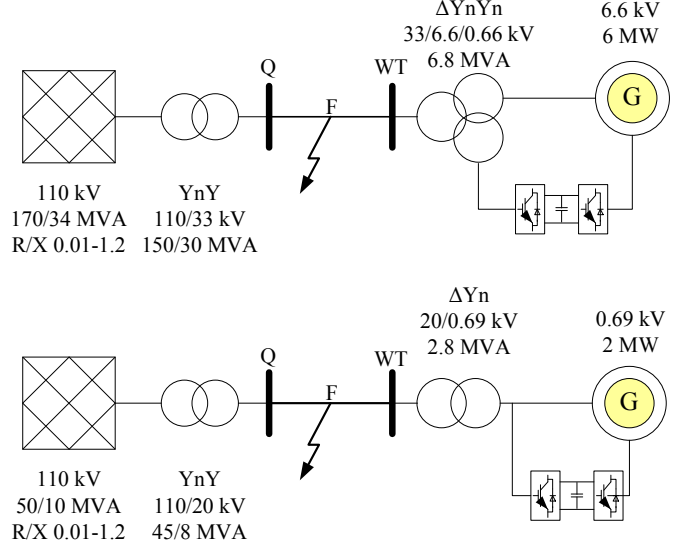


Fig. 2 Network configurations for simulation study

B. Equivalent Circuit Diagram

Fig. 3 shows the equivalent circuit diagram of the network, where the ratio of the symmetrical locked-rotor current I_{LR} to the rated current I_r of the DFIG was used to estimate the transient impedance Z_{WT}^+ of the DFIG-WT as follow:

$$Z_{WT}^+ = \frac{1}{I_{LR}/I_r} \cdot \frac{U_r^2}{S_r} \quad (5)$$

The total initial symmetrical current is first calculated using the total equivalent impedance seen from the short-circuit location, then a current divider rule was applied between the DFIG-WT and the feeder to calculate the contribution of the DFIG-WT to the total initial symmetrical short-circuit current. It is worth noting that the contribution of the line side converter (LSC) to the total initial symmetrical short-circuit current is not considered; because the IEC-60909 didn't define a method to consider the contribution of voltage source converters (VSC) to short-circuit current.

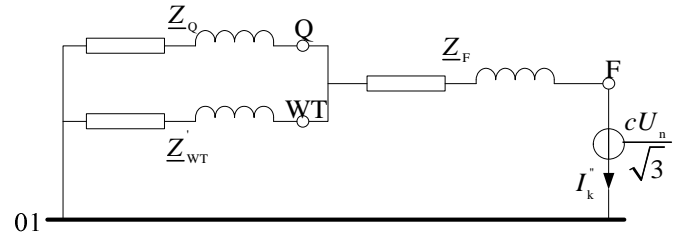


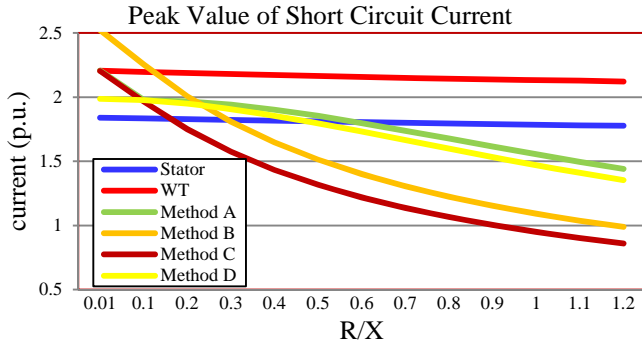
Fig. 3 Equivalent circuit diagram

C. Simulation Results

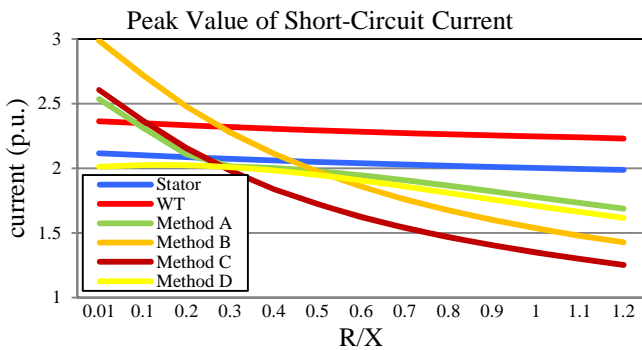
The R/X ratios were estimated based on IEC-60909 methods (A, B and C) with an additional fourth method (Method D) based on the total impedance seen from the DFIG-WT location was also used. i_p of DFIG-WT and DFIG stator based on the four methods and from simulation results are shown in Fig. 4.

I_k^* of DFIG-WT and DFIG stator were extracted from simulation results. The results from simulation and (1) are shown in Fig. 5.

The rate of decay of DC current component of DFIG-WT and DFIG stator were also extracted from simulation results. The results from simulation and the four methods of R/X ratio calculation are show in Fig. 6.

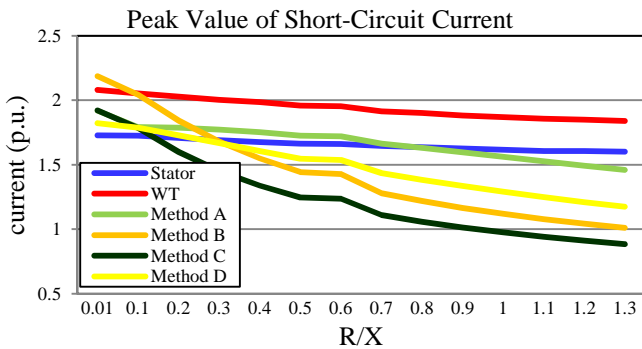


(a) 6 MW DFIG-WT connected to 170 MVA feeder

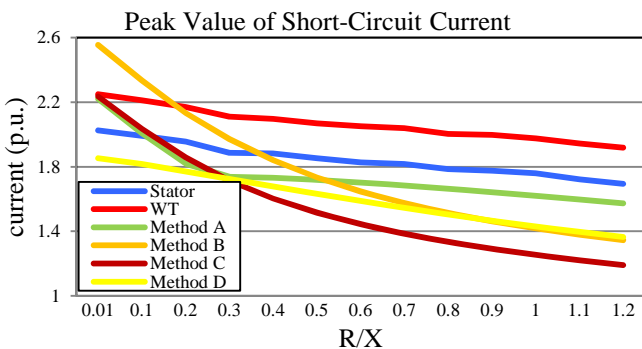


(b) 2 MW DFIG-WT connected to 52 MVA feeder

Fig. 4 Peak short-circuit current under strong network

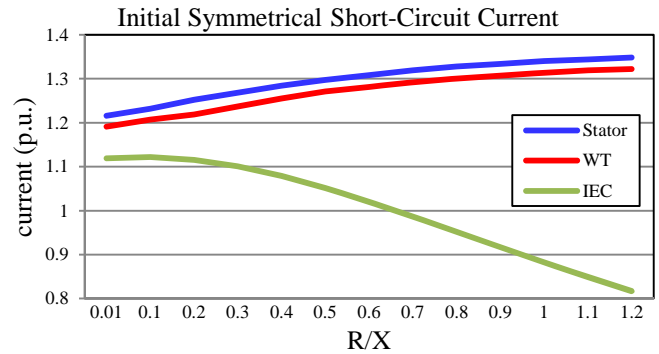


(a) 6 MW DFIG-WT connected to 34 MVA feeder

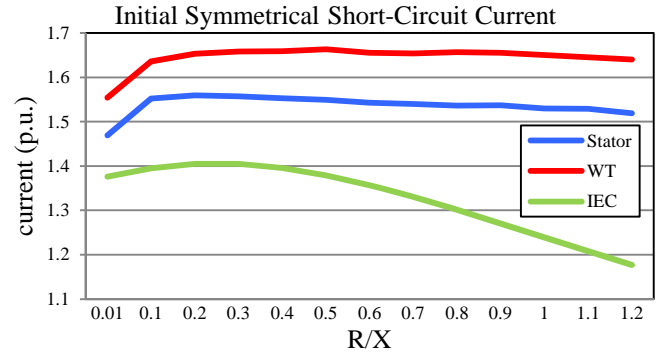


(b) 2 MW DFIG-WT connected to 10 MVA feeder

Fig. 5 Peak short-circuit current under weak network

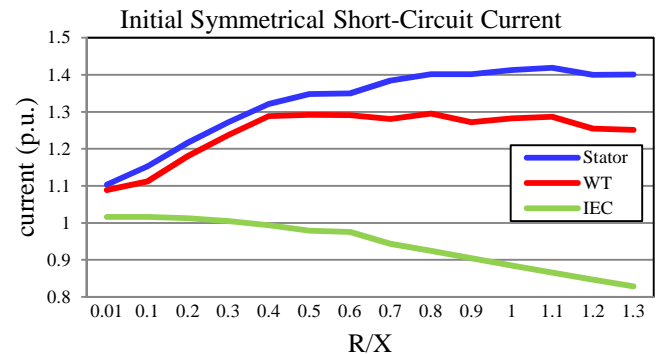


(a) 6 MW DFIG-WT connected to 170 MVA feeder

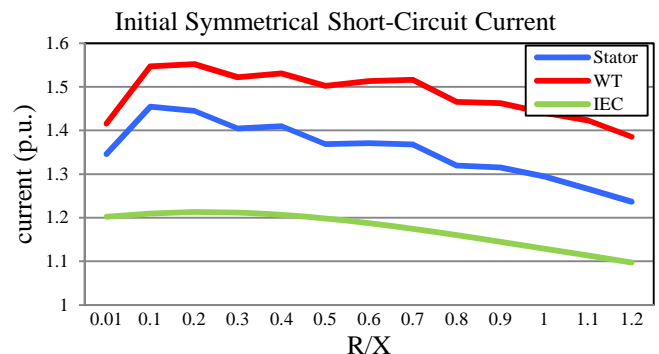


(b) 2 MW DFIG-WT connected to 52 MVA feeder

Fig. 6 Initial symmetrical short-circuit current under strong network



(a) 6 MW DFIG-WT connected to 34 MVA feeder



(b) 2 MW DFIG-WT connected to 10 MVA feeder

Fig. 7 Initial symmetrical short-circuit current under weak network

D. Simulation Results Discussion

Due to the large difference between the short-circuit capacity of the network feeder (170, 52 MVA) and the DFIG-WT (6.8, 2.08 MVA), the fault current would be supplied mostly from the network feeder, and when the ratio of the R/X ratio of the network changes, the i_p of the DFIG-WT

would be almost constant as it sees a negligible change in network impedance, which can be observed from simulation results in Fig. 4. However, when the difference in the short circuit capacity is not large, in case of 34 and 10 MVA, the contribution of the DFIG-WT becomes significant, and the change in the R/X ratio of the network would influence the value of i_p of the DFIG-WT as can be seen in Fig. 5. Although, the amount of change in the value of the i_p of the DFIG-WT is not that much, due to the low R/X ratio of the DFIG-WT, 0.008 and 0.2 for the 6 and 2 MW DFIG-WT respectively.

The calculated values of i_p based on the three methods proposed by IEC-60909 (A, B and C) as well as the values based on the fourth method proposed here didn't match the values from the simulation results and the error between the calculated values and the values from the simulation results were high, more than 5%, especially at high values of R/X ratio. The reason for the large error would be related to the factor κ , where the factor κ accounts for the decaying of the DC current component and the decay of the AC current component is accounted by special fictitious ratios R_f/X_f , which are provided from the manufacturer. These ratios are considerably higher than the natural ratios and would result in lower values for factor κ and consequently i_p , but the calculated values are already lower than the actual values. Additionally, the fictitious ratios R_f/X_f are not provided by the WT manufacturers.

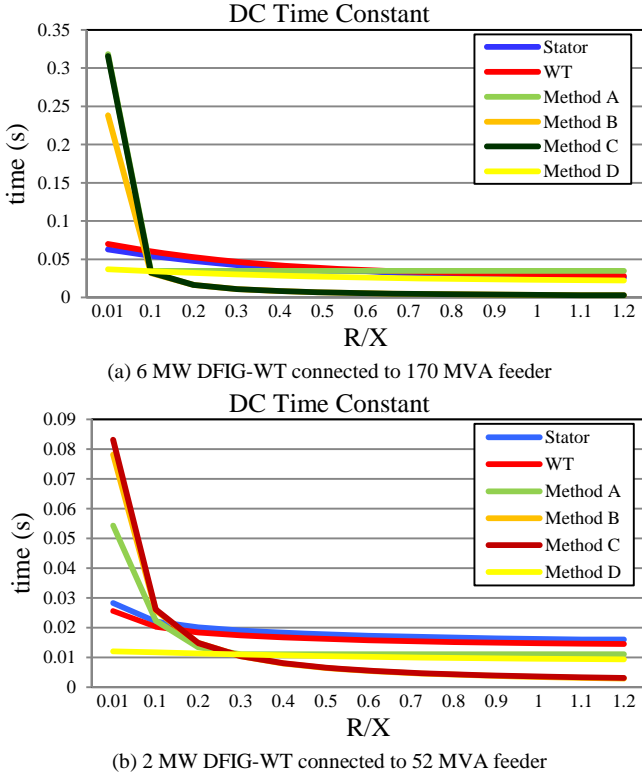


Fig. 8 DC time constant under strong network

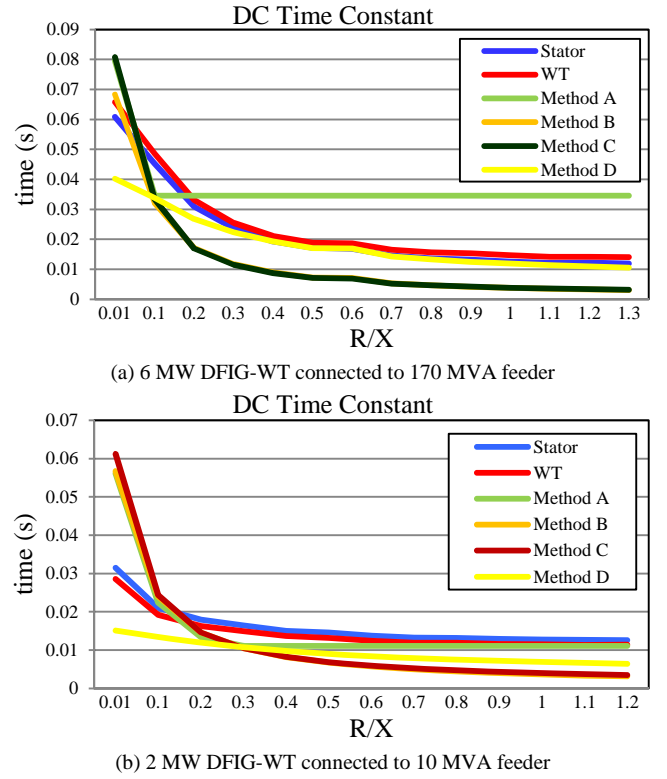


Fig. 9 DC time constant under weak network

The expression described by (3) were derived to lead to the maximum instantaneous value of the short-circuit current, which would occur when short-circuit is applied at the zero crossing of the voltage and i_p occurs 10 ms after the short-circuit occurrence. i_p will occur 10 ms after the short-circuit occurrence when the R/X ratio is equal to zero, even the R/X ratio of the DFIG-WT is low, especially for the 6 MW DFIG-WT, i_p doesn't occur 10 ms after the short-circuit occurrence, which shows the great influence of the controller on the short-circuit response of the DFIG-WT; also it is not always the case when the short-circuit is applied at the zero crossing of the voltage the maximum instantaneous short-circuit current will occur, because i_p of the DFIG-WT is formed from the DFIG stator current and the LSC current, and when both currents from the DFIG stator and LSC are in phase the maximum instantaneous short-circuit current would occur, but when the current from the DFIG stator and LSC are not in phase the maximum instantaneous short-circuit current will not occur. This could be easily observed in Fig. 6, where I_k^+ of the DFIG-WT are smaller than the I_k^+ of the DFIG stator of 6 MW DFIG-WT and this is reversed in the 2 MW DFIG-WT.

In Fig. 6 and 7 I_k^+ of the 6 MW DFIG-WT increases with every increase in the R/X ratio; also I_k^+ of the stator is higher than the I_k^+ of the DFIG-WT. on the other hand, I_k^+ of the 2 MW DFIG-WT first increases with every increase in the R/X ratio

then it starts to decrease; also I_k^+ of the DFIG-WT is higher than the I_k^+ of the stator. The last statement shows that the DFIG-WT short-circuit response have a different natures and it is not always the same short-circuit response under different ratings, configurations, parameters and controller settings of the DFIG-WT; also the LSC have a considerable contribution and influence which cannot be ignored.

There is a large error between the values of I_k^+ from the simulation results and the results based on (1) as can be observed in Fig. 6 and 7. This is due to the usage of the locked-rotor impedance to represent the transient impedance of the DFIG-WT. the locked-rotor impedance could be used only under short circuited rotor, but when there is a continuous voltage control from the rotor, the locked-rotor impedance would give a non-accurate values, this is because the controller parameters, especially the gain of the voltage and current controller, play an important role in the internal impedance of the DFIG-WT and the usage of the locked-rotor impedance would not consider the controller role. Additionally, even the LSC don't undergo any transient phenomena but it has a considerable effect as it behaves as a constant current source, and the negligence of the LSC contribution is not appropriate, which shows the need to establish a standard definition for the VSC short-circuit contribution.

The error in calculation of I_k^+ would consequently lead to an error in the calculation of i_p , which is also a reason why a large error occurred between the actual and calculated values of i_p in Fig. 4 and 5.

The DC time constants, shown in Fig. 8 and 9, decrease with the increase in R/X ratio, which is normal due to the increased resistance value. The three methods A, B and C weren't able to provide a good value for the DC time constant. However, method D was able to give a good value, because it depends on the impedance seen from DFIG-WT location not on the total impedance seen from the fault location, but due to the usage of the locked-rotor impedance, the values provided at low R/X ratio were not accurate enough.

IV. CONCLUSION

This paper investigated the influence of different R/X ratio on the short-circuit quantities of the DFIG-WT under different network configurations and ratings. The simulation results show that i_p is merely the same when the DFIG-WT is connected to a strong network. However, when the DFIG-WT is connected to a weak network i_p decreases more or less in a linear form with every increase in the network R/X ratio. The different configurations of the DFIG-WT as well as different ratings and controller setting influence the value of I_k^+ when the

network R/X ratio changes.

A new method for R/X ratio calculation in meshed networks with large number of wind energy sources should be introduced. The locked-rotor impedance is not the right value for short-circuit current calculation and a new value is needed. The LSC have a considerable influence/contribution and new standards should be introduced to consider it. IEC-60909 definitions for short-circuit quantities need to be updated to consider the influence of large wind energy source on short-circuit contribution.

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